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# **Properties of Prealloyed Steel Powder Metallurgy Products**

**Battelle Memorial Institute**

**prepared for  
Army Weapons Command, Rock Island, Illinois**

**DECEMBER 1972**

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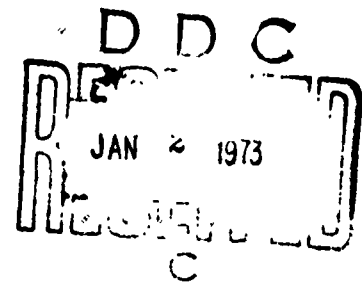
SWERR-TR-72-83

**PROPERTIES OF PREALLOYED STEEL  
POWDER METALLURGY PRODUCTS  
- FINAL REPORT -**



**TECHNICAL REPORT**

DECEMBER 1972



**RESEARCH DIRECTORATE  
WEAPONS LABORATORY, WECOM  
RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE  
U. S. ARMY WEAPONS COMMAND**

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| 13. ABSTRACT<br>A program to evaluate the properties of prealloyed steel powders, consolidated by various fabrication techniques, was conducted under the direction of the Research Directorate, Weapons Laboratory, WECOM. Sixteen lots of low-alloy prealloyed steel powder, representing seven different major alloys (4130, 1040, 8620, 4640, 4650, 8650, and 9450) were formed into test specimens, heat treated, and tested. Processes used to fabricate the test specimens included die press and sinter, isostatic press and sinter, hot repress (limited deformation forging), and high-energy rate forming (HERF). With all fabrication procedures employed, commercial practice was closely adhered to; no attempt was made to optimize any given fabrication procedure. Tensile and impact property data, and the dependence of these values on fabrication and heat treatment parameters are presented. Specimens fabricated by hot repressing and HERF methods exhibited tensile and impact properties far superior to specimens fabricated by cold pressing and sintering. Optimization of the hot repress operation, to include improved oxidation protection during preform preheating and a greater degree of metal flow during pressing, should result in specimens exhibiting properties close to those normally associated with wrought materials. (U) (Westerman, R. E. and Sump, K. R.) |                                                                                                                               |                                                    |

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- FINAL REPORT -

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## FOREWORD

This report was prepared by Dr. R. E. Westerman and K. R. Sump of the Pacific Northwest Laboratories, Battelle Memorial Institute, in compliance with Contract MIPR A1-1-50248-M1-Ws under the direction of the Research Directorate, Weapons Laboratory, WECOM, U. S. Army Weapons Command, with W. V. Cassell as project engineer.

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## 1. INTRODUCTION

The successful application of powder metallurgy fabrication techniques to ordnance components offers substantial economic incentives. In order to gain acceptance for such applications, powder metallurgy (P/M) products must demonstrate an overall utility and reliability comparable to that of the wrought or cast components they are intended to replace.

It is well known that products produced by conventional die press and sinter P/M fabrication techniques generally exhibit mechanical properties inferior to those of their wrought counterparts, because of the high concentration of pores within the bulk material. This problem can be minimized by employing fabrication procedures which lead to high densification, such as hot repressing and forging. Densification of the product is especially important when considering the fabrication of P/M components from high strength, heat treatable steels, as the high-strength characteristics of these steels are inefficiently utilized unless the density approaches the theoretical maximum. This makes the fabrication process, and the resulting compact density, extremely important considerations when optimum properties are sought in a given part.

The hot repressing and forging of steel P/M preforms is currently receiving a great deal of attention, particularly in the automotive industry. Improvements in powders, manufacturing procedures, and preform design are making the economic advantages of components produced in this fashion increasingly evident. A number of papers have been published which outline the economic advantages of high-strength hot repressed or forged steel P/M components and the problems involved in their manufacture, and which list some physical/mechanical properties of resulting parts or test pieces.<sup>(1-26)</sup>

The primary advantages of P/M hot repressing or forging over forging of wrought material are 1) a reduced number of fabrication steps, 2) material saving due to reduction of scrap loss, 3) reduced pressure requirement, and 4) reduced machining costs due to close tolerances and good surface finish. With proper preform design, appropriate powder

composition, caution in handling the preform to avoid contamination prior to forging, and a high degree of densification, mechanical properties approaching those exhibited by wrought materials can be obtained.

## 2. PROGRAM OBJECTIVES

The mechanical properties which can be obtained from heat-treatable steel P/M parts have not yet been adequately determined. There has been a lack of work and published data in this area, partly due to the proprietary nature of much of the advanced work currently in progress. Also, the work which has been published has been the result of a variety of evaluation procedures, frequently specialized, applied to parts or samples which have been fabricated by substantially differing fabrication techniques.

The limits of applicability of conventional P/M fabrication techniques have not been well defined, particularly as applied to prealloyed steel powders. Also, the use of specialized testing procedures, not typical of those commonly applied to wrought products, has given the design engineers little opportunity to compare the characteristics of P/M materials with those of wrought products.

The present program has four major objectives:

- To determine the physical and mechanical properties of P/M products made from a wide range of prealloyed steel powders and produced by conventional powder metallurgy fabrication techniques, viz., die press/sinter and isostatic press/sinter. Cold and hot repress operations are included in this series of tests.
- To determine the physical/mechanical properties of products of the same powders resulting from the more advanced high-energy-rate-forming (HERF) fabrication process. Resulting compacts approach theoretical density, and so can be considered close P/M analogs to wrought products.
- To investigate the influence of a range of hot repress fabrication parameters on a selected group of steel powders.

- To compare the results of the foregoing fabrication procedures, determine the utility of currently employed fabrication techniques as applied to prealloyed steel powders, and present the data in a form usable by designers. Available vendor data are also presented. Testing procedures used for wrought products have been applied throughout. Fabrication process/powder combinations yielding inferior properties are included in the presentation, to help define the limits of P/M process applications and to help form the foundation for future developmental work.

A total of sixteen different steel powders was employed in the fabrication processes. Of these, ten were totally prealloyed, and six were prealloyed with the exception of carbon. The broad spectrum of powders used assured the formation of valid general conclusions regarding the suitability of conventional P/M fabrication techniques as applied to alloy steel powders. All materials used are nominally heat treatable, and all samples were evaluated in the heat-treated (quenched and tempered) condition.

It must be emphasized that the objective of this program was not the optimization of P/M properties through development of powder compositions, preform designs, or fabrication procedures. Emphasis was placed instead on determining and cataloging properties obtained by applying more or less conventional P/M processing to a range of prealloyed powders. This permits the establishment of a P/M property baseline, so that the need for, or effects of, optimization may become apparent.

### 3. PROGRAM DESCRIPTION

This program is divided into three tasks. Each task will be briefly described in this section.

#### 3.1 Task A

Task A was concerned with the basic application of the conventional die press/sinter process to prealloyed steel powders. Process parameters

were confined to compacting at 80 ksi and sintering at 2050°F, followed by a standard heat treatment procedure.

A total of eight powders was processed. Six were various modifications of type 4130, differing in mesh size, chemistry, and atomization technique. The remaining two powders were types 1040 and 8620, each totally prealloyed. The 8620 specimens were tested in the carburized (15-mil case) and heat-treated condition, with no surface preparation following carburization or heat treatment.

The green density and the sintered density were determined for each material. The Charpy V-notch impact strength and the room temperature tensile strength of the materials were determined after the sintering operation. A number of compacts produced in Task A were too fragile to handle, and so could not progress to the mechanical property determination stage, which necessarily involved machining and handling operations. Ability to withstand handling and machining was treated throughout this program as a qualitative material property.

The results of preliminary Task A studies on 4130 powder of three mesh sizes were used to define the most suitable mesh sizes of powders used in the next task (Task B), as well as the 1040 and 8620 powders included in Task A.

### 3.2 Task B

The P/M fabrication processes employed in this task were intended to extend beyond the limited Task A work, in that three major processes were to be employed: die press and sinter (with cold and hot repress), isostatic press and sinter (with cold and hot repress), and high-energy-rate-forming (HERF).

In the case of die pressing, three initial compaction pressures were used, two sintering temperatures, two hot repress temperatures, and a cold repress operation. The isostatic press process sequence was identical, with the exception that only one initial compaction pressure was used.

The HERF fabrication technique was restricted to two temperatures and two impact pressures.

Six powders were used in the major Task B study: a 4130 prealloy, processed throughout the entire fabrication procedure outlined above, and five "shelf item" prealloys, processed only through the die press/sinter operation outlined in the foregoing.

An important part of the Task B effort was termed the "Cursory Study," in which the subprocess of each major process (die press, iso-press, HERF) which yielded the best mechanical properties using 4130 prealloyed powder was applied to four additional powders. By this means data on relatively high quality compacts were made available over a broader range of materials.

The density of all compacts resulting from all Task B processes was determined. The tensile properties and hardness were determined on all compacts except those resulting from the original compaction (green compacts). Impact properties were determined on all nonshelf-item powder compacts resulting from a "best process," and all shelf-item powder compacts resulting from an 80 ksi die compaction, 2050°F sinter process. This latter process was chosen to correspond with results of Task A impact tests.

All Task B Charpy tests were performed over a range of temperatures, from -40°F to 450°F.

### 3.3 Task C

The third part of the program, Task C, was primarily a hot repressing (limited deformation forging) investigation, to determine the influence of hot repressing temperatures and pressures on the mechanical properties of the resulting products. Four powders were selected for study, based on their behavior in the preceding task and overall programmatic considerations. Tensile and Charpy V-notch impact data were obtained on all samples. An additional tempering temperature was also investigated, viz., 1100°F, to gain additional tempering data; all previous samples had been tempered at either 900°F (noncarburized samples) or 450°F (carburized samples).

An overall outline of the program is shown in Figure 1. Detailed operational sequences and parameters have been omitted from this outline.

#### 4. MATERIALS

##### 4.1 Steel Powders

Materials used in the present study are described in detail in Figures 2, 3, 4, and 5. The shapes of typical as-received particles of each lot are shown in Figure 6.

The Hoeganaes -100 mesh 4130 (Code B) powder, water atomized and reduced, was the powder emphasized throughout the study. It was bought in two lots, B1 and B2, of somewhat different sieve analysis and chemistry. The two lots were later found to exhibit markedly different compaction characteristics.

The powders used in Task A are Codes A through H. The mesh size specification of powders A, B1, and C ranged from -40 to -200, for determination of the effect of this parameter on mechanical properties. They were derived from the same ingot, for control of chemistry. The final carbon level is controlled by the postatomization reduction process, and so does not depend on the carbon level in the original melt. Powders D through F were not reduced after atomization, and the atomization process itself varies from powder to powder as a process parameter.

The powders used in Task B include lots B1 and B2, plus F through N. Powders F, G, H, and I were used in the Cursory Study. Powder I, prealloyed 4100 with 0.3 percent carbon blended in, is included for comparison with the totally prealloyed 4130 powders.

Powders J through N are shelf item powders, included in the program for extension of available vendor data as well as to permit comparison of their properties with those resulting from the special heat powders which make up the remainder of the program. Powder J is completely prealloyed powder; the rest of this group require blending of appropriate amounts of carbon.

| TASK | STEEL        | CODE (LOT) | PROCESSING                                                                                                                                    | DATA                           |        |
|------|--------------|------------|-----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|--------|
|      |              |            |                                                                                                                                               | TENSILE                        | IMPACT |
| A    | 4130         | A          | Compaction 80 ksi<br>Sinter 2050°F<br><br>with<br>Standard heat treatment:<br>Austenitize 1575°F,<br>water quench<br>temper for 1 hr at 900°F | X                              | X      |
|      |              | B1,2       |                                                                                                                                               | X                              | X      |
|      |              | C          |                                                                                                                                               | X                              | X      |
|      |              | D          |                                                                                                                                               | Compacts too fragile to handle |        |
|      |              | E          |                                                                                                                                               |                                |        |
|      |              | F          |                                                                                                                                               |                                |        |
|      | 1040         | G          |                                                                                                                                               | X                              | X      |
|      | 8620         | H          | Same as above, but carburized. Given standard heat treatment, except tempered at 450°F                                                        | X                              | X      |
| B    | 4130         | B1         | Die press (DP)<br>Iso press (IP) } standard heat treatment<br>HERF<br><br>One best process from each of above                                 | X                              | X      |
|      |              | B2         |                                                                                                                                               |                                |        |
|      | 4130         | F          | HERF only - standard heat treatment                                                                                                           | X                              | X      |
|      | 4100 + 0.3 C | I          | One best process from each major process: DP, IP and HERF } - standard heat treatment                                                         | X                              | X      |
|      | 1040         | G          |                                                                                                                                               |                                |        |
|      | 8620         | H          |                                                                                                                                               |                                |        |
|      | 4650         | J          | Die press portion of Task B, with standard heat treatment<br><br>80 ksi compaction, 2050°F sinter, standard heat treatment                    | X                              | X      |
|      | 4600 + 0.5 C | K          |                                                                                                                                               |                                |        |
|      | 4600 + 0.5 C | L1         |                                                                                                                                               |                                |        |
|      | 8600 + 0.5 C | M          |                                                                                                                                               |                                |        |
|      | 9400 + 0.5 C | N          |                                                                                                                                               |                                |        |
| C    | 4130         | B2         | Compact at 100 ksi, sinter 2050°F                                                                                                             | X                              | X      |
|      | 4600 + 0.4 C | L2         | Hot repress at 80 ksi, 120 ksi, 160 ksi at 1800°F, 2000°F, 2200°F                                                                             | X                              | X      |
|      | 4650         | J          | Austenitize, water quench, temper at 900°F and 1100°F                                                                                         | X                              | X      |
|      | 8620         | H          | Same, except carburized, and tempered at 450°F and 900°F                                                                                      | X                              | X      |
|      |              |            |                                                                                                                                               |                                |        |

FIGURE 1. Basic Outline of Powder Metallurgy Program

| CODE                                    |      | A                       | B1                      | B2                      | C                       |
|-----------------------------------------|------|-------------------------|-------------------------|-------------------------|-------------------------|
| TYPE                                    |      | 4130                    | 4130                    | 4130                    | 4130                    |
| VENDOR                                  |      | Hoeganaes               | Hoeganaes               | Hoeganaes               | Hoeganaes               |
| PROCESS                                 |      | water atomized, reduced | water atomized, reduced | water atomized, reduced | water atomized, reduced |
| MESH                                    |      | -40                     | -100                    | -100                    | -200                    |
| Chemical Analysis, wt.percent           | C    | 0.28                    | 0.26                    | 0.28                    | 0.28                    |
|                                         | Cr   | 1.00                    | 1.00                    | 1.00                    | 1.00                    |
|                                         | Mn   | 0.48                    | 0.48                    | 0.58                    | 0.48                    |
|                                         | Mo   | 0.21                    | 0.21                    | 0.23                    | 0.21                    |
|                                         | Ni   |                         |                         |                         |                         |
|                                         | P    |                         |                         |                         |                         |
|                                         | Si   | 0.40                    | 0.40                    | 0.20                    | 0.40                    |
|                                         | S    |                         |                         |                         |                         |
|                                         | Fe   | bal.                    | bal.                    | bal.                    | bal.                    |
| H <sub>2</sub> Loss percent             |      |                         | 0.40                    | 0.58                    |                         |
| Sieve Analysis wt.percent U.S. Standard | 80   | 12.7                    | T*                      | T                       | T                       |
|                                         | 100  |                         | 0.6                     | 0.7                     | T                       |
|                                         | 140  | 26.7                    | 8.7                     | 13.4                    | T                       |
|                                         | 200  | 15.5                    | 19.7                    | 23.0                    | 0.6                     |
|                                         | 230  |                         | 6.4                     | 6.4                     | 1.1                     |
|                                         | 270  |                         |                         |                         |                         |
|                                         | 325  | 17.2                    | 22.5                    | 19.1                    | 23.6                    |
|                                         | -325 | 27.8                    | 42.1                    | 37.4                    | 74.7                    |
| Apparent Density, gm/cm <sup>3</sup>    |      |                         |                         |                         |                         |

\* T = Trace

**FIGURE 2. Metal Powder Characteristics**

| CODE                                 |      | D              | E              | F             | G                       |
|--------------------------------------|------|----------------|----------------|---------------|-------------------------|
| TYPE                                 |      | 4130           | 4130           | 4130          | 1040                    |
| VENDOR                               |      | Glidden-Durkee | Federal-Mogul  | Federal-Mogul | Hoeganaes               |
| PROCESS                              |      | water atomized | water atomized | gas atomized  | water atomized, reduced |
| MESH                                 |      | -100           | -100           | -100          | -100                    |
| Chemical Analysis, wt.percent        | C    | 0.52           | 0.28           | 0.29          | 0.41                    |
|                                      | Cr   | 0.94           | 1.02           | 1.09          |                         |
|                                      | Mn   | 0.58           | 0.56           | 0.40          | 0.81                    |
|                                      | Mo   | 0.36           | 0.20           | 0.23          |                         |
|                                      | Ni   |                |                |               |                         |
|                                      | P    |                | 0.011          | 0.010         | 0.01                    |
|                                      | Si   | 0.42           | 0.31           | 0.23          |                         |
|                                      | S    | 0.008          | 0.014          | 0.011         | 0.009                   |
|                                      | Fe   | bal.           | bal.           | bal.          | bal.                    |
| H <sub>2</sub> Loss, percent         |      |                |                |               | 0.49                    |
| Sieve Analysis<br><br>U.S. Standard  | 80   |                |                |               | T                       |
|                                      | 100  | 0.3            | 3.7            | 2.5           | 1.0                     |
|                                      | 140  | 13.8           | 13.1           | 19.1          | 18.4                    |
|                                      | 200  | 18.4           | 17.1           | 20.5          | 28.2                    |
|                                      | 230  |                |                |               | 6.7                     |
|                                      | 270  |                | 15.4           | 12.6          |                         |
|                                      | 325  | 28.2           | 9.1            | 11.5          | 19.8                    |
|                                      | -325 | 39.3           | 41.6           | 33.8          | 25.9                    |
| Apparent Density, gm/cm <sup>3</sup> |      |                |                |               | 2.71                    |

FIGURE 3. Metal Powder Characteristics

| CODE                                 |     | H                       | I                       | J              | K              |
|--------------------------------------|-----|-------------------------|-------------------------|----------------|----------------|
| TYPE                                 |     | 8620                    | 4100 + 0.30 C*          | 4650           | 4600 + 0.5 C*  |
| VENDOR                               |     | Hoeganaes               | Hoeganaes               | Glidden-Durkee | Glidden-Durkee |
| PROCESS                              |     | water atomized, reduced | water atomized, reduced |                |                |
| MESH                                 |     | -100                    | -100                    | -100           | -100           |
| Chemical Analysis, wt.percent        | C   | 0.20                    | 0.30*                   | 0.46           | 0.59*          |
|                                      | Cr  | 0.38                    | 0.95                    |                |                |
|                                      | Mn  | 0.81                    | 0.58                    | 0.47           | 0.45           |
|                                      | Mo  | 0.24                    | 0.23                    | 0.23           | 0.27           |
|                                      | Ni  | 0.71                    | <0.05                   | 1.94           | 1.99           |
|                                      | P   |                         |                         |                |                |
|                                      | Si  | 0.26                    | 0.19                    | 0.49           | 0.30           |
|                                      | S   |                         | 0.013                   | 0.029          | 0.03           |
|                                      | Fe  | bal.                    | bal.                    | bal.           | bal.           |
| H <sub>2</sub> Loss, percent         |     |                         |                         |                |                |
| Sieve Analysis<br><br>U.S. Standard  | 80  | T                       |                         |                |                |
|                                      | 100 | 0.5                     | T                       | 2.7            | 1.4            |
|                                      | 140 | 14.1                    | 8.9                     | 11.0           | 9.8            |
|                                      | 200 | 26.2                    | 23.8                    | 13.4           | 13.4           |
|                                      | 230 | 6.7                     | 8.9                     |                |                |
|                                      | 270 |                         |                         |                |                |
|                                      | 325 | 19.6                    | 25.0                    | 23.8           | 25.7           |
|                                      | 325 | 32.9                    | 33.4                    | 49.1           | 49.7           |
| Apparent Density, gm/cm <sup>3</sup> |     |                         |                         |                |                |

\* Carbon blended separately

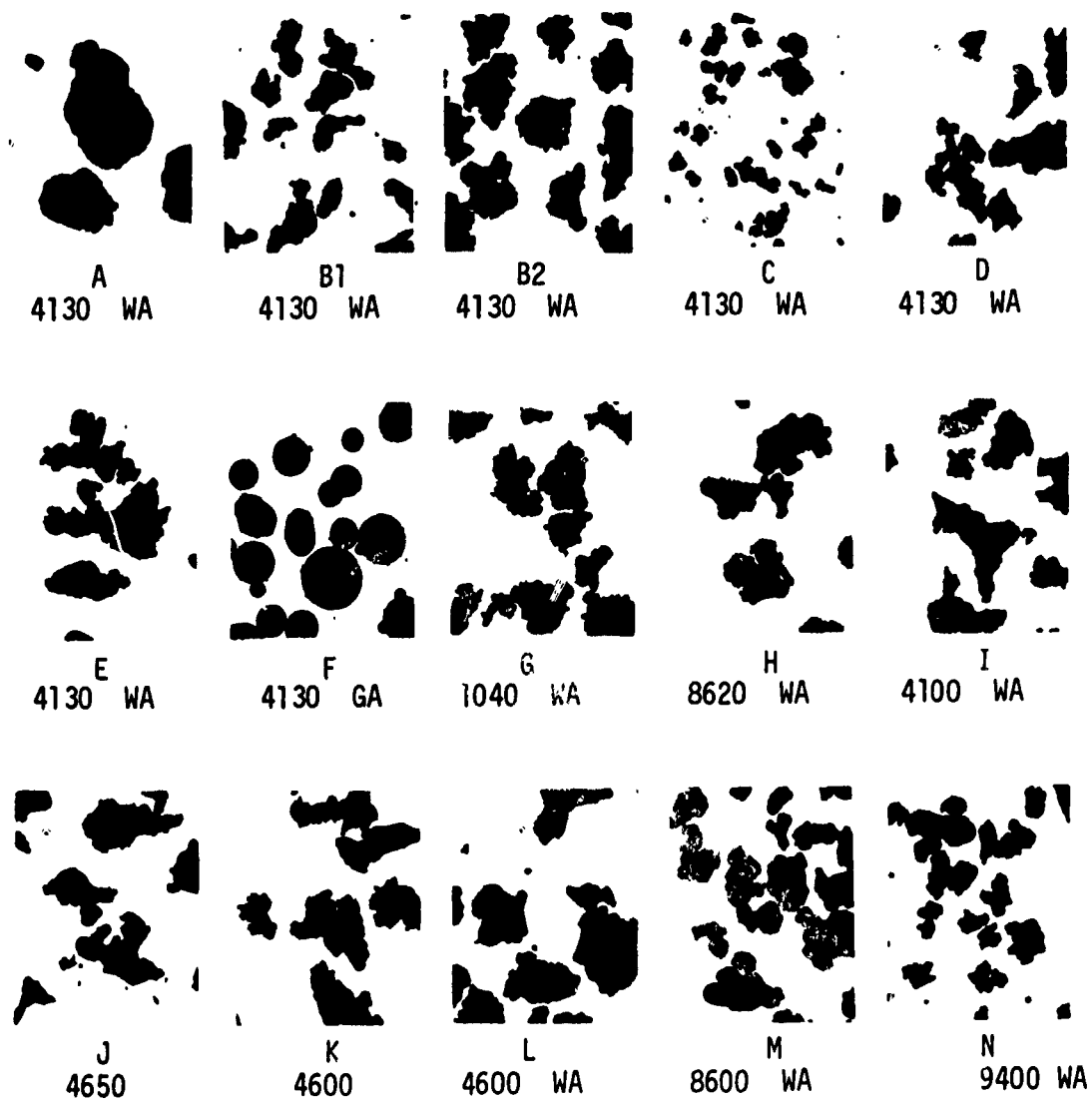
FIGURE 4. Metal Powder Characteristics

| CODE                                 |      | L1                      | L2                        | M                       | N                       |
|--------------------------------------|------|-------------------------|---------------------------|-------------------------|-------------------------|
| TYPE                                 |      | 4600 + 0.5 C*           | 4600 + 0.4 C <sup>†</sup> | 8600 + 0.5 C*           | 9400 + 0.5 C*           |
| VENDOR                               |      | A.O. Smith-Inland       | A.O. Smith-Inland         | A.O. Smith-Inland       | A.O. Smith-Inland       |
| PROCESS                              |      | water atomized, reduced | water atomized, reduced   | water atomized, reduced | water atomized, reduced |
| MESH                                 |      | -100                    | -100                      | -100                    | -100                    |
| Chemical Analysis, wt. percent       | C    | 0.51*                   | 0.41 <sup>†</sup>         | 0.51*                   | 0.51*                   |
|                                      | Cr   |                         |                           | 0.60                    | 0.31                    |
|                                      | Mn   | 0.19                    | 0.19                      | 0.09                    | 0.24                    |
|                                      | Mo   | 0.46                    | 0.46                      | 0.49                    | 0.30                    |
|                                      | Ni   | 2.00                    | 2.00                      | 0.59                    | 0.25                    |
|                                      | P    | 0.005                   | 0.005                     | 0.007                   | 0.008                   |
|                                      | Si   | 0.027                   | 0.027                     | 0.018                   | 0.05                    |
|                                      | S    | 0.016                   | 0.016                     | 0.012                   | 0.014                   |
|                                      | Fe   | bal.                    | bal.                      | bal.                    | bal.                    |
| H <sub>2</sub> Loss, percent         |      | 0.15                    | 0.15                      | 0.42                    | 0.32                    |
| Sieve Analysis<br><br>U.S. Standard  | 80   |                         |                           | 0.5                     |                         |
|                                      | 100  | 2.8                     | 2.8                       | 4.0                     | 0.5                     |
|                                      | 140  | 17.1                    | 17.1                      | 13.5                    | 14.6                    |
|                                      | 200  | 25.9                    | 25.9                      | 24.5                    | 27.4                    |
|                                      | 230  | 4.9                     | 4.9                       | 6.0                     | 6.4                     |
|                                      | 270  |                         |                           |                         |                         |
|                                      | 325  | 22.8                    | 22.8                      | 23.5                    | 23.6                    |
|                                      | -325 | 26.5                    | 26.5                      | 28.0                    | 27.5                    |
| Apparent Density, gm/cm <sup>3</sup> |      | 2.93                    | 2.93                      | 3.29                    | 3.13                    |

\* 0.50 wt.percent carbon blended separately

† 0.40 wt.percent carbon blended separately

FIGURE 5. Metal Powder Characteristics



**FIGURE 6.** Prealloyed Powders Used in Program  
 WA = water atomized GA = gas atomized  
 50X

#### 4.2 Carbon

The carbon used in this program is a product of Southwestern Graphite, Burnet, Texas. It is a natural graphite, of particle size 0.2 to 0.7 micrometer, designated Grade 1651.

### 5. PROCEDURES

#### 5.1 Powder Preparation

Powder preparation involved the addition of a lubricant for cold pressing and the addition of graphite to adjust the carbon content of certain steel powders. No lubricant was required for the isostatic pressing and HERF processes. The blending of lubricant and/or graphite with the metal powders was done in a Hyde paint shaker. Powder, additive, and steel balls were loaded in a two-quart steel container and mixed for 15 minutes.

One-half weight percent of zinc stearate was added to all of the powders fabricated by cold pressing, with the exception of powders D, E, and F in Task A. These materials were difficult to press into coherent green compacts, so one weight percent zinc stearate was added to improve compact strength.

#### 5.2 Die Pressing

Die pressing was the most common means of initial compaction employed in the present program, as it was used exclusively in Task A and was the principal initial compaction method used in Tasks B and C.

One of the punch and die sets used in the program is shown in Figure 7. The cavity of the die used in Tasks A and B is 1.125 in. wide, 4.225 in. long, and 3.000 in. deep. The cavity of the die used in Task C is 0.475 in. wide, 2.715 in. long, and 2.375 in. deep.

The 300-ton hydraulic press used in the die pressing operation is shown in Figure 8. The ram speed is approximately 400 in./minute.

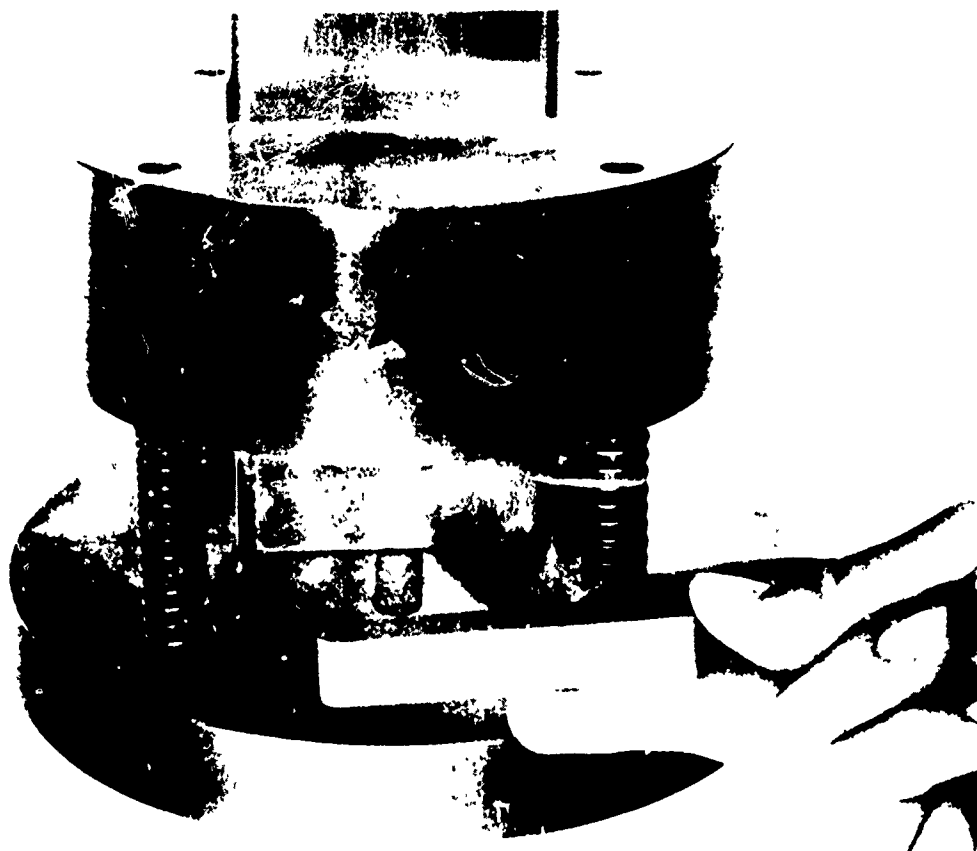
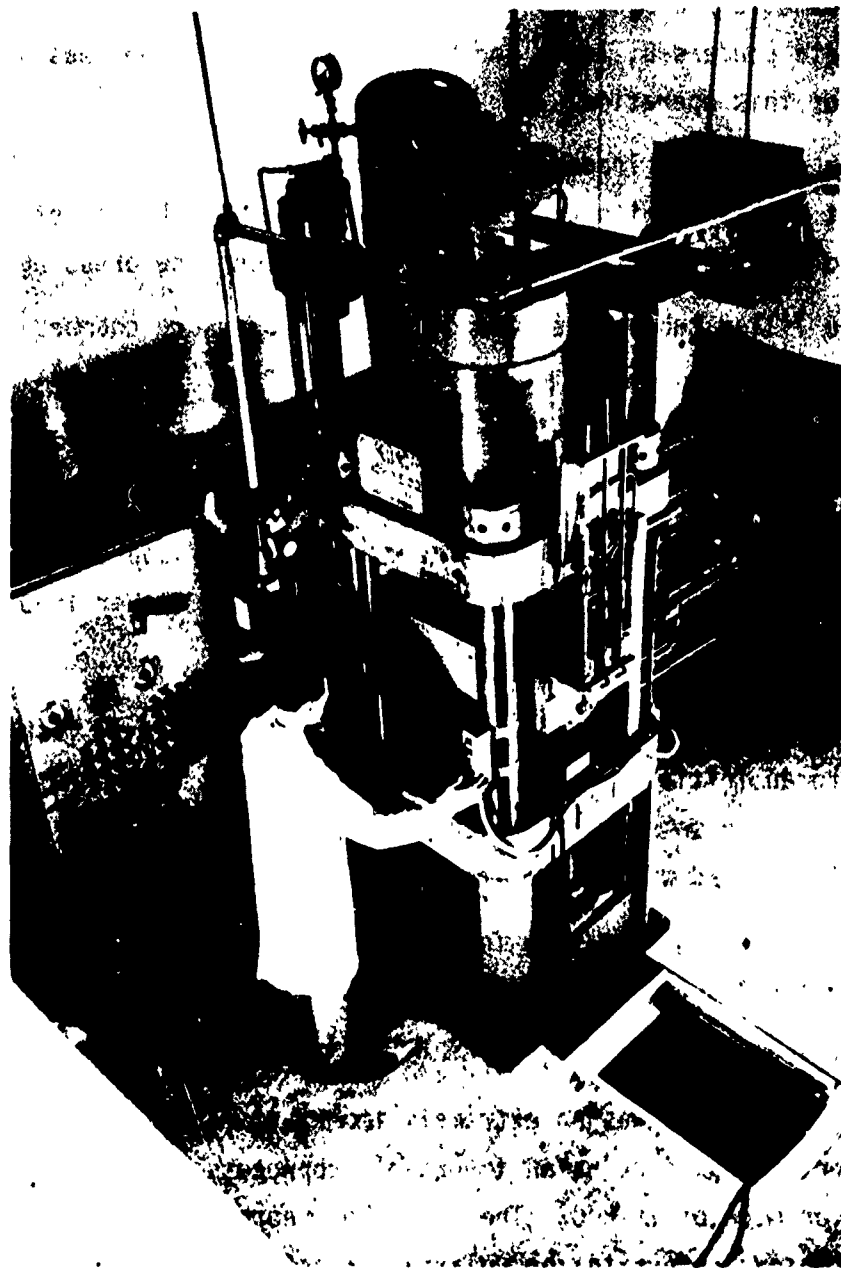


FIGURE 7. Die and Punches Used in Die Pressing Operation,  
with Typical Compact



**FIGURE 8.** Hydraulic Press Used for Die Pressing and Forging

### 5.3 Isostatic Pressing

Isostatic pressing was one of the three principal methods used to consolidate powders B, I, G, and H in Task B. No binder was added to the powder for this operation.

The powder was loaded into thin wall rubber tubing, which was then sealed at both ends with a rubber cork (Figure 9). Pieces of angle iron were used to hold the filled tube straight during the pressing operation.

The filled tubes were loaded in a high pressure chamber (Figure 10), and compacted at 50,000 psi with pressurized oil. The resulting rods were approximately 12 in. long and 0.75 in. in diameter.

### 5.4 Sintering

The samples resulting from the die press and isopress operations were sintered for 1/2 hr in dissociated ammonia at either 1650 or 2050°F.

### 5.5 Cold Repress and Sinter

A cold repress and sinter operation was employed in Task B as a subprocess to an initial die press/sinter operation. The repressing was done at 80 ksi in the same die in which the initial die pressing was done. The die was lubricated with butyl stearate.

The sintering operation following cold repress was done at 2050°F for 1/2 hr in dissociated ammonia.

### 5.6 Hot Repressing

Hot repressing was an extremely important fabrication process in the current study, forming an important subprocess in Task B and the major fabrication mode of Task C. The term "hot repressing" as used in the present context refers to the uniaxial pressing of a heated preform in a close-fitting die with very little lateral metal flow. "Hot repressing" is synonymous with the terms "hot densification,"<sup>(1)</sup> "hot recompaction,"<sup>(2)</sup> "hot coining,"<sup>(3)</sup> or "hot restriking."<sup>(3)</sup> Hot repressing is not as effective as the more conventional forging processes in reducing the porosity of the preform, and so the impact and fatigue properties of parts



FIGURE 9. Powder-Filled Rubber Tubing Ready  
for Isostatic Pressing Operation

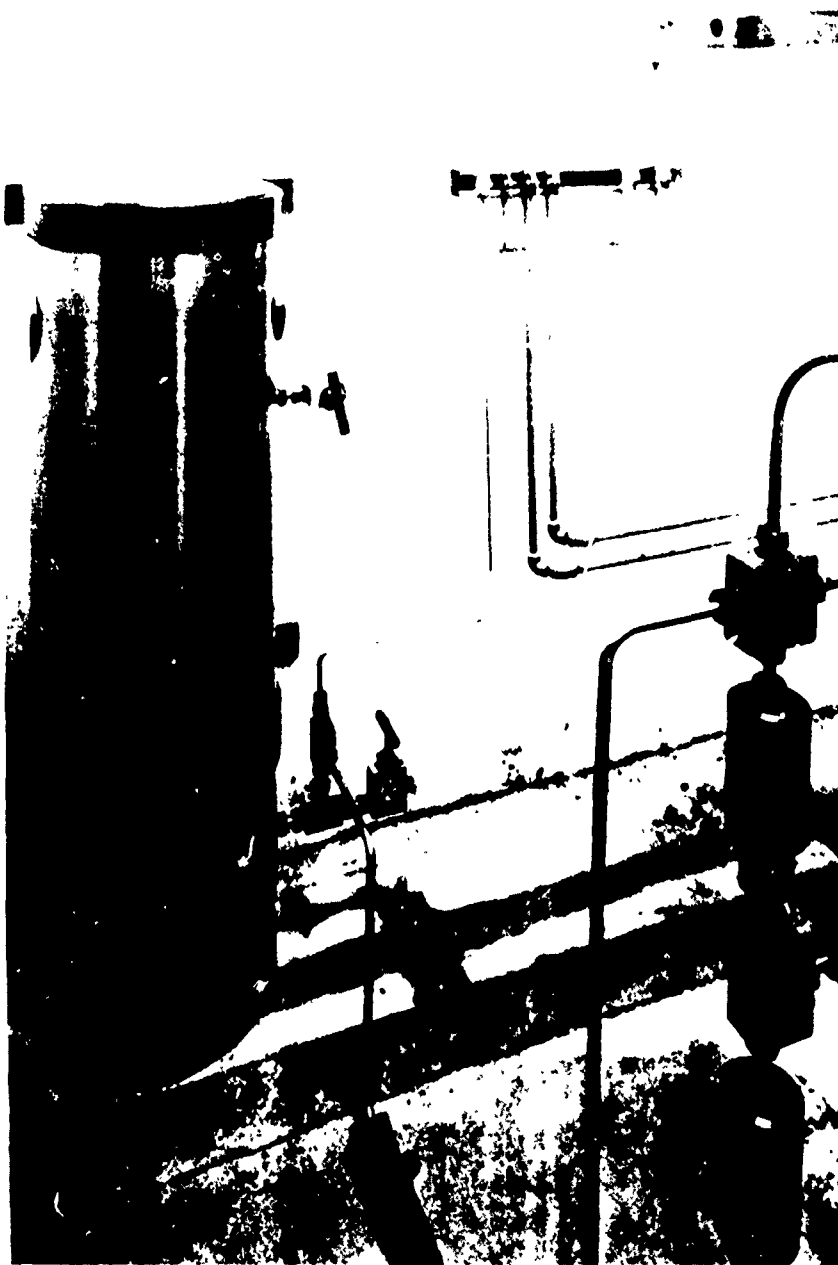


FIGURE 10. High-Pressure Chamber for Isostatic Pressing

made by hot repressing are lower than the properties of parts made by processes involving substantial metal flow.<sup>(4)</sup> Optimization of preform design and fabrication procedures (i.e., forging procedures) can yield parts having substantially better properties than those reported herein. Such optimization was beyond the scope of the present effort.

One of the hot repressing dies used in the program is shown in Figure 11. The hot repressing operations of Task B utilized a die having a cavity 0.565 in. wide, 4.000 in. long, and 1.300 in. deep. The hot repressing operations of Task C utilized a die having a cavity 0.503 in. wide, 3.750 in. long, and 1.250 in. deep. The dies are portable, with upper and lower punches. A commercial graphite-oil mixture was used for die lubrication.

The amount of deformation imposed on any given Task B preform during hot repressing is difficult to estimate, because the preforms varied somewhat in size and shape due to the different processes used to make the preforms, i.e., isostatic pressing and die pressing. Very little lateral flow occurred in any given case, however. In the case of Task C hot repressing, an average lateral flow of 6 percent and an average preform height reduction of 16 percent took place. The height reduction varied from 14 percent to 21 percent, depending on the preform density. Samples of H and L2 materials were the least compressible (14 percent reduction), samples of B and J the most (15 and 21 percent, respectively).

No preheating of the die was done in Task B except for buildup of heat from the hot preforms. The die was preheated to 800°F in the Task C work between each increment of approximately 10 repressing operations.

The hydraulic press shown in Figure 8 was used for all repress work.

Maximum hot repress pressure was held constant at 150 ksi throughout Task B; pressure was considered a variable in Task C. No control of punch motion was imposed beyond this pressure control.

#### 5.7 High-Energy-Rate-Forming (HERF)

The HERF compaction process was the third principal compaction method used in Task B. This technique basically involves compressing a

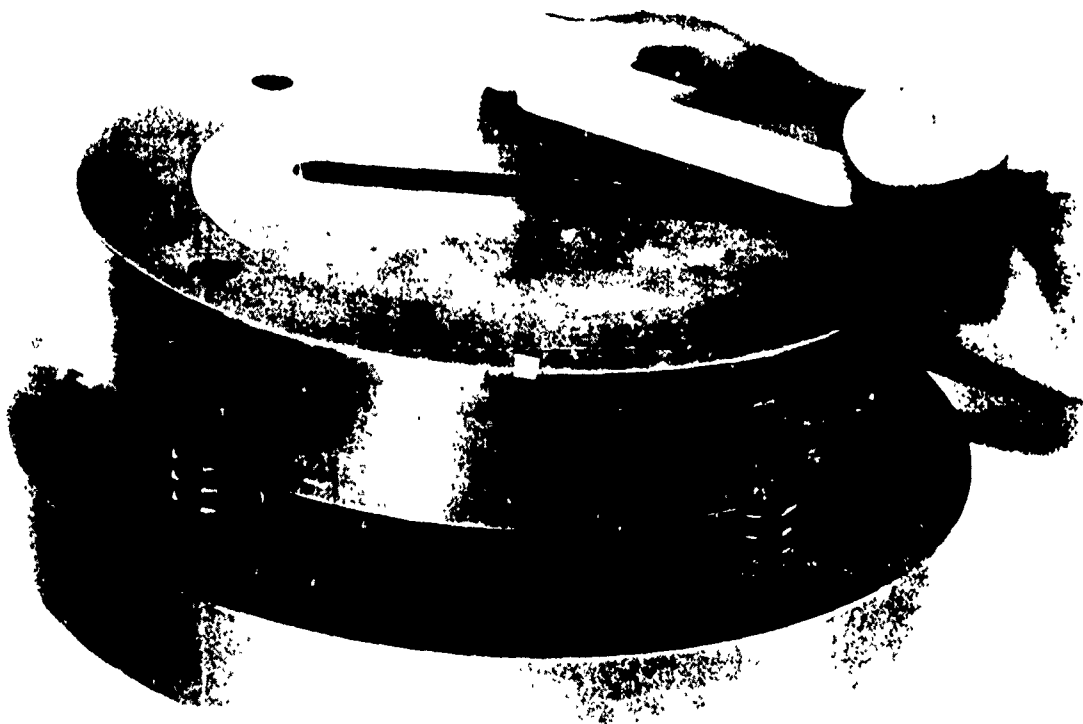


FIGURE 11. Die Used in Hot Repressing Operation, with Typical Bar

preheated powder in a closed die by a heavy ram traveling at high velocity. The ram deceleration produces very high compaction pressures (to 329 ksi in the present study) which, when imposed on a heated, highly plastic powder, allows attainment of densities close to theoretical.

The material to be densified was loaded into cylindrical stainless steel containers, 2 1/2 in. in diameter and 5 1/2 in. long. The first four billets compacted for Task B were made by pressing the powder into the containers. The remaining billets were made by loading the can with a cylinder of material preformed by isostatic pressing. This change facilitated loading and permitted loading more material into the can, resulting in a larger end product. A lid having an outgas stem was welded on each container (Figure 12).

The containers were evacuated during the period of preheating (approximately 1 hr). Two preheat temperatures were used: 1800°F and 2200°F. After the preheat temperature was attained the outgas tube was cut and sealed and the container transferred to the cylindrical closed die of the impaction machine, a Dynapak Model 1220B (Figure 13). Impaction pressures ranged from 172 ksi to 329 ksi. After compaction the billet was ejected from the die and allowed to cool. The container shell was removed by machining, and the cylindrical compact was sliced longitudinally into 1/2 in. thick slabs for heat treatment and machining.

#### 5.8 Heat Treating and Carburizing

All of the steels included in the program can be considered hardenable to some practical extent, so that the mechanical properties of all of the compacts produced can be improved, at least in principle, by an austenitizing, quenching, and tempering sequence. A standard heat treatment was desired which would take advantage of the innate compact hardenability while not contributing excessively to compact brittleness. To accomplish this, a hardness of  $R_c$  40 in the 4130 steel compacts was the heat treatment goal decided on. Compacts of Lot A 4130 steel, 1/2 in. thick, were austenitized at 1575°F in an endothermic gas atmosphere (+70°F dewpoint), quenched in still water at room temperature, and

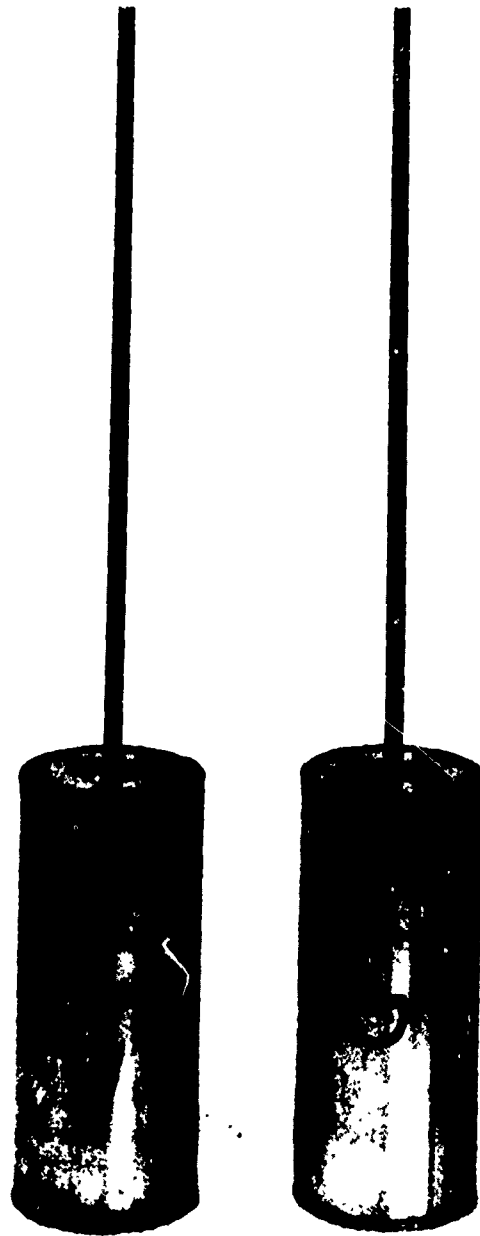


FIGURE 12. Powder Containers for HERF Process,  
with Outgassing Stems



FIGURE 13. Model 1220B Dynapak

tempered at various temperatures for 1 hr. They were then subjected to microhardness (DPH, 100 gm load) traverses, from surface to center of the sample over major particle clusters. A 900°F temper was found to produce the required hardness level. Wrought standards of 4130 yielded the same  $R_C$  40 value. All of the compacts in the program were given this standard heat treatment just prior to specimen machining. All sample blanks in the program were approximately 1/2 in. thick when heat treated, so that the central hardenability of a 1/2 in. thick infinite plate represents a "worst case" situation for heat treatment response.

The 8620 steel (Lot H) was an exception to the standard heat treatment procedure described in the foregoing. This material was always machined into tensile and Charpy V-notch specimens after compact fabrication, then pack carburized in Woodside's Rapid Carburizer\* at 1700°F for 2 hr and allowed to cool. The specimens were then austenitized at 1575°F for 1/2 hr in endothermic gas having a dewpoint of 10°F, oil quenched, and tempered for 1 hr at 450°F (Task B) or 450°F and 900°F (Task C). The resulting carburized case was approximately 15-mil thick on the high density samples, somewhat thicker on the less dense material.

Because of the range of carbon and alloy content of the steels used in the program, a considerable variation of hardnesses, hence mechanical properties, were expected to result from the standard heat treatment universally employed, and this was found to be the case. The other acceptable alternate which could be employed for purposes of comparing steel powders, viz., hardening each steel to the same hardness by varying the tempering temperature to fit the individual steel, was beyond the scope of the present program. In addition, the hardness level was considered to be no more fundamental a parameter than the tempering temperature when the purpose of a study is to provide property data for designers, especially if data over a range of tempering temperatures are to be eventually obtained.

---

\* Product of the Park Chemical Company.

## 5.9 Density Measurements

All density measurements were bulk densities determined from physical measurements and weights of the samples. Densities were taken after each process step prior to heat treatment, and are all expressed in grams per cubic centimeter. Densities obtained in this manner are somewhat lower than true sample densities, because of inevitable sample surface irregularities.

## 5.10 Mechanical Testing

### Tensile Properties

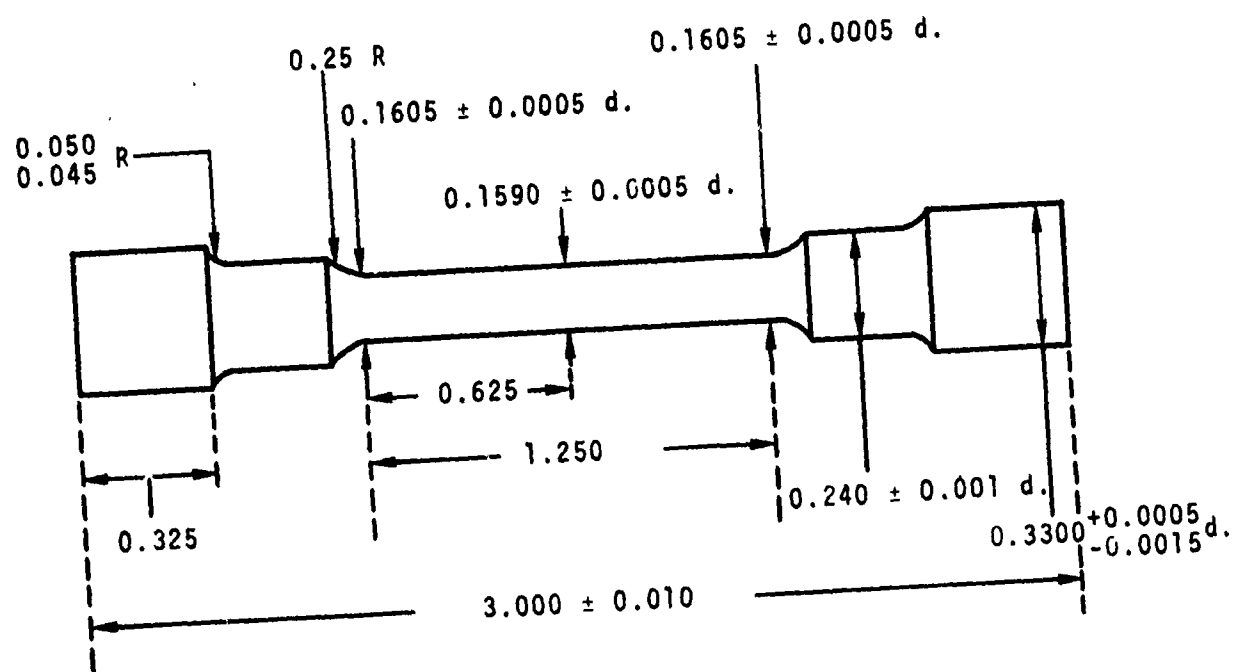
The tensile properties of the P/M products were determined by testing tensile specimens machined from the heat-treated compacts. Burton-head specimens of a special design were employed throughout the program. The dimensions of the standard specimen are given in Figure 14.

The specimens were tested at room temperature in an Instron tensile test machine at a crosshead speed of 0.050 in./min. Elongation was determined over a one-inch portion of the central gage length by means of a high-sensitivity carbide-tipped extensometer.

Breakage outside of the reduced central section was common with many of the powders used, indicating a high sensitivity to surface effects and a low fracture toughness.

Machinability of the P/M products into tensile specimens was considered a basic qualitative material property. In general, duplicate P/M blanks were submitted for machining with instructions to produce two tensile specimens. If both blanks broke, machining of that particular specimen was not attempted again, and no tensile data were recorded. Duplicate tests were attempted on all tensile evaluations.

Where yield strength (YS) data are reported, it always indicates the 0.2 percent offset yield strength. This YS frequently could not be obtained, because limited sample elongation would not permit an extrapolation of the offset line to intersect the stress-strain curve. Absence of YS data can generally be inferred to indicate that lack of sample



**FIGURE 14.** Button Head Tensile Specimen with Tapered Gage Section

ductility is at fault, though for two steels (Lots J and K) the YS data is not reported for some specimens because of erratic extensometer behavior.

### Impact Properties

Selected P/M products were machined into Charpy V-notch specimens according to ASTM specifications A370, sample type A. Four test temperatures were used in the Task B studies: -40°F, 77°F, 210°F, and 450°F. In Task C all specimens were tested in duplicate at room temperature.

### Hardness

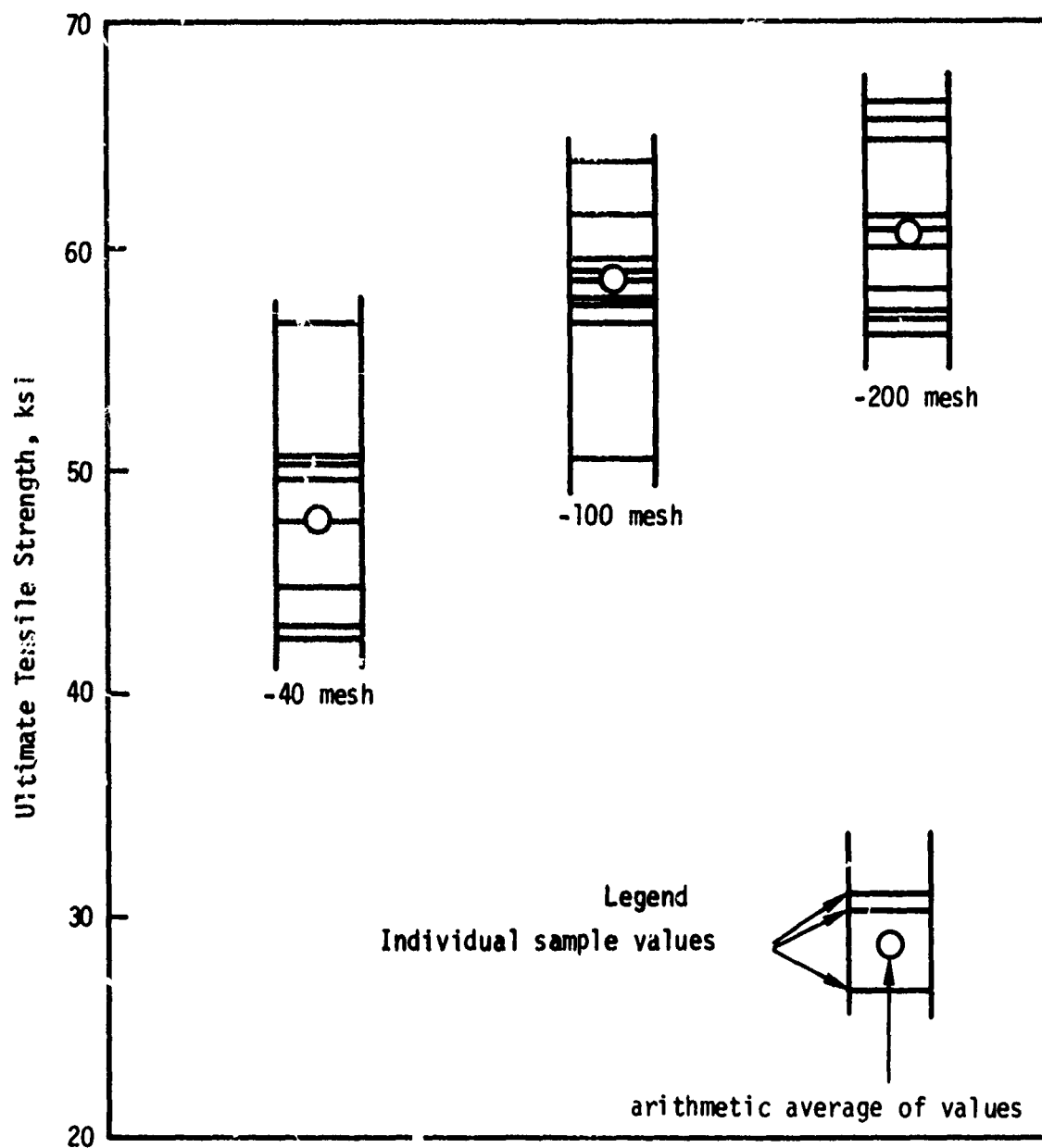
The hardness of all specimens was determined after heat treatment. Two Rockwell scales were used:  $R_C$ , using a Brale indenter and a 150 kg load, and  $R_B$ , using a 1/16-in. ball and a 100 kg load. The hardness determined by these techniques is of course an apparent hardness only, as the hardness of individual particles, or grains, is not being reported, but rather the hardness of the metal-void composite structure.

## 6. RESULTS AND DISCUSSION

### 6.1 Task A

Lots A, B1, and C of 4130 Hoeganaes water-atomized and reduced powders were compacted at 80 ksi, sintered at 2050°F, machined into tensile and Charpy V-notch specimens, and tested. The results of this initial portion of Task A were to be used to define the mesh size of the 1040 and 8620 powders also included in Task A, and also the 4130 powder mesh size to be carried into Task B. Results of a number of tensile tests (approximately ten per lot) are shown in Figure 15.

The -200 mesh material (Lot C) demonstrated the highest average UTS, 60.6 ksi; the -100 mesh material (Lot B1) was slightly lower, with an average UTS of 58.2 ksi. On a strictly comparative basis, the -200 mesh was slightly superior; this advantage, however, was felt to be offset by the fact that -200 mesh material is not as commonly used in the P/M fabrication industry as -100 mesh. For this reason the somewhat superior



**FIGURE 15.** Influence of Mesh Size on Ultimate Tensile Strength Hoeganaes AISI 4130 Powder (A, B) Compacted at 80 ksi, Sintered 2050°F  
Task A

behavior of -200 mesh material was discounted and the decision made to carry through with -100 mesh material.

The water atomized and reduced powders A, B, and C demonstrated good compaction properties. The sintered bars were strong, could be handled roughly, and machined readily. In contrast, compacts produced from the nonreduced materials D, E, and F were too fragile to handle, even after sintering; their densities were low, 5.2 to 5.6 gm/cm<sup>3</sup>. Lot F was carried into the HERF portion of the Cursory Study of Task B; powders D and E were not studied further.

The significant data of Task A are summarized in Figure 16. The table is incomplete, in that yield strength and hardness data are not included. These values may be found in the data compilation appended to the end of the report.

Data for Lots A and C will not be found in this report beyond Figure 16.

Powder Lot B2 was purchased when Lot B1 became exhausted. Lot B2 was found to be more easily compacted than Lot B1; this is evident from the data of Figure 16, and was found to be true whenever a compressibility comparison was made.

The Charpy impact values reported in Figure 16 are an order of magnitude lower than would be expected from wrought products of the same materials hardened to R<sub>c</sub> 40. No increased impact energy absorption is evident when the temperature of testing is increased. Powder Lots A, B, and C show no significant difference in impact properties.

## 6.2 Task B

The Hoeganaes 4130, -100 mesh, water-atomized and reduced steel powder designated "Lot B" was the key powder in the program, in that the processes yielding the best results in this powder were applied, in the Cursory Study, to a broader range of powders. Also, it was processed and tested far more extensively than any other powder in the program. For these reasons, the Task B results obtained using this powder will be

| CODE           | STEEL             | DENSITY<br>gm/cm <sup>3</sup> | UTS<br>ksi        | TOTAL<br>EL., %   | CHARPY V-NOTCH IMPACT<br>ENERGY, ft-lb |      |       |       |
|----------------|-------------------|-------------------------------|-------------------|-------------------|----------------------------------------|------|-------|-------|
|                |                   |                               |                   |                   | -40°F                                  | 77°F | 210°F | 450°F |
| A              | 4130              | 6.40                          | 47.8 <sup>a</sup> | 0.43 <sup>a</sup> | 1.0                                    | 1.0  | 0.8   | 0.8   |
| B1             | 4130              | 6.45                          | 58.2 <sup>a</sup> | 0.64 <sup>a</sup> |                                        |      |       |       |
| B2             | 4130              | 6.60                          |                   |                   | 1.0                                    | 0.9  | 1.0   | 0.8   |
| C              | 4130              | 6.40                          | 60.6 <sup>a</sup> | 0.73 <sup>a</sup> | 1.0                                    | 1.0  | 1.0   | 0.7   |
| G              | 1040              | 6.72                          | 40.0              | 5.1               | 1.7                                    | 2.0  | 2.0   | 1.8   |
| H <sup>b</sup> | 8620 <sup>b</sup> | 6.67                          | 40.0              | 5.1               |                                        |      |       |       |
|                |                   |                               | 57.5              | 0.3               |                                        | 1.0  |       | 0.8   |
|                |                   |                               | 55.6              | 0.3               |                                        |      |       |       |

a - Arithmetic average of approximately 10 specimens.

b - Carburized, 15-mil case; tempered 450°F, instead of 900°F.

**FIGURE 16.** Data Summary, Task A. Powders compacted at 80 ksi, sintered 2050°F, austenitized 1575°F, water quenched, tempered at 900°F.

presented first. The results obtained in the application of the "best processes" to powders F, I, G, and H in the Cursory Study will be presented next. The final Task B discussion will involve the results obtained from the "shelf item" powders J, K, L, M, and N.

#### 4130 (Lot B) Powder, Die Press

This powder was processed by three principal initial fabrication procedures: die press/sinter, isostatic press/sinter, and HERF. The die press results will be described first.

The die press/sinter procedure consisted of three initial compaction pressures. 50 ksi, 80 ksi, and 100 ksi.

Each of these initial compaction processes was followed by one of two sintering temperatures: 1650 or 2050°F.

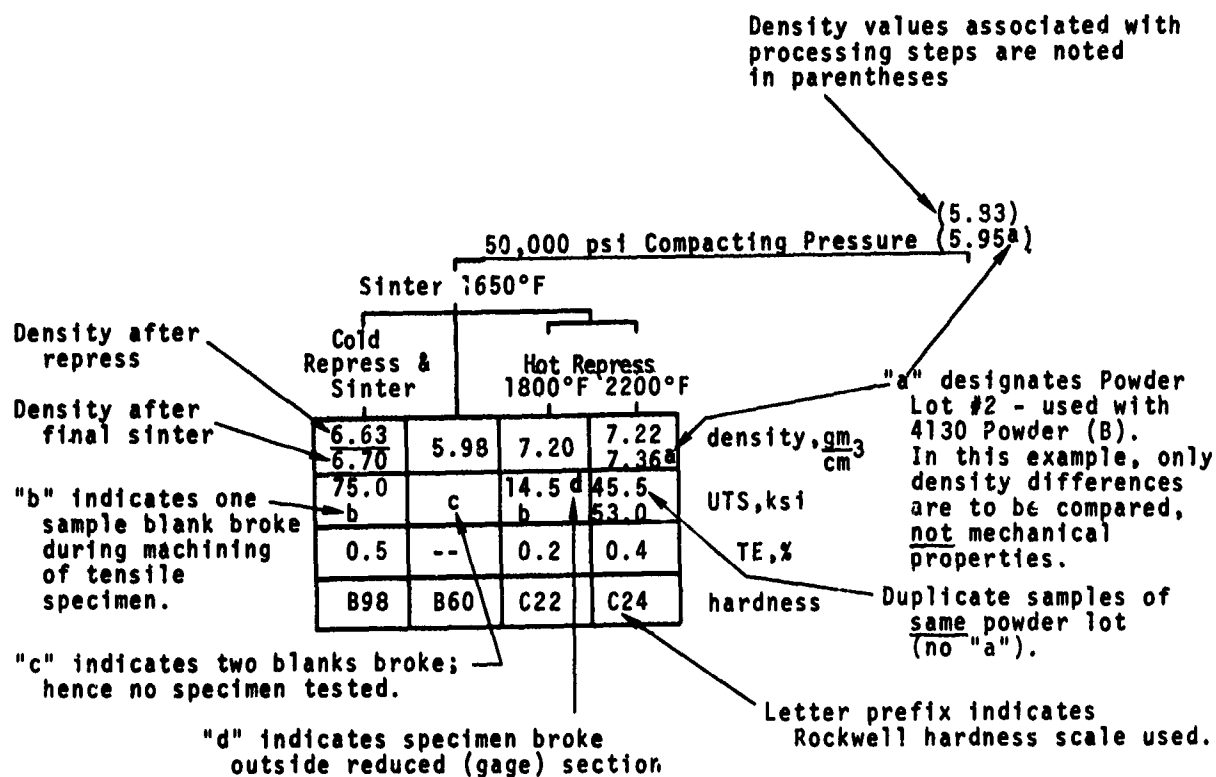
Each combined die press/sinter operation described above was followed by either a cold repress (80 ksi) and sinter (2050°F), or a hot repress (150 ksi, at either 1800°F or 2200°F).

The results of the die press processing of 4130 Lot B powder is presented in Figure 17 in a fashion which reveals the change in mechanical/physical properties as the processing progresses. A guide to assist in understanding the data presentation precedes the figure. Yield strength values have been omitted; they may be found in the handbook section appended to the report.

All mechanical property data presented have been derived from powder Lot B1. Lot B2 data is included for compressibility comparisons only. Note that use of B2 leads to higher density compacts.

High initial compaction pressures (100 ksi) coupled with high temperature forging (2200°F) yield the best properties. The cold repress and sinter operation contributes substantially to the mechanical properties of the sintered compacts. As expected, the compact initially pressed at 50 ksi and sintered at 1650°F has the lowest density and hardness values.

None of the blanks simply sintered at 1650°F without repressing survived the tensile specimen machining operation.



Guide to Understanding Data Presented in  
Figure 17

| 50,000 psi Compacting Pressure (5.81) |      |                              |                          |                          |                           |                              |             |
|---------------------------------------|------|------------------------------|--------------------------|--------------------------|---------------------------|------------------------------|-------------|
| Sinter 1650°F                         |      |                              |                          | Sinter 2050°F            |                           |                              |             |
| Cold Repress<br>& Sinter              |      | Hot Repress<br>1800°F 2200°F |                          | Cold Repress<br>& Sinter |                           | Hot Repress<br>1800°F 2200°F |             |
| $\frac{6.55}{6.60}$                   | 5.83 | 7.05                         | 7.18                     | $\frac{6.51}{6.55}$      | 5.97                      | 7.08                         | 6.98        |
| 69.5<br>67.5                          | c    | 13.8 <sup>d</sup><br>b       | 41.4 <sup>d</sup><br>103 | 61.6<br>58.3             | 21.7 <sup>d</sup><br>35.0 | 70.8<br>52.8                 | 126<br>67.6 |
| 0.4<br>0.4                            | ---  | 0.1                          | 0.3<br>3.4               | 0.4<br>0.3               | 0.3<br>0.2                | 0.5<br>0.2                   | 2.5<br>0.3  |
| B99                                   | B58  | C20                          | C27                      | B99                      | B78                       | C23                          | C27         |

density,  
gm/cm<sup>3</sup>

UTS, ksi

TE, %

hardness

| 80,000 psi Compacting Pressure (6.27) |      |                              |          |                          |              |                              |             |
|---------------------------------------|------|------------------------------|----------|--------------------------|--------------|------------------------------|-------------|
| Sinter 1650°F                         |      |                              |          | Sinter 2050°F            |              |                              |             |
| Cold Repress<br>& Sinter              |      | Hot Repress<br>1800°F 2200°F |          | Cold Repress<br>& Sinter |              | Hot Repress<br>1800°F 2200°F |             |
| $\frac{6.82}{6.85}$                   | 6.31 | 7.00                         | 7.29     | $\frac{6.72}{6.66}$      | 6.43         | 7.11                         | 7.08        |
| 81.0<br>91.4                          | c    | 47.0<br>47.5                 | 126<br>b | 70.4<br>b                | 57.2<br>53.7 | 97.5<br>96.5                 | 131<br>85.2 |
| 0.9<br>1.0                            | ---  | 0.2<br>0.2                   | 0.4      | 0.4                      | 0.4<br>0.4   | 0.4<br>0.4                   | 0.5<br>0.5  |
| B99                                   | B76  | C25                          | C32      | B94                      | B85          | C28                          | B99         |

density,  
gm/cm<sup>3</sup>

UTS, ksi

TE, %

hardness

| 100,000 psi Compacting Pressure (6.48) <sup>a</sup> (6.78) <sup>a</sup> |      |                              |                         |                          |                           |                              |                           |
|-------------------------------------------------------------------------|------|------------------------------|-------------------------|--------------------------|---------------------------|------------------------------|---------------------------|
| Sinter 1650°F                                                           |      |                              |                         | Sinter 2050°F            |                           |                              |                           |
| Cold Repress<br>& Sinter                                                |      | Hot Repress<br>1800°F 2200°F |                         | Cold Repress<br>& Sinter |                           | Hot Repress<br>1800°F 2200°F |                           |
| $\frac{6.95}{6.89}$                                                     | 6.52 | 7.16                         | 7.21                    | $\frac{6.90}{6.90}$      | 6.65<br>6.83 <sup>a</sup> | 7.11                         | 7.25<br>7.49 <sup>a</sup> |
| 89.9<br>94.6                                                            | c    | 41.4<br>54.5                 | 118 <sup>d</sup><br>145 | 89.9<br>82.5             | 61.0<br>57.3              | 94.5<br>93.0                 | 152<br>121                |
| 0.6<br>0.6                                                              | ---  | 0.1<br>0.2                   | ---                     | 0.7<br>0.4               | 0.5<br>0.4                | 0.4<br>0.2                   | 1.8<br>1.1                |
| B94                                                                     | B67  | C20                          | C29                     | B98                      | B91                       | C27                          | C31                       |

density,  
gm/cm<sup>3</sup>

UTS, ksi

TE, %

hardness

- a - Powder Lot #2. Density comparisons only.
- b - One compact broke during machining.
- c - Two compacts broke during machining.
- d - Broke at shoulder.

"Best Process"

FIGURE 17. Task B: Results of Die Press Processing of Hoeganaes Type 4130 Powder (B)

Several samples broke outside the reduced gage section, indicating the presence of stress concentration sites and low resistance to crack propagation. The total elongation (TE) is an order of magnitude below that which would be expected from wrought material of the same composition subjected to the same heat treatment.

Microstructures of pressed-and-sintered and hot repressed samples of Lot B1 material are shown in Figure 18.

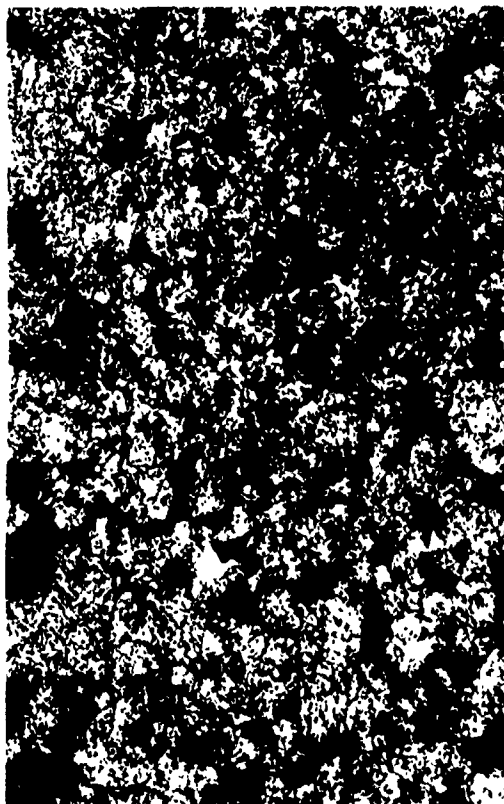
#### 4130 (Lot B) Powder, Isostatic Press

The isostatic press procedure consisted of only one initial compaction pressure, 50 ksi. This was followed by either sintering at 1650°F, sintering at 2050°F, forging at 1800°F, forging at 2200°F, or a combined sinter-forge processing. Results of the tests, and changes in mechanical properties with processing parameters, are shown in Figure 19. Yield strength data may be found in the appendix. Lot B2 data is included for density comparisons only.

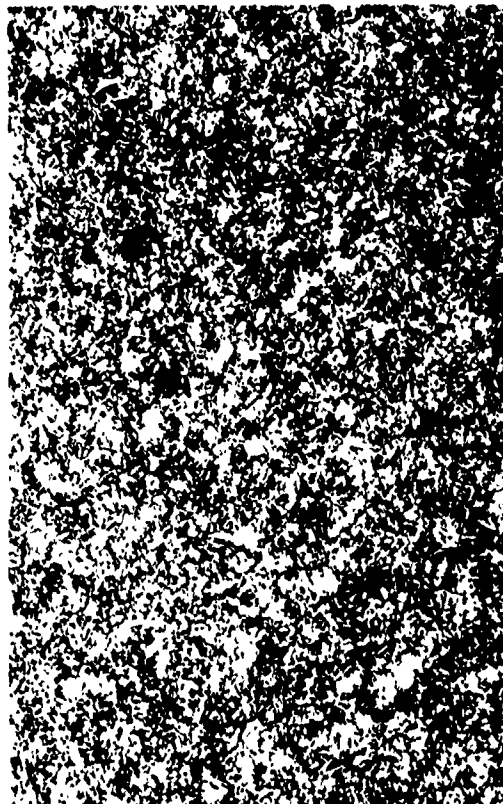
Based on tensile properties, hot repressing at 2200°F once again results in the best product, but the sintering temperature is the lower one employed, 1650°F. Once again, total elongation is low, and somewhat lower than that found in the die press "best process" (Figure 17), though the UTS values are somewhat higher. Also, the apparent hardness and density of the isopress material is higher than the die press material. The reason for this is not known.

Based on the limited data of Figure 19, the contribution of the intermediate sinter to the final forging properties can be considered to be minimal.

It was noted that a number of the more porous specimens tested up to this point in Task B had considerable internal oxidation. This was found to occur during the 900°F temper in air. To determine whether or not this oxidation was exerting undue influence on the mechanical properties of the samples, a number of representative compacts were made up, tempered in a high vacuum furnace instead of the circulating air furnace usually

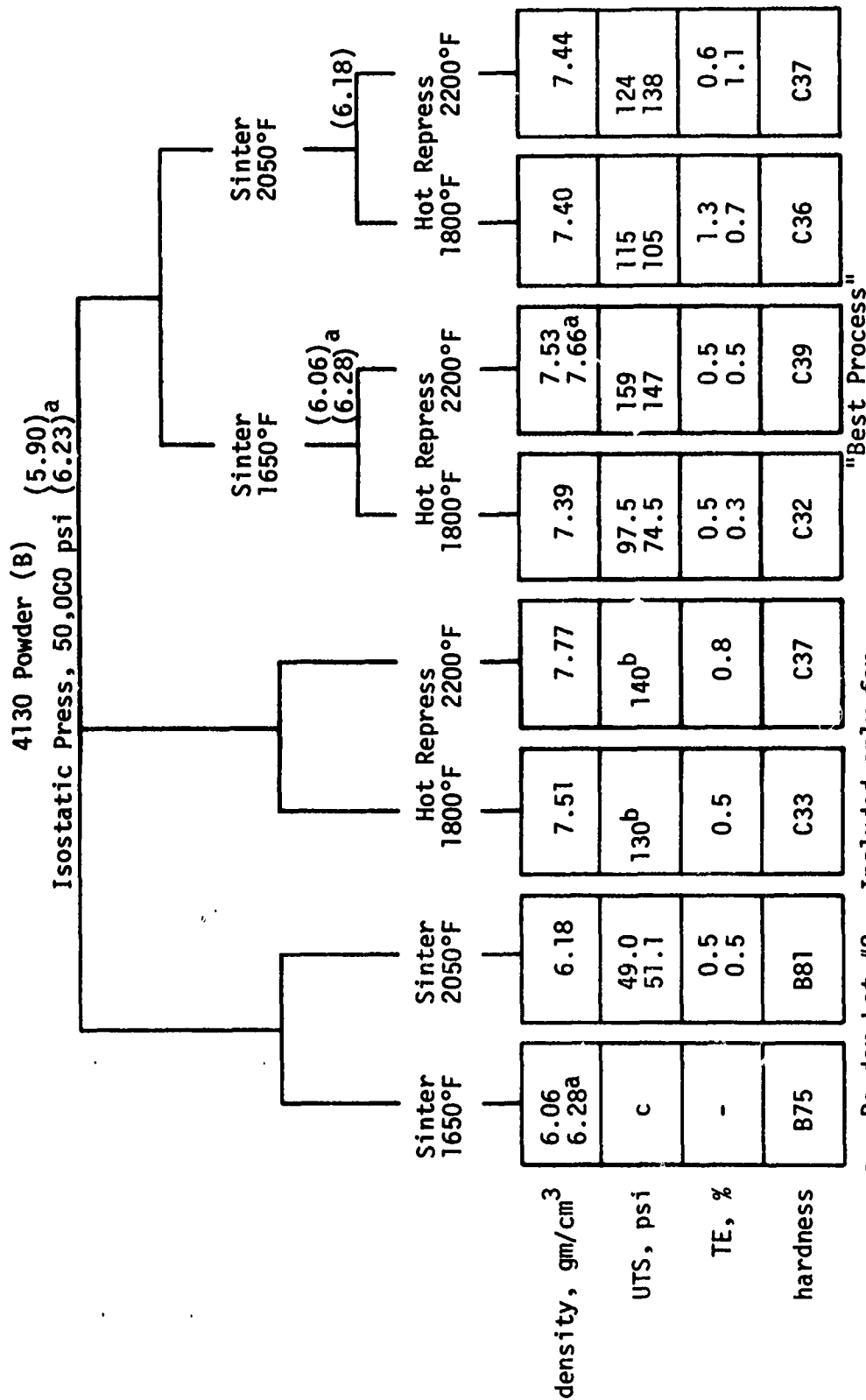


Compacted 100 KSI  
Sintered 2050 °F  
Austenitized, Quenched  
Tempered 900 °F  
Density: 6.65 gm/cm<sup>3</sup>



Compacted 100 KSI  
Sintered 2050 °F  
Hot Repressed 100 KSI at 2200 °F  
Austenitized, Quenched  
Tempered 900 °F  
Density: 7.25 gm/cm<sup>3</sup>

FIGURE 18. Microstructures of Die Pressed and Hot Repressed  
Samples of 4130 Powder (B1) 250X



- a - Powder Lot #2. Included only for density comparisons.  
 b - One sample broke during machining.  
 c - Two samples broke during machining.

FIGURE 19. Task B: Results of Isostatic Press Processing of Hoeganaes Type 4130 Powder (B)

used, and tested. No significant difference in mechanical properties was found, exonerating the air temper procedure.

#### 4130 (Lot B) Powder, HERF

The HERF processing consisted of two impact pressures and two pre-heat temperatures. The resulting properties are shown in Figure 20. Mechanical property data were obtained from both lots of powder B1 and B2.

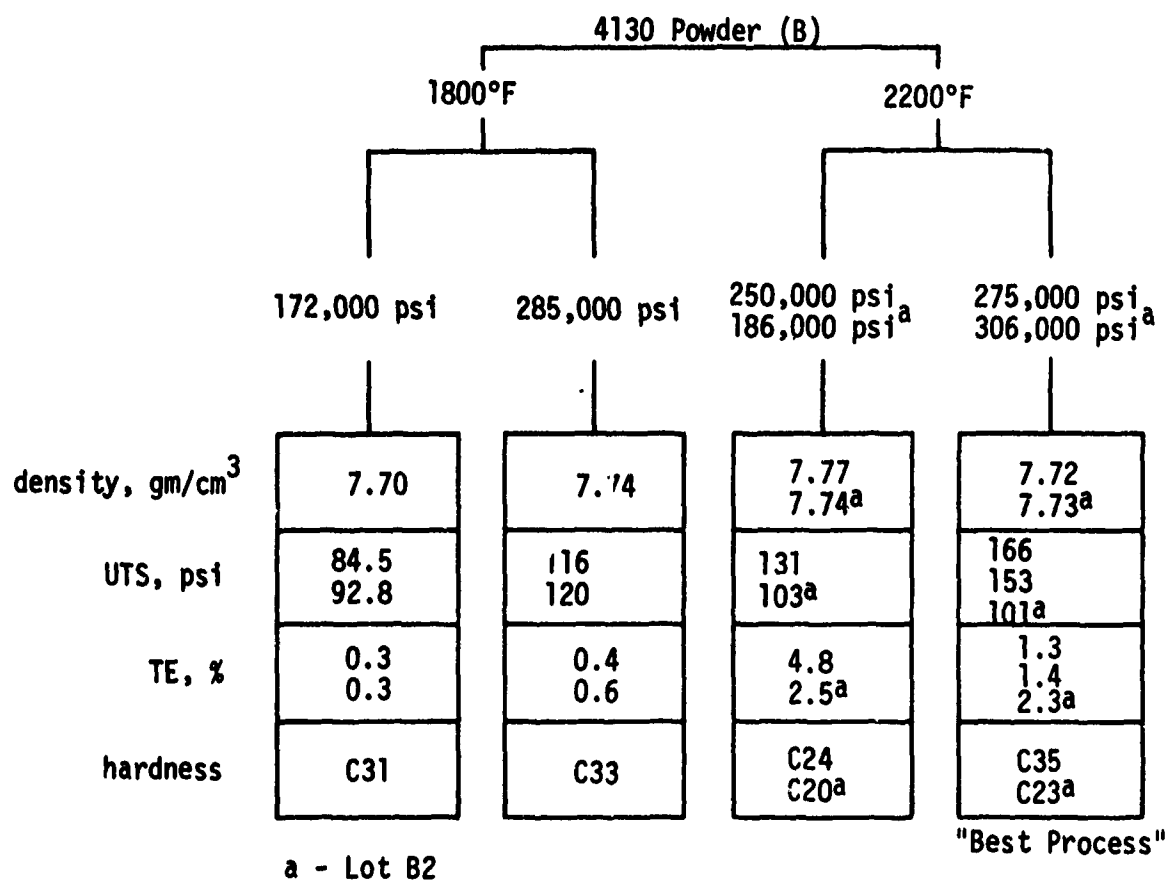
The "best process" was found to result from a 275 ksi compaction pressure and a 2200°F powder preheat, using Lot B1 powder. This hardened to  $R_C$  35, as expected. This billet, however, was the first and only billet produced by the 2200°F preheat procedure to respond satisfactorily to heat treatment. Three other attempts (see Figure 20) failed to attain the hardness levels expected. The microstructure of the "soft" materials appears to be primarily tempered martensite, so that the best reason that can be advanced at present for the soft material is carbon (or other alloy element) loss during the preheat procedure. This failure to harden properly clouds the results of this portion of the investigation. Note the low total elongation found, even in the case of the softer material, in spite of the very high densities obtained by HERF processing.

The microstructure of the "best process" billet which hardened satisfactorily is shown in Figure 21, along with a micrograph of a billet of Lot B2 material which did not harden satisfactorily. Note the presence of some inclusions in the structures. Presence of such inclusions was found to be typical of all of the HERF microstructures examined.

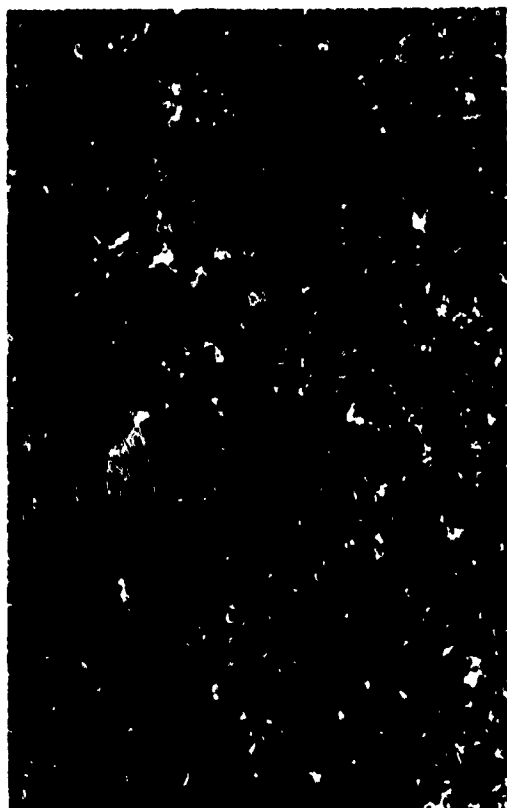
#### 4130 (Lot B) Powder: Impact Properties

Charpy V-notch impact properties were determined for all of the "best process" materials; these data are summarized in Table I.

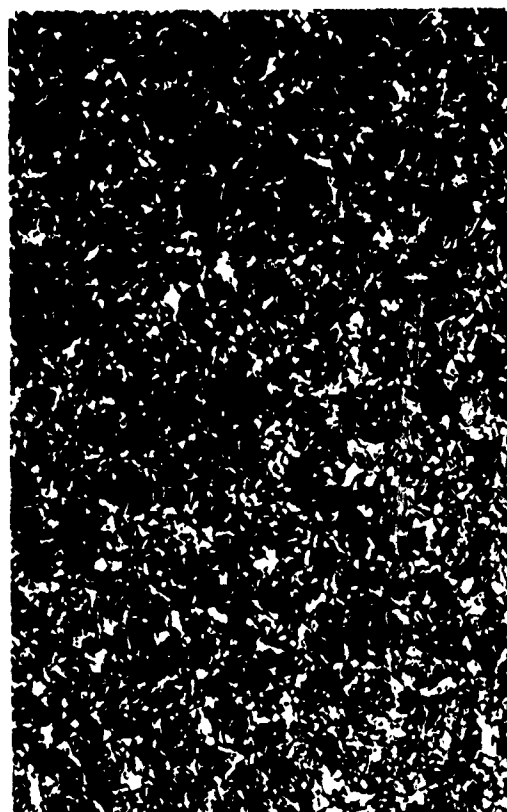
The HERF impact data are surprisingly low, considering the density of the product and its relative softness ( $R_C$  23). The die press and isopress best process materials are substantially better than the Task A material, though they fall far short of wrought properties.



**FIGURE 20.** Task B: Results of HERF Processing of Hoeganaes Type 4130 Powder



Lot B1, "Best Process"  
Hardness After  
900 °F Temper: C35



Lot B2, "Best Process"  
Hardness After  
900 °F Temper: C23

FIGURE 21. Microstructures of HERF Processed Billets of 4130 Powder,  
Lots B1 and B2 250X

**TABLE 1**  
**Charpy V-Notch Impact Properties of Specimens**  
**Produced from 4130 Lot B Powder by "Best Processes"**

|           | Impact Energy, ft-lb |             |              |              |
|-----------|----------------------|-------------|--------------|--------------|
|           | <u>-40°F</u>         | <u>77°F</u> | <u>210°F</u> | <u>450°F</u> |
| Die Press | 4.5                  | 3.2         | 7.3          | 5.9          |
| Isopress  | 1.0                  | 2.3         | 2.1          | 6.2          |
| HERF      | 1.7                  | 1.3         | 1.2          | 1.3          |

### Cursory Study

The "best processes" outlined in the foregoing section (see Figures 17, 19, and 20) were applied to four powders beyond 4130 Lot B, viz., Lots F, I, G, and H. The properties resulting from these processes are shown in Figures 22, 23, 24, and 25, respectively. Yield strength data may be found in the appendix.

Powder Lot F is a gas-atomized, nonreduced prealloyed 4130 powder mentioned in the Task A discussion. It was only processed by HERF in the present study. Comparing the data of Figures 22 and 20 reveals that Lot F is definitely inferior to HERF-processed Lot B in terms of UTS and TE. Comparing the prealloyed 4100 with 0.3 C added (Lot I) of Figure 23 with the results of completely prealloyed Lot B (Figures 17, 19, and 20) we find that Lot B is generally superior (except for the greater TE exhibited by Lot I in the die press best process) even though Lot I material generally exhibits the greater density.

The mechanical properties of the 1040 powder (Lot G) are presented in Figure 24. This material exhibited unusually high densities, elongations and impact properties, and an unusually low hardness in the heat-treated condition.

4130 Gas-Atomized Powder (F)

High-Energy-Rate-Formed  
~310,000 psi at 2200°F

density, gm/cm<sup>3</sup>

7.80

UTS, ksi

77.0

TE, %

0.2

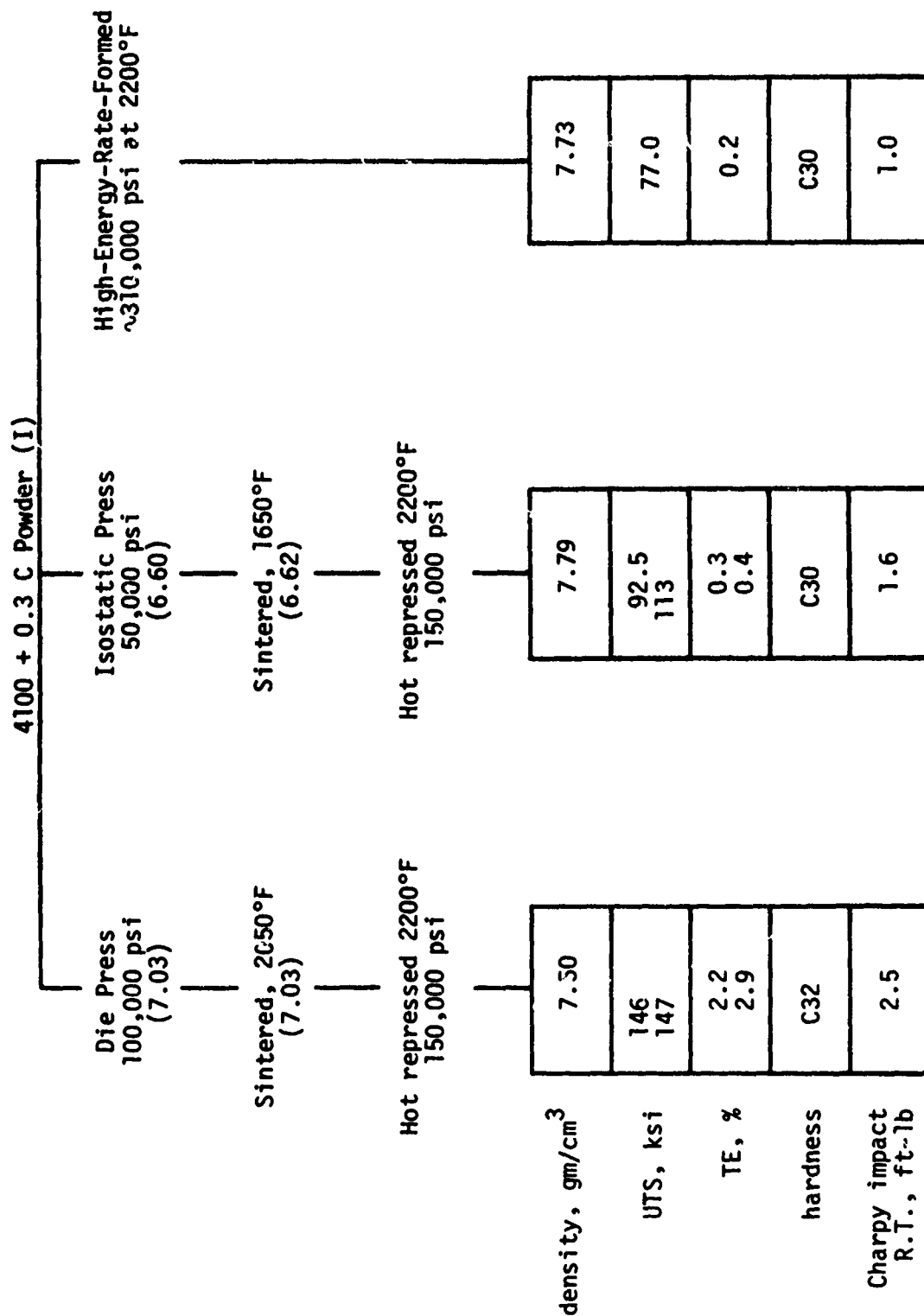
hardness

C32

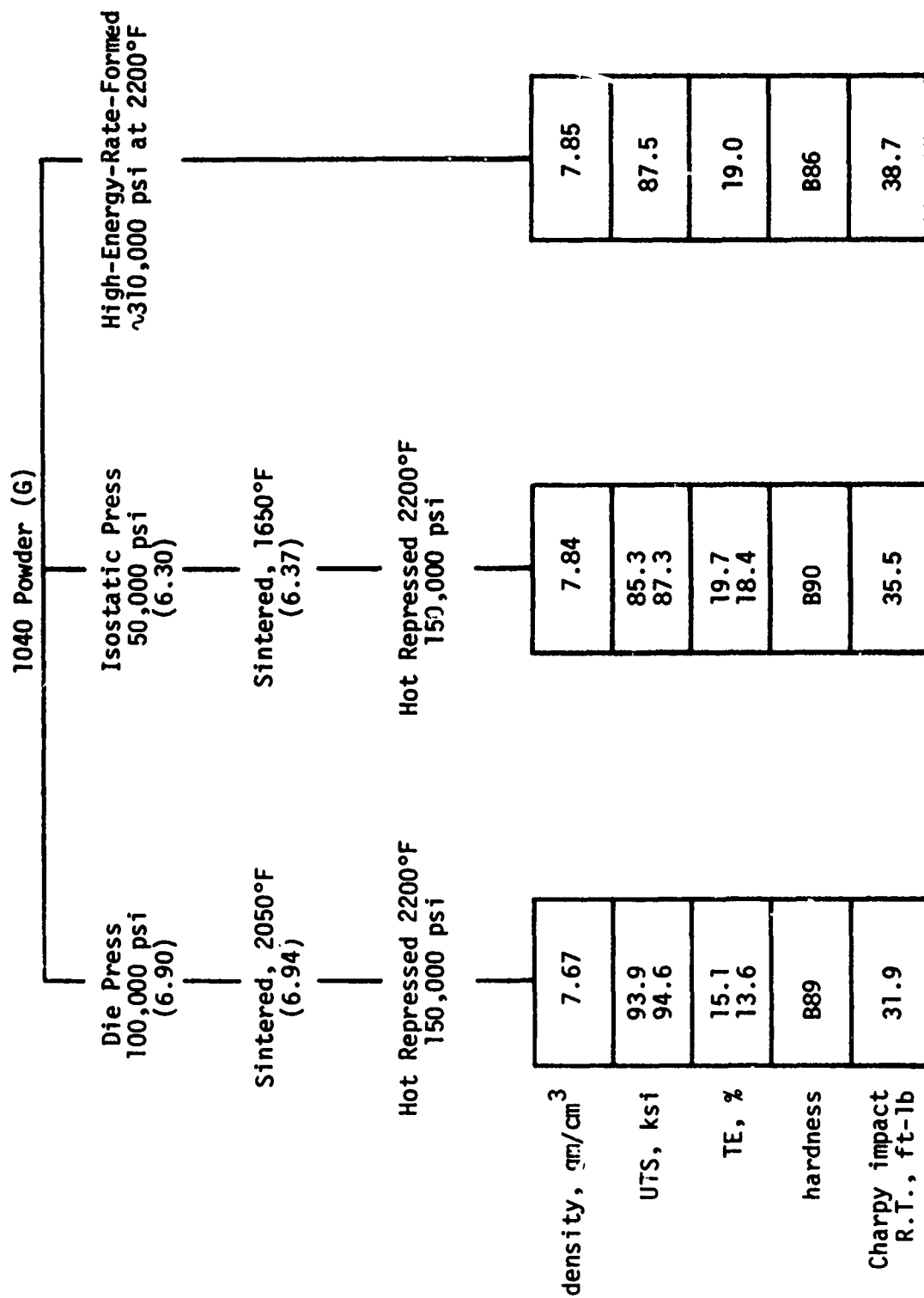
Charpy impact  
R.T., ft-lb

1.6

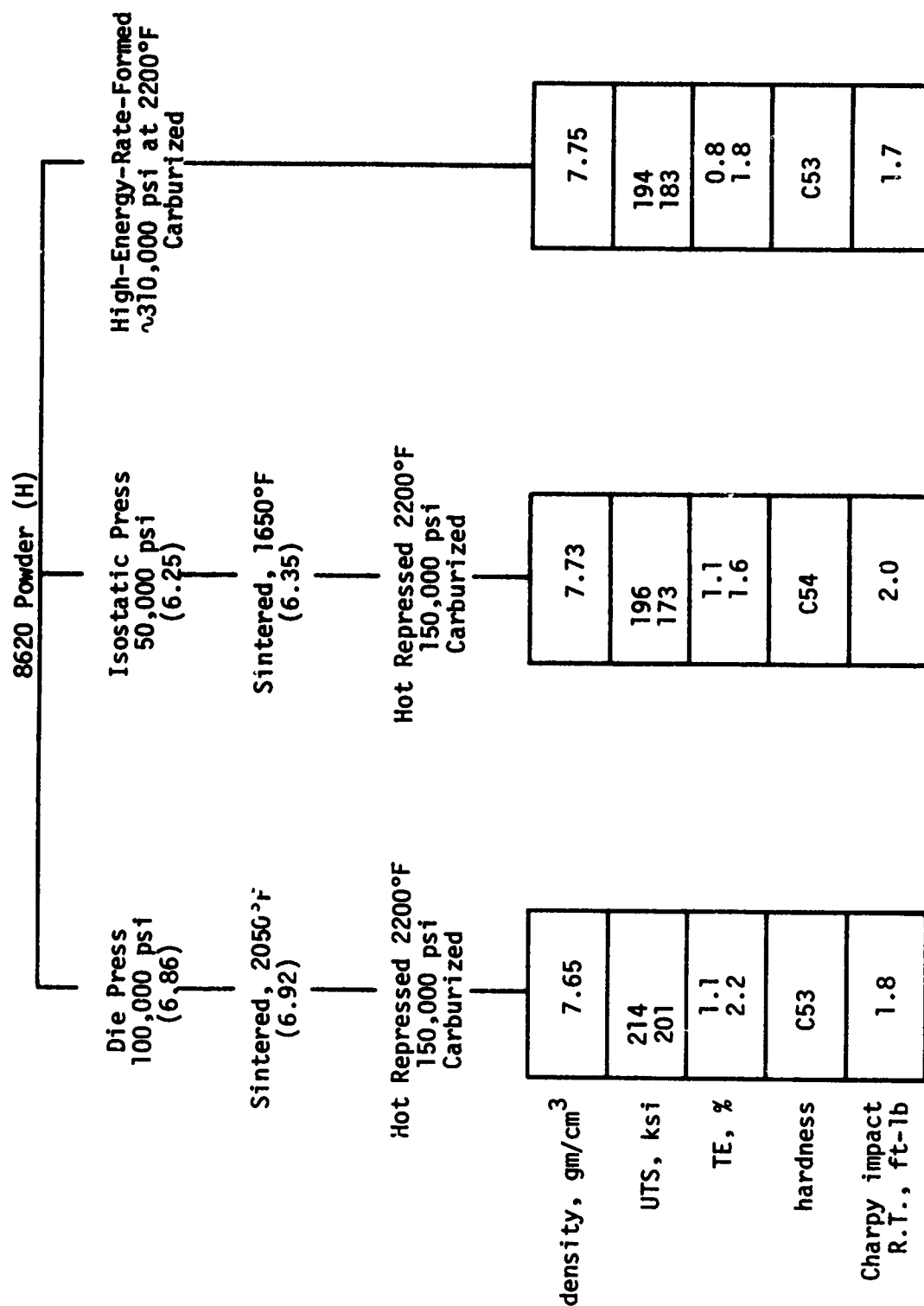
**FIGURE 22.** Cursory Study: Results of HERF Processing  
of Gas-Atomized Federal-  
Mogul Type 4130 Powder (F)



**FIGURE 23.** Cursory Study: Results of Best Processes, Hoeganaes Type 4100 + 0.3 C Powder (I)



**FIGURE 24. Cursory Study: Results of Best Processes, Hoeganaes Type 1040 Powder (G)**



**FIGURE 25.** Cursory Study: Results of Best Processes, Hoeganaes Type 8620 Powder (H)

Type 1040 steel has a lower hardenability than any other material tested in the program, though it was considered adequate<sup>(27,28)</sup> for the through-hardening of the small forgings and 1/2 in. thick HERF slabs, all water quenched from the austenitizing temperature. A hardness of  $R_c$  30 would be expected from a suitably transformed 1040 steel tempered at 900°F. The  $R_b$  readings of 86-90 and the UTS level of 85-90 ksi are typical of a normalized 1040 steel,<sup>(28)</sup> indicating insufficient hardenability in the P/M products to respond to a quench-temper operation. Products of this steel powder were the only ones tested which did not appear to center-harden.

The Task A processing of 1040 powder resulted in much poorer properties than those obtained from the best processes of the cursory study (compare Figures 16 and 24).

The properties of the 8620 powder (Lot H) are presented in Figure 25. The samples tested were all in the as-carburized and heat-treated condition, with a 15-mil case. A 450°F temper was used, instead of the standard 900°F temper.

This material exhibited the highest tensile strength of any steel used in the present study. It densified well, and of course had a very high apparent surface hardness, which is the hardness value given in the table. The apparent hardness of the material underlying the case would be much lower than the hardness values listed.

The Charpy V-notch values for powder Lots F, I, G, and H as a function of temperature are given in Table 2.

All impact strengths listed in Table 2 are of the same order of magnitude regardless of temperature or surface condition, with the exception of the high results of powder G. This is also the only material which indicates existence of a transition temperature.

**TABLE 2**  
**Charpy V-Notch Impact Properties of Specimens**  
**Produced from Powder Lots F, G, H, and I by "Best Processes"**

|           |        | Impact Energy, ft-lb |      |       |       |
|-----------|--------|----------------------|------|-------|-------|
|           | Powder | -40°F                | 77°F | 210°F | 450°F |
| Die Press | G      | 9.4                  | 31.9 | 34.8  | 29.9  |
|           | I      | 2.6                  | 2.5  | 3.2   | 1.9   |
|           | H      | -                    | 1.8  | -     | 2.5   |
| Isopress  | G      | 14.4                 | 35.5 | 26.8  | 32.0  |
|           | I      | 0.8                  | 1.6  | 1.8   | 0.8   |
|           | H      | -                    | 2.0  | -     | 1.7   |
| HERF      | F      | 1.6                  | 1.5  | 1.5   | 1.3   |
|           | G      | 11.5                 | 38.7 | 39.0  | 36.2  |
|           | I      | 1.4                  | 1.0  | 1.0   | 1.1   |
|           | H      | -                    | 1.7  | -     | 1.6   |

**"Shelf Item" Powders**

Five "shelf item" prealloyed powders, Lots J, K, L1, M, and N, were obtained from three major powder producers, and taken through the entire die press and sinter process already described in Figure 17 for the case of 4130 Lot B powder. Only the die press process was used as the initial compaction procedure on these powders. Charpy impact data was obtained as a function of temperature on specimens of each powder pressed at 80 ksi and sintered at 2050°F in the fashion of Task A processing.

Mechanical/physical property data for the shelf item powders may be found in Figures 26 through 30. Note that high temperature sintering followed by hot repressing produces the best properties. A large number of Lot J blanks and a few of Lot K did not survive the tensile specimen machining operation. Of the three 4650 type powders used in this portion of the program (J, K, and L1), Lot L1 exhibited superior densification, tensile strength, and elongation properties. It is interesting to note that initial compaction pressure had little if any effect on the properties of hot repressed material of these three powders; the subsequent sintering temperature appears to exert a much stronger influence.

| 50,000 psi Compacting Pressure (5.83) |             |              |                         |                                |                          |             |            |            |
|---------------------------------------|-------------|--------------|-------------------------|--------------------------------|--------------------------|-------------|------------|------------|
| Sinter 1650°F                         |             |              |                         |                                | Sinter 2050°F            |             |            |            |
| Cold Repress<br>& Sinter              | Hot Repress |              |                         |                                | Cold Repress<br>& Sinter | Hot Repress |            |            |
|                                       | 1800°F      | 2200°F       | 1800°F                  |                                |                          | 2200°F      |            |            |
| $\frac{6.27}{6.40}$                   | 5.78        | 7.59         | 7.67                    | density,<br>gm/cm <sup>3</sup> | $\frac{6.27}{6.31}$      | 5.95        | 7.69       | 7.72       |
| 60.0<br>66.3                          | c           | 96.0<br>89.0 | 157 <sup>d</sup><br>176 | UTS, ksi                       | 50.0<br>52.0             | c           | 193<br>145 | 137<br>184 |
| 0.7<br>0.5                            | ---         | 0.9<br>0.3   | 1.0<br>0.6              | TE, %                          | 0.5<br>0.4               | ---         | 2.0<br>0.5 | 2.2<br>2.4 |
| B86                                   | B80         | C43          | C39                     | hardness                       | B87                      | B78         | C41        | C39        |

| 80,000 psi Compacting Pressure (6.18) |      |                              |      |                                |                          |              |                              |            |
|---------------------------------------|------|------------------------------|------|--------------------------------|--------------------------|--------------|------------------------------|------------|
| Sinter 1650°F                         |      |                              |      |                                | Sinter 2050°F            |              |                              |            |
| Cold Repress<br>& Sinter              |      | Hot Repress<br>1800°F 2200°F |      |                                | Cold Repress<br>& Sinter |              | Hot Repress<br>1800°F 2200°F |            |
| $\frac{6.39}{6.52}$                   | 6.13 | 7.53                         | 7.61 | density,<br>gm/cm <sup>3</sup> | $\frac{6.43}{6.52}$      | 6.31         | 7.63                         | 7.66       |
| 57.8<br>64.7                          | c    | 94.0<br>89.0                 | c    | UTS, ksi                       | 65.0<br>64.0             | 39.0<br>41.0 | 162<br>168                   | 146<br>177 |
| 0.3<br>0.4                            | ---  | 0.4<br>0.3                   | ---  | TE, %                          | 0.5<br>0.4               | 0.5<br>0.3   | 1.3<br>0.5                   | 1.2<br>1.0 |
| B90                                   | B85  | C42                          | C43  | hardness                       | B92                      | B91          | C39                          | C38        |

| 100,000 psi Compacting Pressure (6.33) |                              |                   |      |                                |                          |                              |                   |                   |
|----------------------------------------|------------------------------|-------------------|------|--------------------------------|--------------------------|------------------------------|-------------------|-------------------|
| Sinter 1650°F                          |                              |                   |      |                                | Sinter 2050°F            |                              |                   |                   |
| Cold Repress<br>& Sinter               | Hot Repress<br>1800°F 2200°F |                   |      |                                | Cold Repress<br>& Sinter | Hot Repress<br>1800°F 2200°F |                   |                   |
| $\frac{6.55}{6.68}$                    | 6.38                         | 7.60              | 7.59 | density,<br>gm/cm <sup>3</sup> | $\frac{6.64}{6.70}$      | 6.59                         | 7.65              | 7.73              |
| $\frac{67.5}{65.7}$                    | c                            | 87.8 <sup>b</sup> | c    | UTS, ksi                       | $\frac{66.3}{72.0}$      | $\frac{59.0}{55.3}$          | $\frac{158}{177}$ | $\frac{150}{197}$ |
| $\frac{1.0}{0.3}$                      | ---                          | 0.7               | ---  | TE, %                          | $\frac{0.7}{0.4}$        | $\frac{0.4}{0.3}$            | $\frac{1.7}{1.1}$ | $\frac{1.2}{0.5}$ |
| B96                                    | B88                          | C43               | C39  | hardness                       | B96                      | B92                          | C38               | C41               |

b - One sample broke during machining.  
c - Two samples broke during machining.  
d - Sample broke at head.

FIGURE 26. Task B: Results of Die Press Processing of Glidden-Durkee Type 4650 Powder (J)

| 50,000 psi Compacting Pressure (6.10) |      |                         |                         |                             |                   |                           |            |
|---------------------------------------|------|-------------------------|-------------------------|-----------------------------|-------------------|---------------------------|------------|
| Sinter 1650°F                         |      |                         |                         | Sinter 2050°F               |                   |                           |            |
| Cold Repress & Sinter                 |      | Hot Repress 1800 2200°F |                         | Cold Repress & Sinter       |                   | Hot Repress 1800°F 2200°F |            |
| 6.71<br>6.82                          | 6.03 | 7.60                    | 7.70                    | 6.36<br>6.44                | 6.17              | 7.64                      | 7.67       |
| 76.0<br>76.1                          | c    | c                       | 152 <sup>d</sup><br>183 | 62.0<br>58.5                | 32.0 <sup>b</sup> | 188<br>189                | 160<br>178 |
| 0.4<br>0.3                            | ---  | ---                     | 0.6<br>2.1              | 0.3<br>0.3                  | 0.3               | 1.9<br>2.6                | 1.1<br>2.3 |
| B91                                   | B56  | C39                     | C39                     | B86                         | B81               | C39                       | C38        |
| density, gm/cm <sup>3</sup>           |      |                         |                         | density, gm/cm <sup>3</sup> |                   |                           |            |
| UTS, kwi                              |      |                         |                         | UTS, kwi                    |                   |                           |            |
| TE, %                                 |      |                         |                         | TE, %                       |                   |                           |            |
| hardness                              |      |                         |                         | hardness                    |                   |                           |            |

| 80,000 psi Compacting Pressure (6.58) |                    |                           |                  |                             |              |                           |            |
|---------------------------------------|--------------------|---------------------------|------------------|-----------------------------|--------------|---------------------------|------------|
| Sinter 1650°F                         |                    |                           |                  | Sinter 2050°F               |              |                           |            |
| Cold Repress & Sinter                 |                    | Hot Repress 1800°F 2200°F |                  | Cold Repress & Sinter       |              | Hot Repress 1800°F 2200°F |            |
| 6.80<br>6.96                          | 6.48               | 7.61                      | 7.64             | 6.73<br>6.82                | 6.65         | 7.67                      | 7.68       |
| 87.0 <sup>b</sup>                     | 8.0 <sup>d,b</sup> | 155<br>163                | 150 <sup>b</sup> | 78.0<br>91.9                | 68.5<br>69.7 | 180<br>87.0               | 178<br>172 |
| 0.4                                   | 0.2                | 0.6<br>2.3                | 0.8              | 0.5<br>0.4                  | 0.5<br>0.4   | 1.3<br>0.4                | 2.1<br>0.9 |
| C24                                   | B62                | C39                       | C40              | B97                         | B93          | C38                       | C38        |
| density, gm/cm <sup>3</sup>           |                    |                           |                  | density, gm/cm <sup>3</sup> |              |                           |            |
| UTS, ksi                              |                    |                           |                  | UTS, ksi                    |              |                           |            |
| TE, %                                 |                    |                           |                  | TE, %                       |              |                           |            |
| hardness                              |                    |                           |                  | hardness                    |              |                           |            |

| 100,000 psi Compacting Pressure (6.79) |                     |                           |            |                             |              |                           |            |
|----------------------------------------|---------------------|---------------------------|------------|-----------------------------|--------------|---------------------------|------------|
| Sinter 1650°F                          |                     |                           |            | Sinter 2050°F               |              |                           |            |
| Cold Repress & Sinter                  |                     | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |              | Hot Repress 1800°F 2200°F |            |
| 6.98<br>7.08                           | 6.69                | 7.64                      | 7.62       | 6.90<br>6.98                | 6.85         | 7.66                      | 7.67       |
| 101<br>41.6                            | 15.8 <sup>d,b</sup> | 128 <sup>b</sup>          | 142<br>153 | 90.0<br>105                 | 69.0<br>63.8 | 171<br>177                | 175<br>175 |
| 0.5<br>1.0                             | 0.2                 | 0.6                       | 1.2<br>1.6 | 0.6<br>1.0                  | 0.3<br>0.3   | 0.7<br>2.0                | .1<br>2.0  |
| C26                                    | B79                 | C35                       | C41        | C23                         | B94          | C40                       | C39        |
| density, gm/cm <sup>3</sup>            |                     |                           |            | density, gm/cm <sup>3</sup> |              |                           |            |
| UTS, ksi                               |                     |                           |            | UTS, ksi                    |              |                           |            |
| TE, %                                  |                     |                           |            | TE, %                       |              |                           |            |
| hardness                               |                     |                           |            | hardness                    |              |                           |            |

- b - One sample broke during machining.  
c - Two samples broke during machining.  
d - Sample broke at shoulder.

FIGURE 27. Task B: Results of Die Press Processing of Glidden - Durkee Type 4600 + 0.5 C Powder (K)

| 50,000 psi Compacting Pressure (6.46) |              |                           |            |                             |              |                           |            |
|---------------------------------------|--------------|---------------------------|------------|-----------------------------|--------------|---------------------------|------------|
| Sinter 1650°F                         |              |                           |            | Sinter 2050°F               |              |                           |            |
| Cold Repress & Sinter                 |              | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |              | Hot Repress 1800°F 2200°F |            |
| $\frac{7.01}{7.05}$                   | 6.45         | 7.70                      | 7.65       | $\frac{6.60}{6.56}$         | 6.43         | 7.84                      | 7.72       |
| 127<br>112                            | 33.8<br>36.5 | 143<br>159                | 177<br>177 | 87.8<br>88.0                | 77.5<br>75.8 | 182<br>180                | 178<br>174 |
| 1.4<br>1.2                            | 0.4<br>0.2   | 3.1<br>2.8                | 4.9<br>4.8 | 0.6<br>0.2                  | 0.6<br>0.2   | 5.2<br>6.5                | 5.8<br>6.0 |
| B99                                   | B43          | C30                       | C36        | B83                         | B89          | C37                       | C36        |
| density, gm/cm <sup>3</sup>           |              |                           |            | density, gm/cm <sup>3</sup> |              |                           |            |
| UTS, ksi                              |              |                           |            | UTS, ksi                    |              |                           |            |
| TE, %                                 |              |                           |            | TE, %                       |              |                           |            |
| hardness                              |              |                           |            | hardness                    |              |                           |            |

| 80,000 psi Compacting Pressure (6.89) |              |                           |            |                             |            |                           |            |
|---------------------------------------|--------------|---------------------------|------------|-----------------------------|------------|---------------------------|------------|
| Sinter 1650°F                         |              |                           |            | Sinter 2050°F               |            |                           |            |
| Cold Repress & Sinter                 |              | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |            | Hot Repress 1800°F 2200°F |            |
| $\frac{7.22}{7.33}$                   | 6.91         | 7.77                      | 7.60       | $\frac{6.99}{7.00}$         | 6.93       | 7.80                      | 7.77       |
| 150<br>145                            | 97.0<br>83.0 | 125<br>151                | 152<br>184 | 128<br>120                  | 107<br>116 | 188<br>184                | 185<br>180 |
| 1.7<br>2.2                            | 1.0<br>1.5   | 3.2<br>3.2                | 0.7<br>5.1 | 0.7<br>1.3                  | 0.4<br>1.0 | 5.9<br>6.2                | 6.2<br>5.9 |
| C24                                   | B54          | C26                       | C36        | C20                         | B98        | C38                       | C35        |
| density, gm/cm <sup>3</sup>           |              |                           |            | density, gm/cm <sup>3</sup> |            |                           |            |
| UTS, ksi                              |              |                           |            | UTS, ksi                    |            |                           |            |
| TE, %                                 |              |                           |            | TE, %                       |            |                           |            |
| hardness                              |              |                           |            | hardness                    |            |                           |            |

| 100,000 psi Compacting Pressure (7.11) |              |                           |            |                             |            |                           |            |
|----------------------------------------|--------------|---------------------------|------------|-----------------------------|------------|---------------------------|------------|
| Sinter 1650°F                          |              |                           |            | Sinter 2050°F               |            |                           |            |
| Cold Repress & Sinter                  |              | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |            | Hot Repress 1800°F 2200°F |            |
| $\frac{7.34}{7.38}$                    | 7.08         | 7.76                      | 7.67       | $\frac{7.19}{7.19}$         | 7.15       | 7.81                      | 7.72       |
| 157<br>152                             | 35.0<br>36.0 | 160<br>158                | 185<br>180 | 138<br>133                  | 137<br>132 | 189<br>185                | 184<br>181 |
| 2.3<br>2.0                             | 1.0<br>1.4   | 2.6<br>3.6                | 4.0<br>3.4 | 1.5<br>1.8                  | 1.2<br>1.2 | 3.6<br>6.2                | 4.3<br>6.6 |
| C28                                    | B58          | C32                       | C37        | C21                         | C21        | C38                       | C34        |
| density, gm/cm <sup>3</sup>            |              |                           |            | density, gm/cm <sup>3</sup> |            |                           |            |
| UTS, ksi                               |              |                           |            | UTS, ksi                    |            |                           |            |
| TE, %                                  |              |                           |            | TE, %                       |            |                           |            |
| hardness                               |              |                           |            | hardness                    |            |                           |            |

FIGURE 28. Task B: Results of Die Press Processing of A. O. Smith - Inland Type 4600 + 0.5 C Powder (L1)

| 50,000 psi Compacting Pressure (6.31) |                   |                           |            |                             |              |                           |            |
|---------------------------------------|-------------------|---------------------------|------------|-----------------------------|--------------|---------------------------|------------|
| Sinter 1650°F                         |                   |                           |            | Sinter 2050°F               |              |                           |            |
| Cold Repress & Sinter                 |                   | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |              | Hot Repress 1800°F 2200°F |            |
| $\frac{6.99}{6.93}$                   | 6.30              | 7.64                      | 7.82       | $\frac{6.81}{6.88}$         | 6.32         | 7.68                      | 7.83       |
| 89.3<br>89.9                          | 23.9 <sup>b</sup> | 62.3<br>62.0              | 157<br>170 | 89.5<br>91.6                | 40.2<br>46.0 | 166<br>168                | 163<br>167 |
| 1.2<br>1.1                            | 0.2               | 1.8<br>1.4                | 0.7<br>4.2 | 0.8<br>1.4                  | 0.3<br>0.6   | 3.4<br>2.5                | 4.8<br>5.0 |
| B91                                   | B13               | B86                       | C37        | B92                         | B72          | C34                       | C32        |
| density, gm/cm <sup>3</sup>           |                   |                           |            | density, gm/cm <sup>3</sup> |              |                           |            |
| UTS, ksi                              |                   |                           |            | UTS, ksi                    |              |                           |            |
| TE, %                                 |                   |                           |            | TE, %                       |              |                           |            |
| hardness                              |                   |                           |            | hardness                    |              |                           |            |

| 80,000 psi Compacting Pressure (6.81) |              |                           |            |                             |              |                           |            |
|---------------------------------------|--------------|---------------------------|------------|-----------------------------|--------------|---------------------------|------------|
| Sinter 1650°F                         |              |                           |            | Sinter 2050°F               |              |                           |            |
| Cold Repress & Sinter                 |              | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |              | Hot Repress 1800°F 2200°F |            |
| $\frac{7.09}{7.09}$                   | 6.77         | 7.74                      | 7.70       | $\frac{7.03}{7.06}$         | 6.81         | 7.83                      | 7.83       |
| 106<br>108                            | 13.5<br>19.7 | 64.0<br>59.6              | 173<br>124 | 96.0<br>103                 | 81.0<br>75.8 | 173<br>171                | 166<br>165 |
| 0.5<br>2.6                            | 0.2<br>0.3   | 2.2<br>0.9                | 1.1<br>1.1 | 0.6<br>1.6                  | 0.4<br>1.4   | 2.4<br>3.8                | 4.2<br>5.0 |
| B96                                   | B31          | B89                       | C36        | B91                         | B88          | C34                       | C35        |
| density, gm/cm <sup>3</sup>           |              |                           |            | density, gm/cm <sup>3</sup> |              |                           |            |
| UTS, ksi                              |              |                           |            | UTS, ksi                    |              |                           |            |
| TE, %                                 |              |                           |            | TE, %                       |              |                           |            |
| hardness                              |              |                           |            | hardness                    |              |                           |            |

| 100,000 psi Compacting Pressure (7.01) |                   |                           |            |                             |                   |                           |            |
|----------------------------------------|-------------------|---------------------------|------------|-----------------------------|-------------------|---------------------------|------------|
| Sinter 1650°F                          |                   |                           |            | Sinter 2050°F               |                   |                           |            |
| Cold Repress & Sinter                  |                   | Hot Repress 1800°F 2200°F |            | Cold Repress & Sinter       |                   | Hot Repress 1800°F 2200°F |            |
| $\frac{7.29}{7.20}$                    | 6.97              | 7.68                      | 7.90       | $\frac{7.14}{7.16}$         | 7.00              | 7.80                      | 7.81       |
| 104<br>111                             | 88.5 <sup>b</sup> | 68.5<br>68.6              | 160<br>161 | 107<br>103                  | 86.0 <sup>b</sup> | 158<br>159                | 155<br>156 |
| 0.7<br>1.6                             | 0.7               | 2.1<br>1.4                | 3.8<br>2.6 | 0.9<br>1.0                  | 0.5               | 2.8<br>3.9                | 3.7<br>5.0 |
| B96                                    | B95               | B89                       | C35        | B98                         | B89               | C32                       | C33        |
| density, gm/cm <sup>3</sup>            |                   |                           |            | density, gm/cm <sup>3</sup> |                   |                           |            |
| UTS, ksi                               |                   |                           |            | UTS, ksi                    |                   |                           |            |
| TE, %                                  |                   |                           |            | TE, %                       |                   |                           |            |
| hardness                               |                   |                           |            | hardness                    |                   |                           |            |

b - One sample broke during machining

FIGURE 29. Task B: Results of Die Press Processing of A. O. Smith - Inland Type 8600 + 0.5 C Powder (M)

| 50,000 psi Compacting Pressure (6.33) |              |                              |            |                          |              |                              |            |
|---------------------------------------|--------------|------------------------------|------------|--------------------------|--------------|------------------------------|------------|
| Sinter 1650°F                         |              |                              |            | Sinter 2050°F            |              |                              |            |
| Cold Repress<br>& Sinter              |              | Hot Repress<br>1800°F 2200°F |            | Cold Repress<br>& Sinter |              | Hot Repress<br>1800°F 2200°F |            |
| $\frac{7.06}{7.01}$                   | 6.35         | 7.64                         | 7.72       | $\frac{6.87}{6.87}$      | 6.30         | 7.63                         | 7.72       |
| 93.5<br>93.0                          | 22.4<br>20.2 | 80.6<br>82.0                 | 145<br>133 | 77.0<br>74.4             | 46.8<br>47.0 | 172<br>140                   | 166<br>153 |
| 0.8<br>2.0                            | 1.5<br>1.1   | 7.4<br>7.5                   | 6.5<br>7.6 | 0.9<br>1.6               | 0.6<br>1.0   | 4.2<br>5.0                   | 5.7<br>6.2 |
| B93                                   | B5           | B88                          | C30        | B78                      | B70          | C31                          | C32        |

density,  
gm/cm<sup>3</sup>

UTS, ksi

TE, %

hardness

| 80,000 psi Compacting Pressure (6.86) |              |                              |            |                          |              |                              |            |
|---------------------------------------|--------------|------------------------------|------------|--------------------------|--------------|------------------------------|------------|
| Sinter 1650°F                         |              |                              |            | Sinter 2050°F            |              |                              |            |
| Cold Repress<br>& Sinter              |              | Hot Repress<br>1800°F 2200°F |            | Cold Repress<br>& Sinter |              | Hot Repress<br>1800°F 2200°F |            |
| $\frac{7.20}{7.18}$                   | 6.86         | 7.70                         | 7.71       | $\frac{7.07}{7.05}$      | 6.85         | 7.77                         | 7.83       |
| 103<br>93.3                           | 75.8<br>29.4 | 76.5<br>84.8                 | 130<br>127 | 86.0<br>87.2             | 66.0<br>65.4 | 128<br>133                   | 145<br>146 |
| 1.4<br>1.6                            | 3.8<br>2.6   | 7.0<br>7.8                   | 7.3<br>7.5 | 0.2<br>1.6               | 0.6<br>1.0   | 3.5<br>7.6                   | 6.1<br>6.4 |
| B96                                   | B26          | B85                          | C30        | B91                      | B80          | C30                          | C30        |

density,  
gm/cm<sup>3</sup>

UTS, ksi

TE, %

hardness

| 100,000 psi Compacting Pressure (7.05) |              |                              |            |                          |              |                              |            |
|----------------------------------------|--------------|------------------------------|------------|--------------------------|--------------|------------------------------|------------|
| Sinter 1650°F                          |              |                              |            | Sinter 2050°F            |              |                              |            |
| Cold Repress<br>& Sinter               |              | Hot Repress<br>1800°F 2200°F |            | Cold Repress<br>& Sinter |              | Hot Repress<br>1800°F 2200°F |            |
| $\frac{7.25}{7.23}$                    | 7.03         | 7.70                         | 7.75       | $\frac{7.16}{7.17}$      | 7.01         | 7.80                         | 7.86       |
| 102<br>109                             | 32.5<br>33.3 | 80.3<br>87.3                 | 134<br>132 | 95.5<br>94.9             | 78.0<br>78.1 | 142<br>137                   | 135<br>138 |
| 1.3<br>1.7                             | 2.2<br>2.4   | 7.4<br>8.0                   | 6.3<br>7.0 | 0.9<br>2.2               | 0.8<br>0.8   | 5.5<br>4.3                   | 7.9<br>7.8 |
| B91                                    | B40          | B87                          | C30        | B96                      | B83          | C30                          | C30        |

density,  
gm/cm<sup>3</sup>

UTS, ksi

TE, %

hardness

FIGURE 30. Task B: Results of Die Press Processing of A. O. Smith - Inland Type 9400 + 0.5 C Powder (N)

Metallography of pressed-and-sintered and hot repressed samples of the five shelf item powders are shown in Figures 31 and 32.

Yield data may be found in the section appended to this report. Yield data were not obtained on some samples of J and K materials because of erratic extensometer behavior. The impact properties of the shelf item powders are presented in Table 3.

**TABLE 3**  
**Charpy V-Notch Impact Properties of Specimens**  
**Produced from Powder Lots J, K, L1, M, and N**  
**Compacted 80 ksi, Sintered 2050°F, Tempered 900°F**

| <u>Powder</u> | <u>Impact Energy, ft-lb</u> |             |              |              |
|---------------|-----------------------------|-------------|--------------|--------------|
|               | <u>-40°F</u>                | <u>77°F</u> | <u>210°F</u> | <u>450°F</u> |
| J             | 1.1                         | 0.9         | 0.8          | 0.8          |
| K             | 1.0                         | 1.0         | 0.9          | 0.8          |
| L             | 1.4                         | 1.4         | 1.4          | 1.3          |
| M             | 1.2                         | 1.2         | 1.3          | 1.4          |
| N             | 1.2                         | 1.5         | 1.5          | 1.3          |

Impact properties are low, with no apparent temperature effect. The data of Table 3 shows a slight superiority of Lot L1 over Lots J and K.

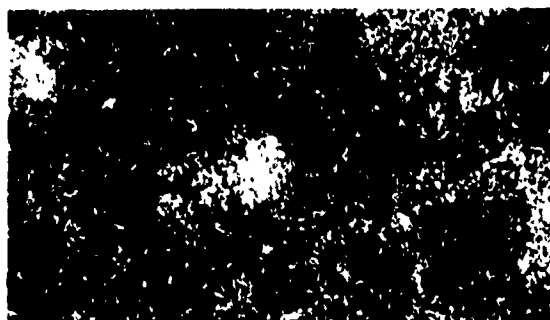
#### Task B Data Summary

In this concluding portion of the Task B Discussion Section, data obtained from the six powders taken through the extensive die press and sinter process sequence are graphically presented to permit a better understanding and comparison of their various properties.

The effect of compacting pressure and compacting pressure plus sintering on density of the resulting product is shown in Figures 33 and 34, respectively. Powder Lot L1 yields compacts of the highest density, while the carbon-alloyed powders, Lots B and J, yield compacts of the lowest density.

Samples Pressed 100 KSI  
Sintered 2050 °F  
Austenitized, Quenched  
Tempered 900 °F

Samples Pressed 100 KSI  
Sintered 2050 °F  
Hot Repressed 2200 °F at 150 KSI  
Austenitized, Quenched  
Tempered 900 °F

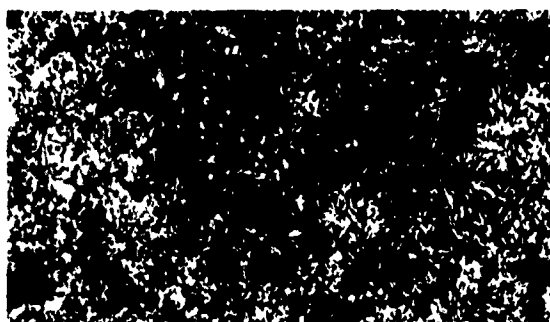


Density 6.59 gm/cm<sup>3</sup>

4650 (J)



Density 7.73 gm/cm<sup>3</sup>

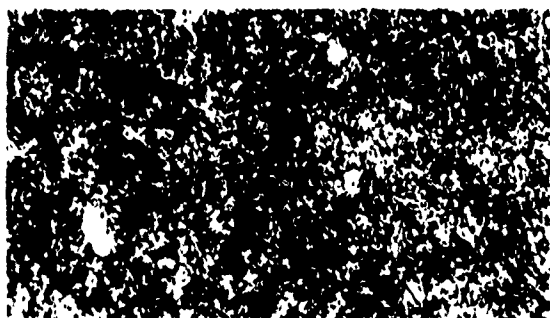


Density 6.85 gm/cm<sup>3</sup>

4600 + 0.5C (K)



Density 7.67 gm/cm<sup>3</sup>



Density 7.15 gm/cm<sup>3</sup>

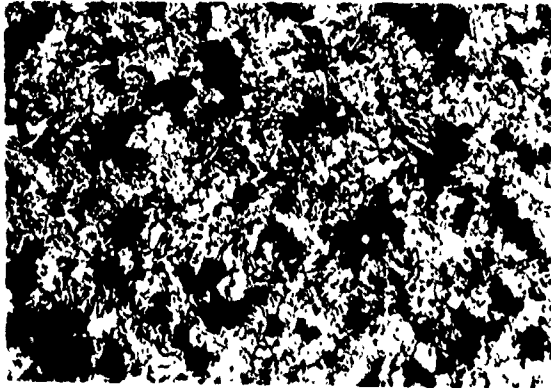
4600 + 0.5C (L1)



Density 7.72 gm/cm<sup>3</sup>

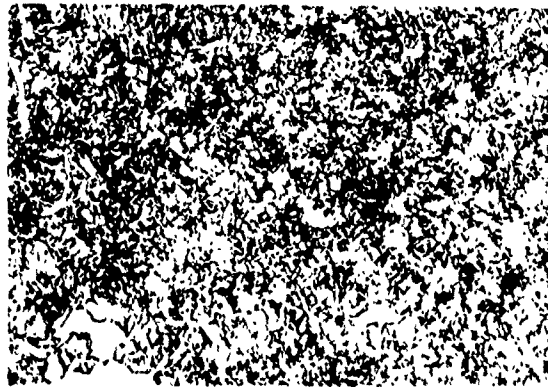
FIGURE 31. Microstructures of Pressed-and-Sintered  
and Hot Repressed Samples 250X

Samples Pressed 100 KSI  
Sintered 2050 °F  
Austenitized, Quenched  
Tempered 900 °F



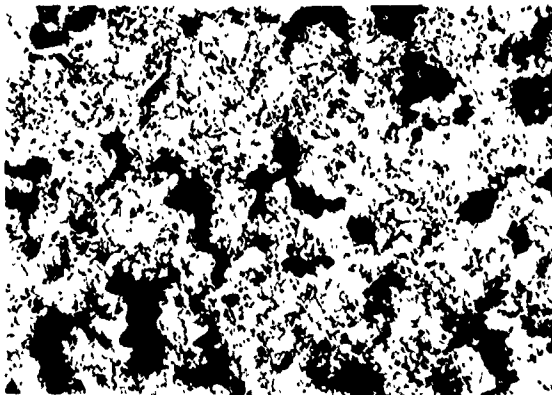
Density 7.00 gm/cm<sup>3</sup>

Samples Pressed 100 KSI  
Sintered 2050 °F  
Hot Repressed 2200 °F at 150 KSI  
Austenitized, Quenched  
Tempered 900 °F

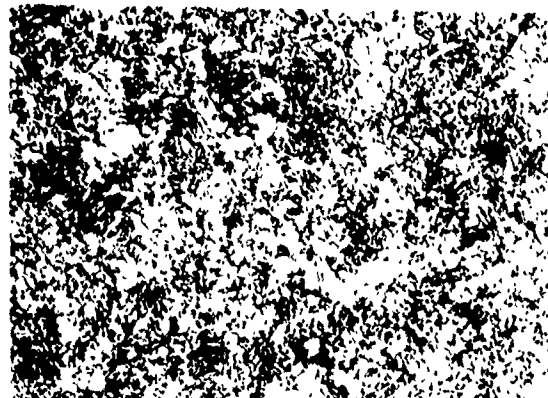


Density 7.81 gm/cm<sup>3</sup>

8600 + 0.5C (M)



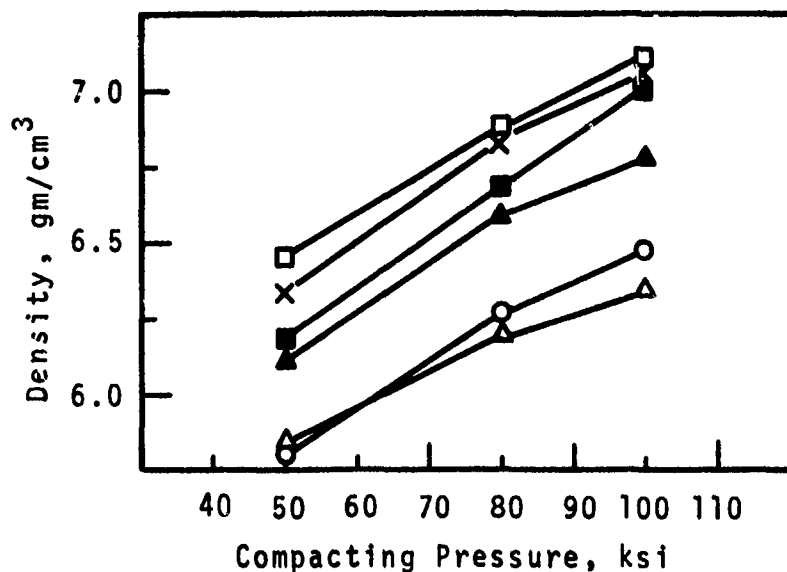
Density 7.01 gm/cm<sup>3</sup>



Density 7.86 gm/cm<sup>3</sup>

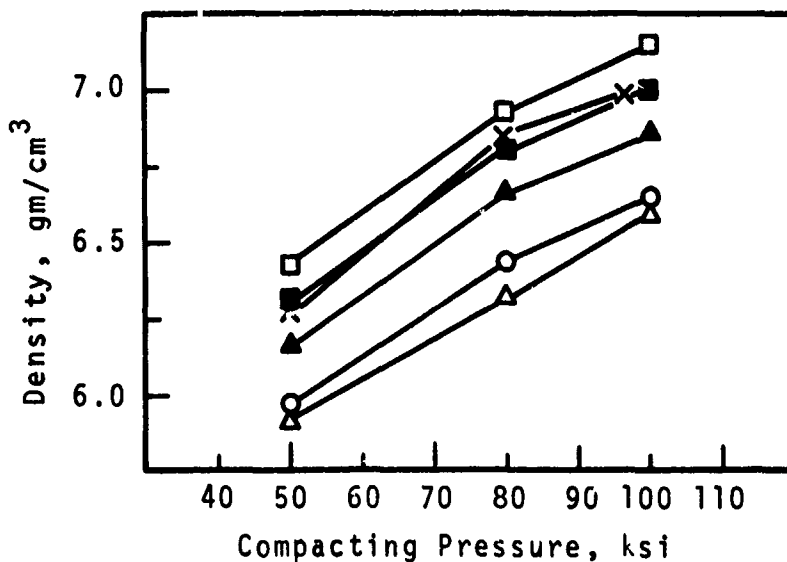
9400 + 0.5C (N)

**FIGURE 32.** Microstructures of Pressed-and-Sintered  
and Hot Repressed Samples 250X



**FIGURE 33.** Effect of Compacting Pressure on Density

- Legend**
- 4130, Lot 1 (B1)
  - △ 4650, Glidden (J)
  - ▲ 4600 + 0.5 C Glidden (K)
  - 4600 + 0.5 C A. O. Smith (L1)
  - 8600 + 0.5 C A. O. Smith (M)
  - × 9400 + 0.5 C A. O. Smith (N)



**FIGURE 34.** Combined Effect of Compacting Pressure and 2050°F Sinter on Density

The effect of compaction followed by a repress and a resinter on density is shown in Figure 35. The beneficial effect of high initial compacting pressure on ultimate density is still apparent. Initial compaction pressure becomes a variable of minor importance, however, when the process culminates in a hot repress operation (Figure 36).

The relationship between the hardness and the ultimate tensile strength of the die-press produced compacts is shown in Figure 37. Only samples with hardnesses  $>R_c 20$  were plotted on this figure.

With the exception of some low values, notably data points associated with powder Lots B and J (the totally prealloyed materials), there is a good agreement between apparent product hardness and UTS of the P/M products with published data for wrought steels. Steel powders producing compacts of high density, such as Lot L1, are found above the wrought-product line; low density materials, such as Lots B and J, are found below. The relationship between UTS and density is explored further in Figure 38. Materials in the top part of the scatter band, such as Lot L1 at a density of  $7.7 \text{ gm/cm}^3$ , have a high strength/density ratio; materials in the bottom (e.g., Lot K at a density of  $6.9 \text{ gm/cm}^3$ ) are relatively inefficient.

### 6.3 Task C

Task C was a hot repressing study, in which repressing pressure and temperature were varied over a wide range, and the effect of this variance on the mechanical properties of the resulting test piece determined. The hot repressing fabrication mode was emphasized because it is recognized that optimum P/M properties will eventually be routinely obtained by some preform forging process. While the hot repressing operation utilized here does not produce the optimum mechanical properties (notably impact strength) which can be obtained by forging processes which involve extensive lateral metal flow (see Section 5.6, Hot Repressing), the study shows relative behavior of materials, relative response to repressing variables, and properties obtainable from commercial powders by state-of-the-art repressing operations without emphasizing preform design.

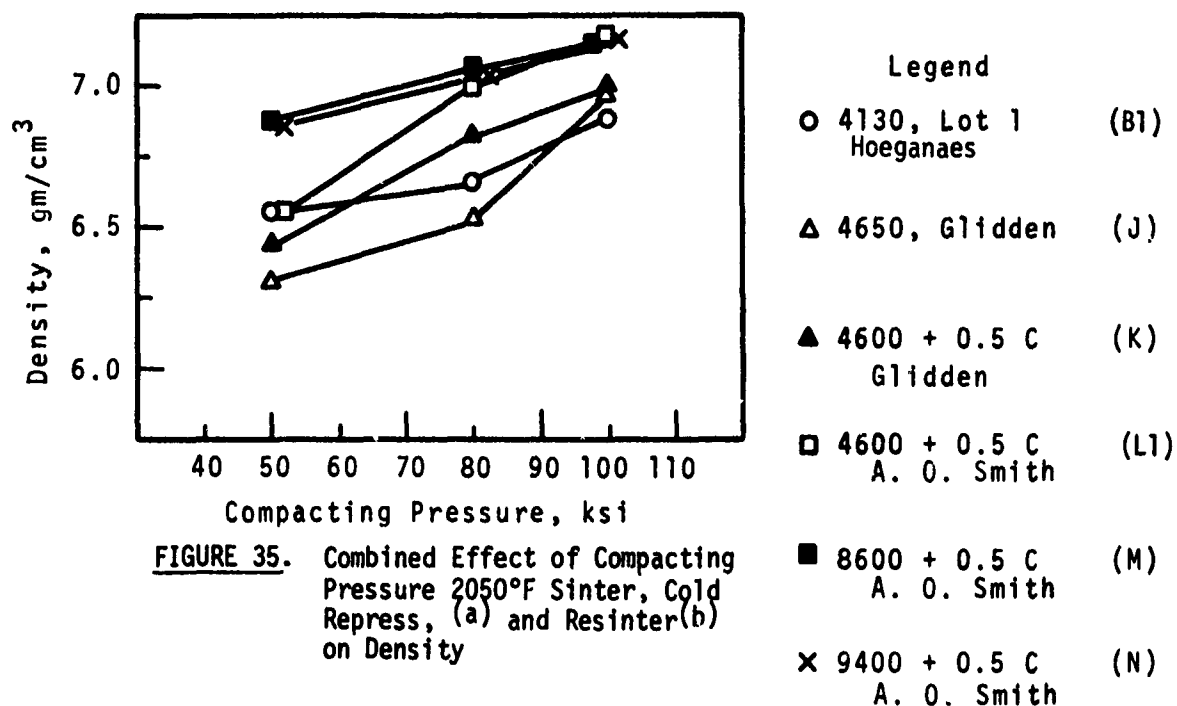


FIGURE 35. Combined Effect of Compacting Pressure 2050°F Sinter, Cold Repress, (a) and Resinter(b) on Density

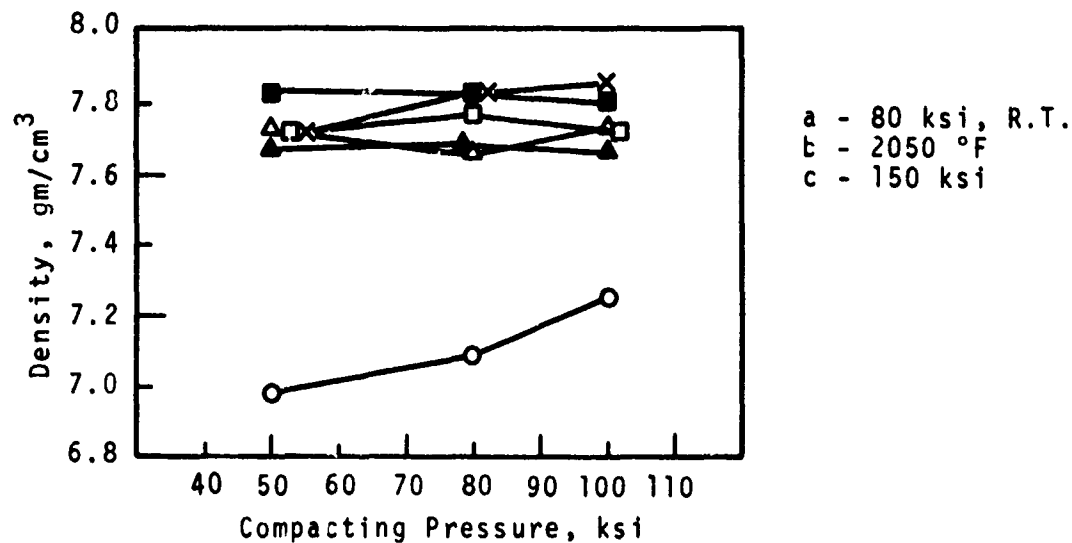
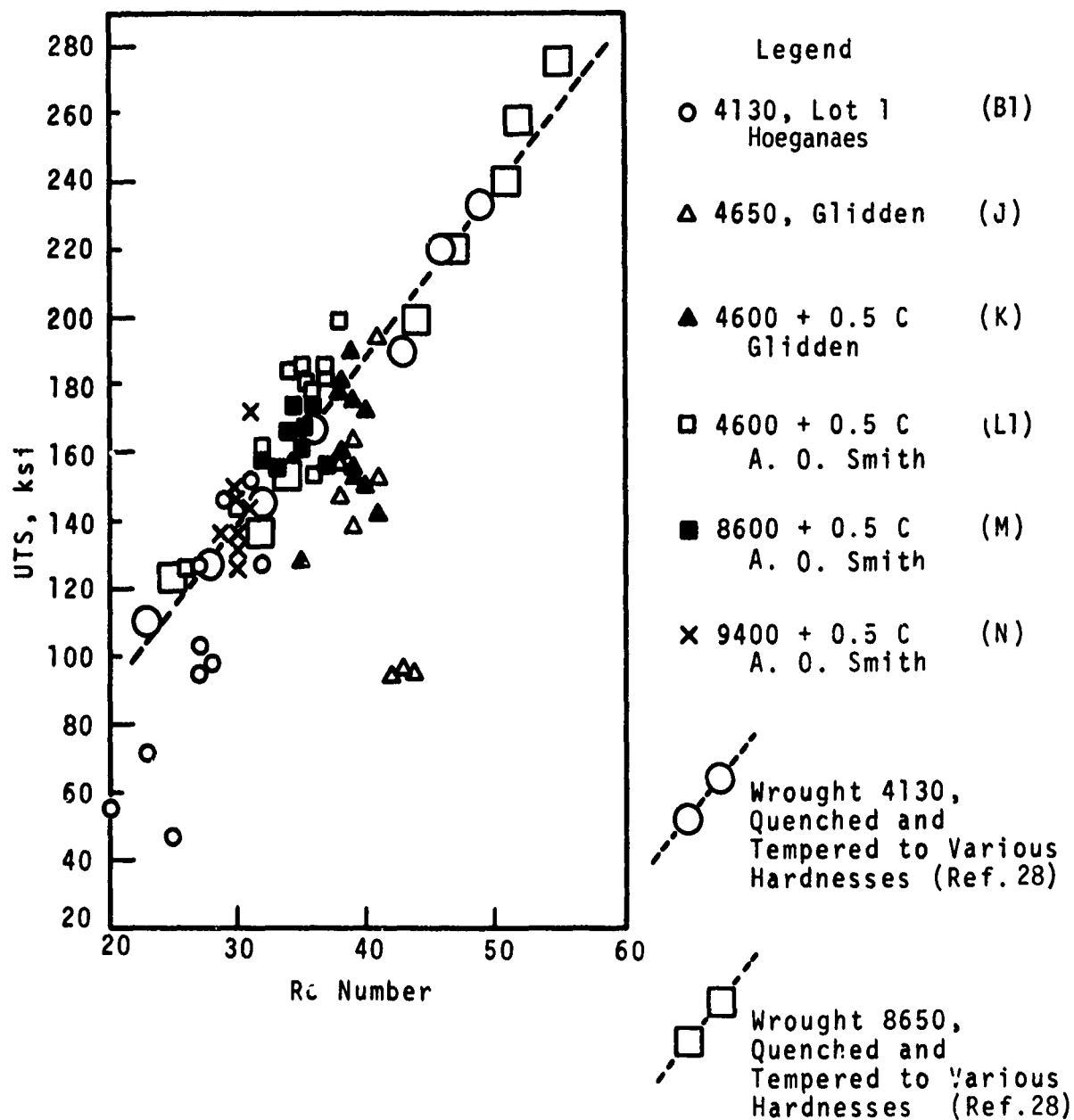
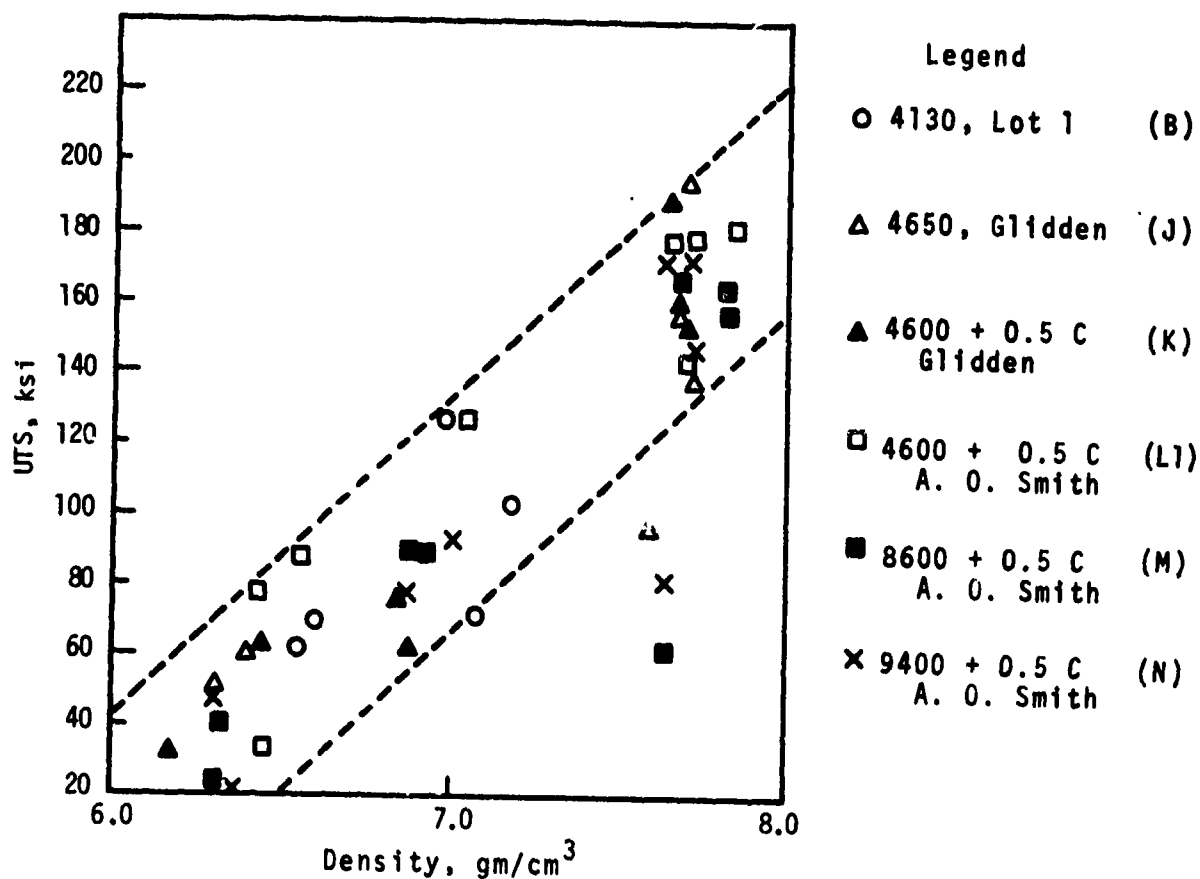


FIGURE 36. Combined Effect of Compacting Pressure, 2050°F Sinter, and 2200°F Hot Repress (c) on Density



**FIGURE 37.** Relationship Between Ultimate Tensile Strength and Rockwell C Hardness Number (For Die Press Processed Samples with Hardnesses >Rc 20)



**FIGURE 38.** Relationship Between Ultimate Tensile Strength and Density  
(For Die Press Processed Samples Compacted Initially  
at 50 ksi)

Four prealloyed steel powders were selected for the Task C hot repressing study:

- 4130, Hoeganaes (B2)
- 4600 + 0.4 C, A. O. Smith-Inland (L2)
- 4650, Glidden-Durkee (J)
- 8620, Hoeganaes (H)

All powders are described in detail in the section of the report entitled MATERIALS.

Three repressing pressures were used: 80 ksi, 120 ksi, and 160 ksi; and three forging temperatures: 1800°F, 2000°F, and 2200°F.

All preforms were formed by cold compaction at 100,000 psi, followed by a 2050°F sinter. The preforms so produced varied widely in density before the hot repress operation. This variation is shown in Table 4.

TABLE 4  
Density of Preforms After Compaction (100 ksi)  
and Sinter (2050°F)

| <u>Material</u>   | <u>Preform Density, gm/cm<sup>3</sup></u> |                     |
|-------------------|-------------------------------------------|---------------------|
|                   | <u>After Compaction</u>                   | <u>After Sinter</u> |
| 4130 (B2)         | 6.86                                      | 6.92                |
| 4600 + 0.4 C (L2) | 7.20                                      | 7.21                |
| 4650 (J)          | 6.50                                      | 6.60                |
| 8620 (H)          | 6.97                                      | 7.05                |

The preforms were brought to temperature in a flowing argon atmosphere prior to repressing. They were rapidly transferred to the repressing dies (<5 seconds transfer time), and pressed. The dies were preheated to 800°F.

After repressing, the bars of B2, L2, and J were austenitized at 1575°F in endothermic gas, water quenched, tempered at either 900°F or 1100°F, and machined into test specimens. The bars of 8620 (H) were machined to shape, pack carburized to yield a case approximately 15-mil

thick (see Section 5.8, Heat Treating and Carburizing), austenitized at 1575°F, water quenched, then tempered at either 900°F or 450°F.

All bars of J material showed some degree of cracking after the water quench (see Figure 39). Most cracks were confined to the surface, and so generally did not affect the final test piece. No other material was susceptible to cracking.

The effect of pressure and temperature on sample density is shown in Figure 40. Powder L2, 4600 + 0.4 C, densifies far more easily than the other powders tested, and is influenced relatively little by repress temperature. The densification of powder J, a completely prealloyed 4650 which is relatively difficult to press, was significantly aided by increased repress temperature.

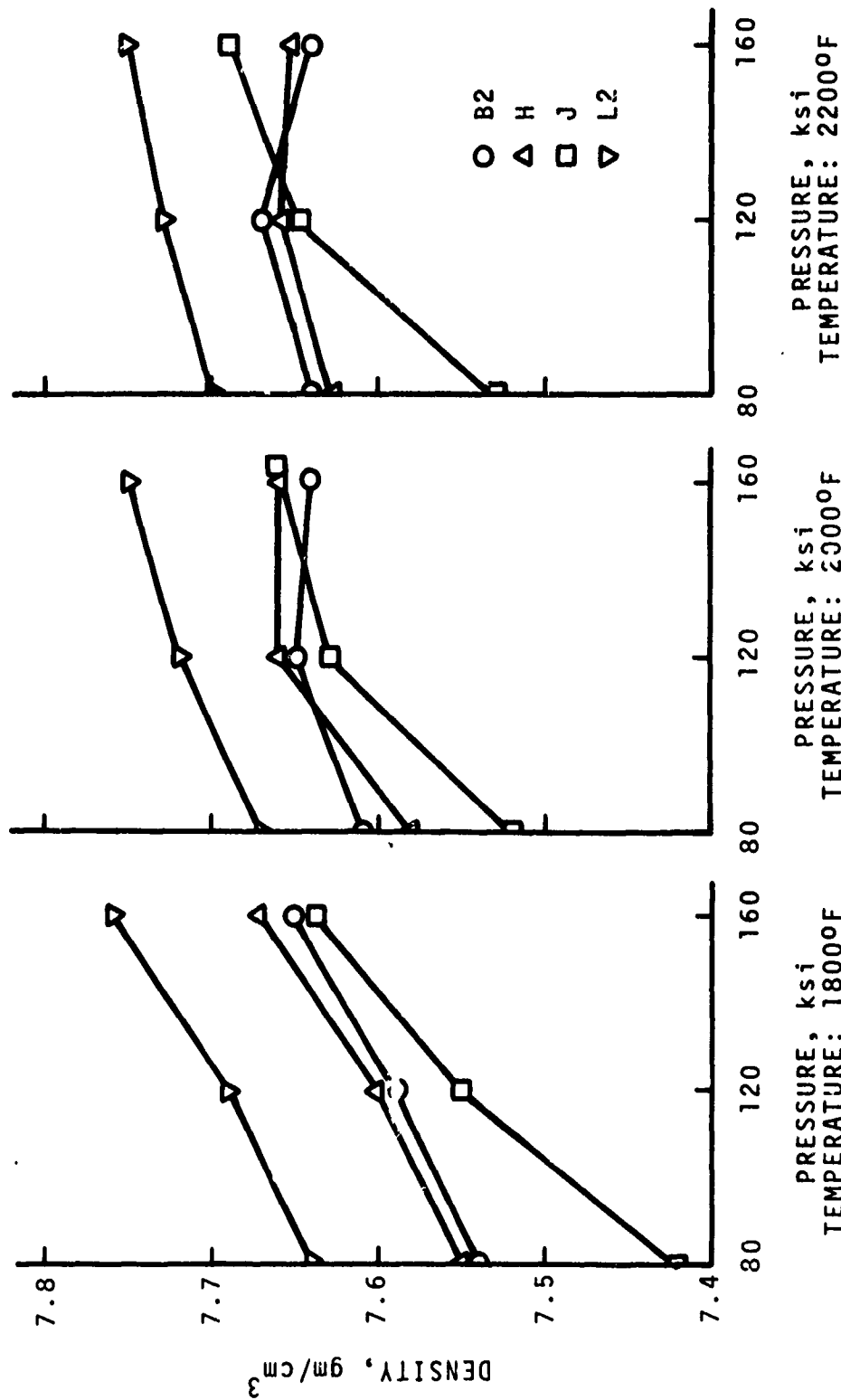
The hardness of the final samples as a function of repress temperature and pressure is shown in Figure 41. The 8620 material (H) was carburized prior to taking hardness measurements, hence the high values for that material. On the whole, the hardness is relatively insensitive to the density changes induced by the repressing parameters employed.

The absolute values of hardness found in Task C work were somewhat less than those obtained in Task B for equivalent materials heat treated in seemingly identical fashion. For example, bars of J material fabricated for Task B studies exhibited hardness values in the range C38 to C43 after a 900°F temper; J material in Task C varied from C34 to C39 after the same heat treatment. Other materials show a similar decrease in hardness. The exact reason for the lower hardness values is not known. It is possible that slight differences in endothermic gas composition during the austenitizing treatment may have resulted in lower carbon levels, hence lower hardness values, in the Task C samples.

The relationship between ultimate tensile strength and repressing parameters is shown in Figure 42. The average elongation of the samples represented by each curve is also noted in the figure. The data of this figure are derived from the single samples yielding the highest UTS of the duplicate samples of each material tested. Note that the UTS is almost



FIGURE 39. Bars of 4650 (J) Material After Quench



**FIGURE 40.** Effect of Hot Repress Pressure and Temperature on Density  
All samples cold pressed 100 ksi, sintered 2050°F prior to forging.

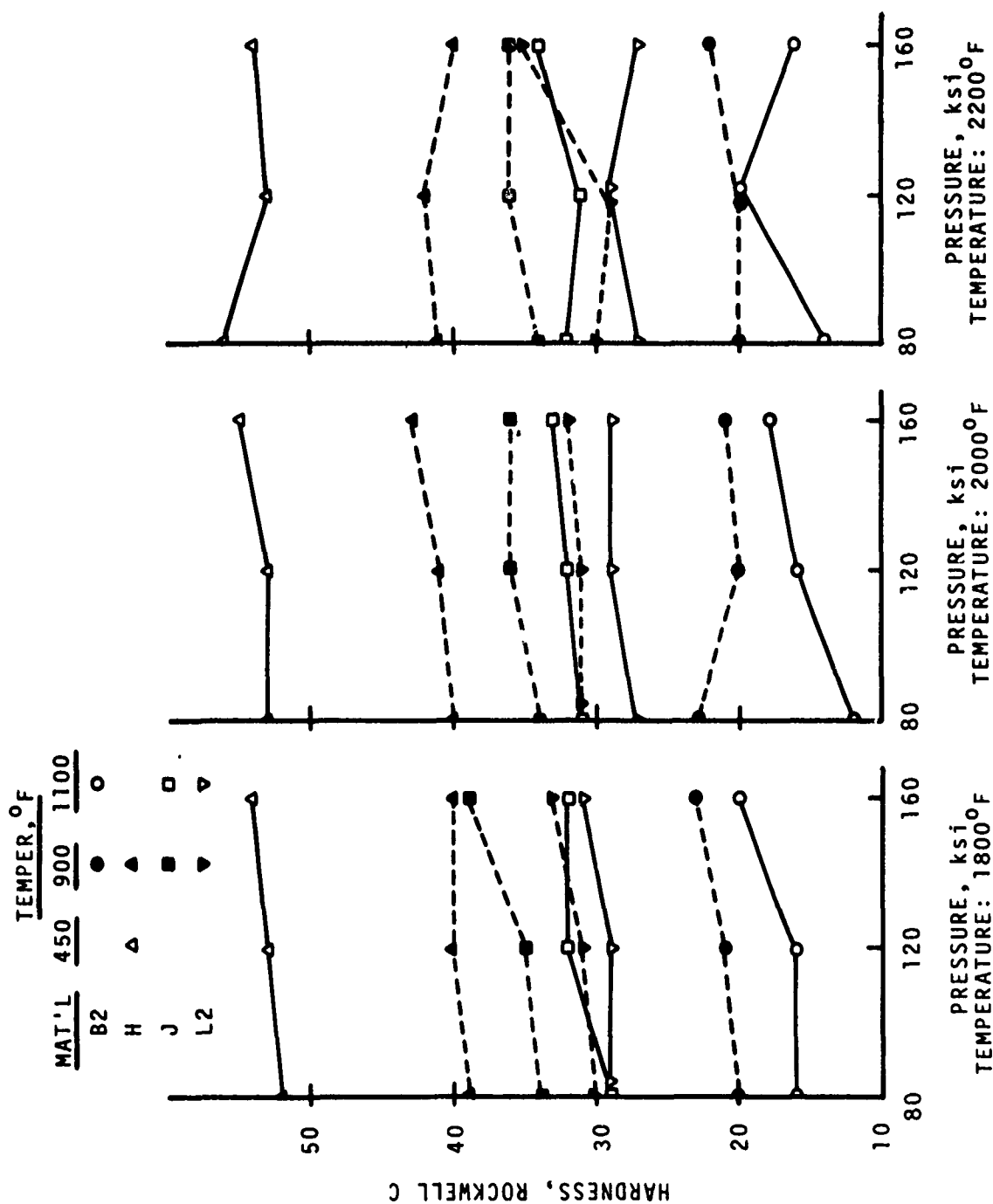


FIGURE 41.  
Effect of Hot R.p. Press Pressure and Temperature  
on Hardness of Final Heat-Treated Samples

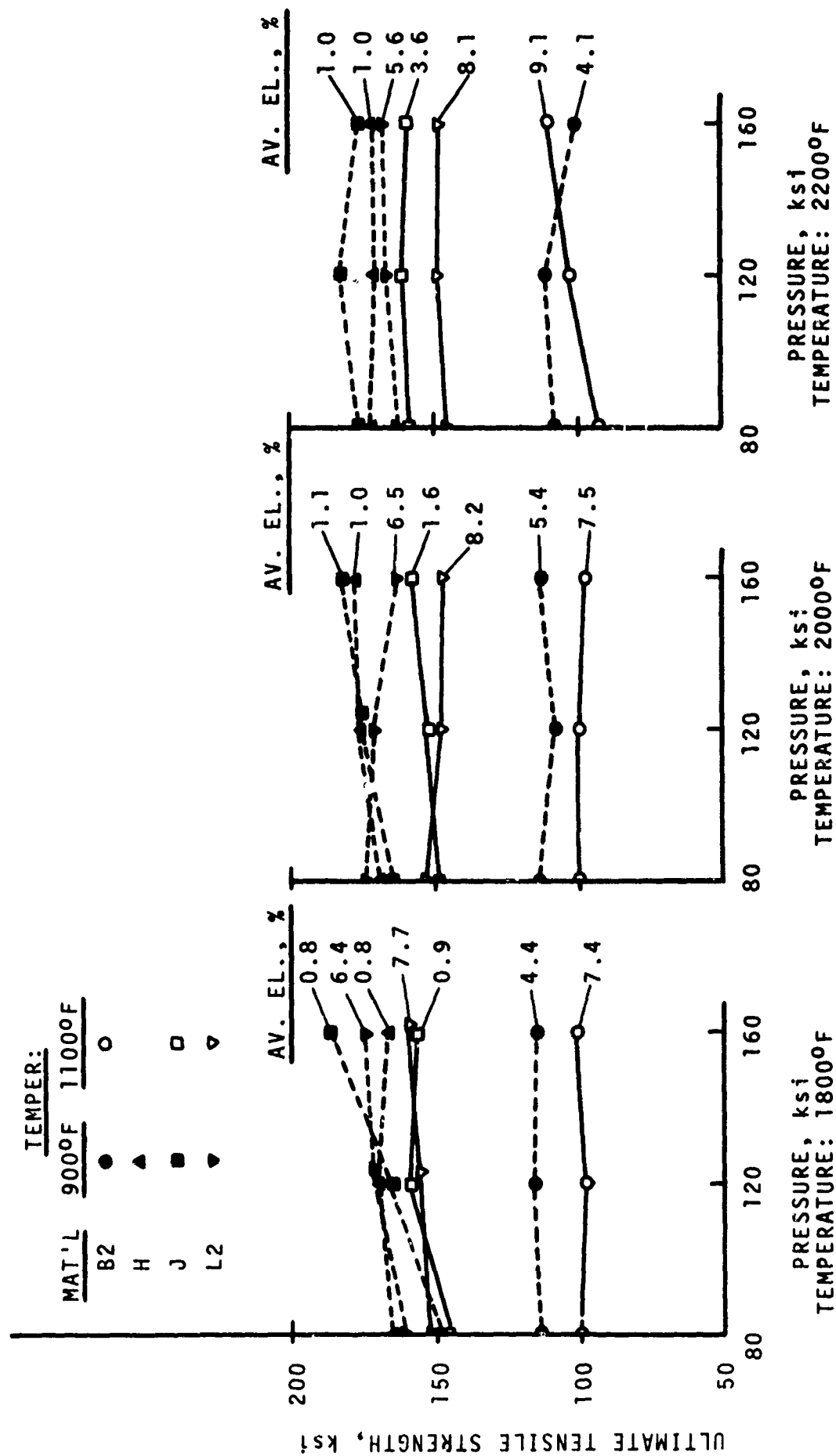


FIGURE 42. Effect of Hot Repress Pressure and Temperature on Ultimate Tensile Strength

independent of repressing parameters over the range of pressure and temperature chosen for study. The UTS values compare favorably with those of wrought materials at the same hardness levels. The elongation values, however, are much lower than those expected for wrought materials.

Elongation data are presented for the individual Task C samples in the appendix, along with the detailed YS and UTS data.

The relationship between impact properties and repressing parameters is shown in Figure 43. All of the impact property values are low and relatively independent of repressing pressure and temperature, with the exception of the 4600 + 0.4 C (L2) samples, which show a decided improvement in properties with increasing temperature and pressure. The data of Figure 43 represent the single samples yielding the highest impact energy absorption of the duplicate samples tested. Detailed impact data are presented in the appendix.

Some representative microstructures of the Task C materials are shown in Figures 44 and 45. Note that the carburized case on the less dense samples of 8620 (H) extends considerably deeper than the approximate 15-mil case depth found on dense samples (Figure 45).

It appears likely that the low tensile elongation and low impact strength values generally found in the present work (Task B as well as Task C) can be related to two major factors: possible internal oxidation of the sample during the preform preheat and subsequent transfer to the repress dies, and lack of substantial transverse metal flow during the repress operation. No effort was made in the present study to inhibit oxidation of the preform during the transfer operation, and significant internal oxidation could have taken place, which would tend to embrittle the material.<sup>(5)</sup> Transverse metal flow was not permitted by die design, so that very high densities could not be generally obtained. Such metal flow would also be expected to assist in breaking up internal oxide films, so that some of the inherent qualities of the material could be recovered.

The 4600 + 0.4 C (L2) material which formed the densest preform also yielded the best impact properties and generally the best elongation

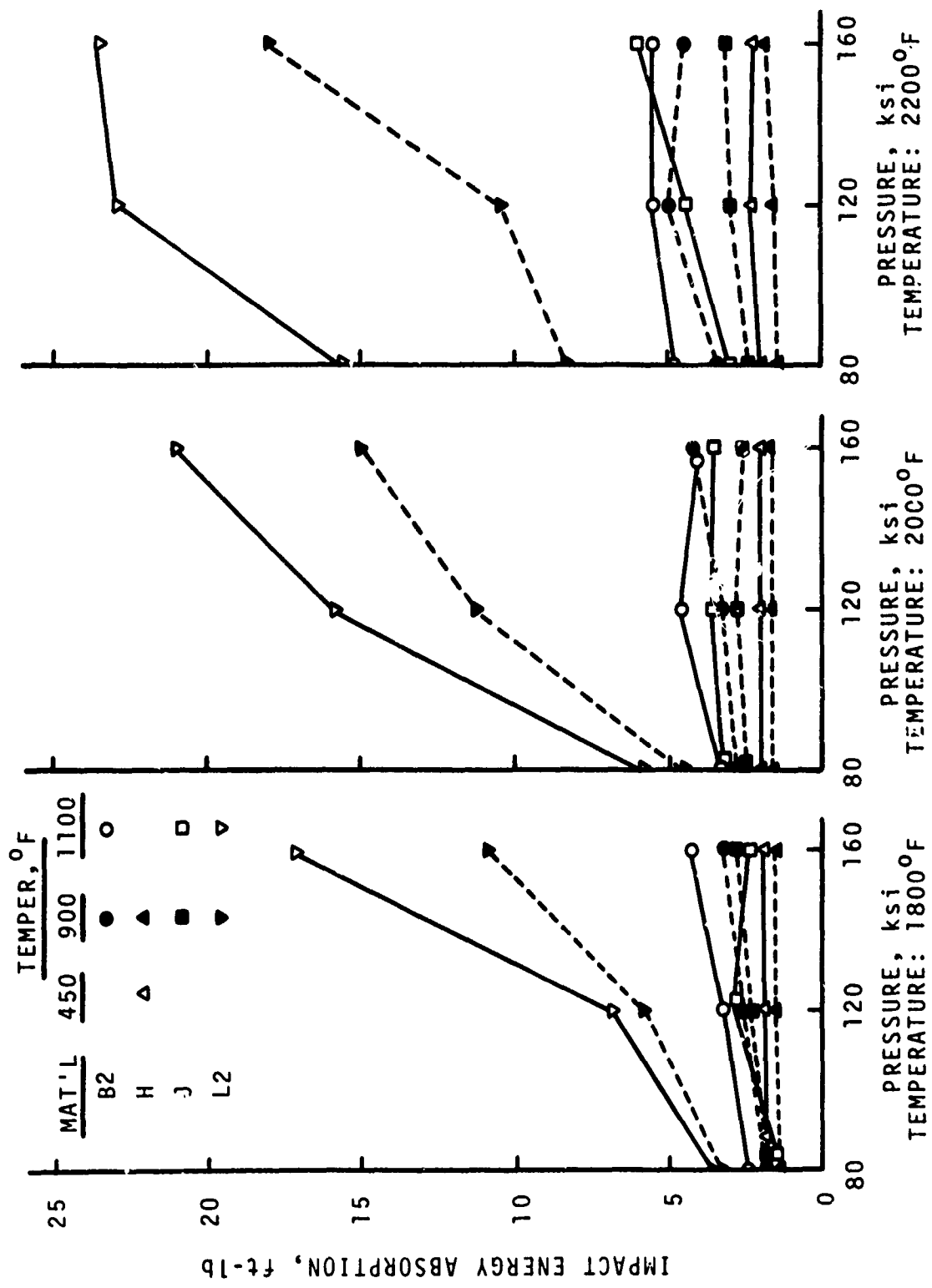
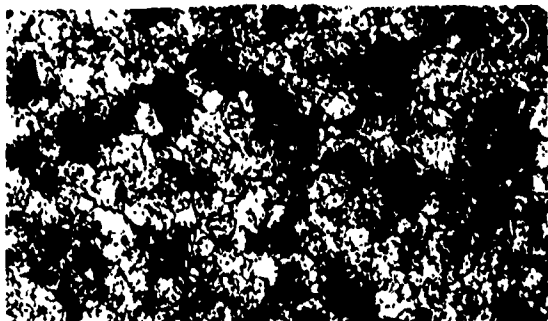


FIGURE 43. Effect of Hot Repress Pressure and Temperature on Room Temperature Impact Properties

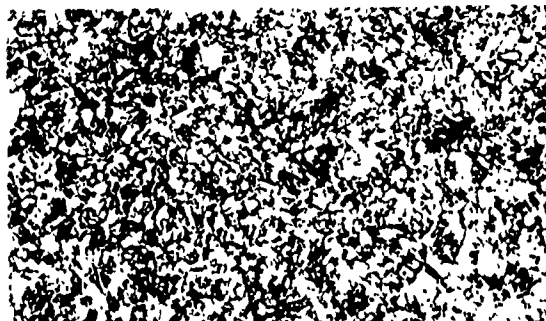
Samples Pressed 100 ksi  
Sintered 2050 °F  
Austenitized, Quenched  
Tempered 900 °F

Samples Pressed 100 ksi  
Sintered 2050 °F  
Hot Repressed 2200 °F, 160 ksi  
Austenitized, Quenched  
Tempered 900 °F

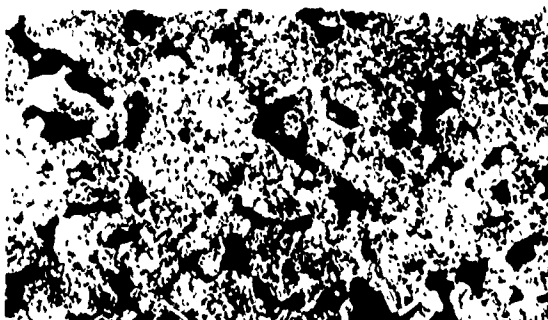


Density 6.92 gm/cm<sup>3</sup>

4130 'B2)



Density 7.64 gm/cm<sup>3</sup>

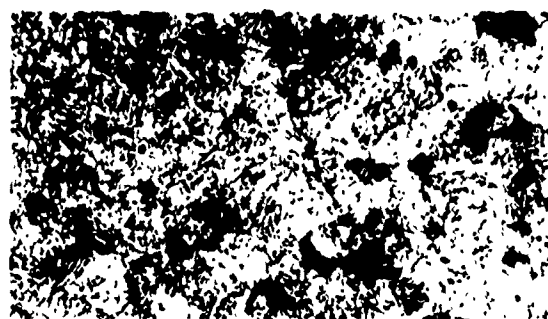


Density 6.60 gm/cm<sup>3</sup>

4650 (J)



Density 7.69 gm/cm<sup>3</sup>



Density 7.21 gm/cm<sup>3</sup>

4600 + 0.4C (L2)

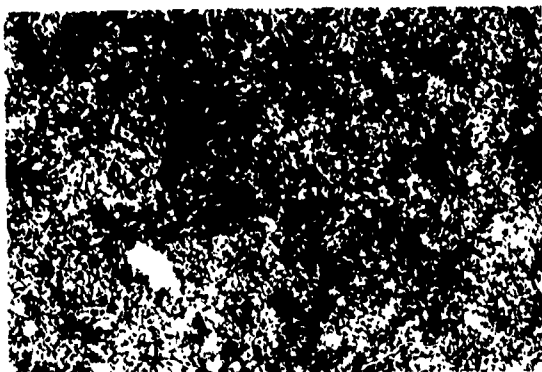


Density 7.75 gm/cm<sup>3</sup>

FIGURE 44. Microstructures of Pressed-and-Sintered  
and Hot Repressed Samples 250X

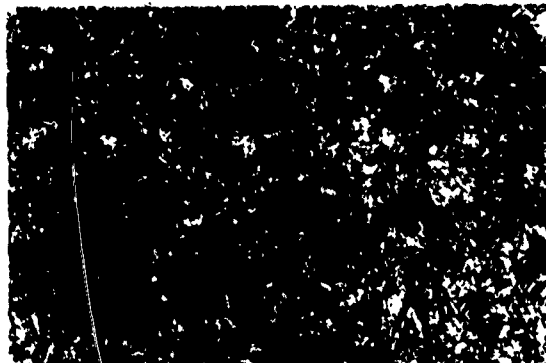
Sample Pressed 100 ksi  
Sintered 2050 °F  
Pack Carburized 1700 °F, 2 hr  
Austenitized, Quenched  
Tempered 900 °F

Sample Pressed 100 ksi  
Sintered 2050 °F  
Hot Repressed 2200 °F, 150 ksi  
Pack Carburized 1700 °F, 2 hr  
Austenitized, Quenched  
Tempered 900 °F



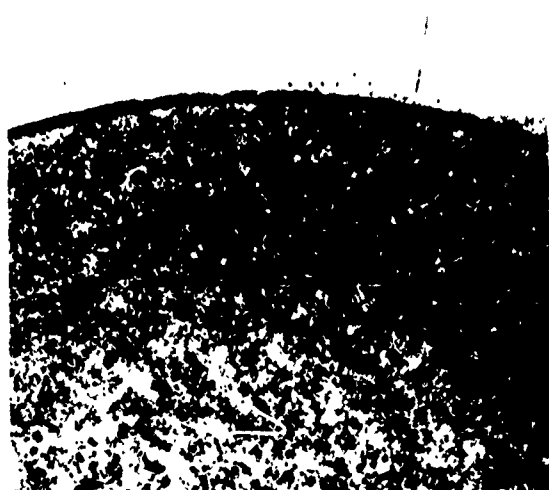
Sample Center

250X



Sample Center

250X



Sample Surface

40X



Sample Surface

40X

**FIGURE 45.** Microstructures of Pressed-and-Sintered and Hot Repressed Samples of Carburized 8620(H) Material

properties of the materials studied. The denseness of the preform, coupled with the chromium-free steel composition and the graphite admix could have significantly inhibited internal oxidation of this material relative to the other materials. The carburized material (H) exhibited the poorest elongation and impact properties of any of the materials tested.

There was no effort made to quantify the relative contributions of the various factors suspected of contributing to the general lack of elongation and impact strength of the materials studied, as such investigations were beyond the scope of the present program. The results obtained, however, illustrate the necessity of preform design to insure adequate metal flow, oxidation protection of the preform during preheat and transfer operations, and careful investigatory work during formulation of any preform forging procedure to detect and eliminate any factors which might contribute to undue property degradation.

It is interesting to compare mechanical property values obtained in the present work with those obtained by other investigators. It is generally difficult to make direct comparisons, because of the wide variety of materials, fabrication processes, heat treatments and testing procedures employed by various investigators. It is possible, however, to make a fairly meaningful comparison between the mechanical property values obtained by several investigators on forged, heat treated 4600 + 0.4 - 0.5 C steel bars. This comparison is made in Table 5. The 4600 prealloyed powder is A. O. Smith water atomized material in all cases. Forging procedures differed substantially, however.

The properties reported actually show fairly good agreement, in spite of the wide variation in forging procedures employed. Unfortunately, impact data, one of the most sensitive indicators of sample quality, is not available in all cases.

By way of comparison, wrought 4640 material is expected to exhibit a Charpy impact value of 39 ft-lbs, an elongation of 12.0 percent, and an ultimate strength of 182,200 lb/in.<sup>2</sup> at a hardness of C36 (800°F temper). (17)

**TABLE 5**  
**Comparison of Mechanical Properties**  
**of 4600 + 0.4 - 0.5 C Material**  
**Fabricated by Different Investigators**

| <u>C</u>  | <u>Density</u><br><u>% Th.</u> | <u>Temper.</u><br><u>°F</u> | <u>Rockwell</u><br><u>Hardness</u> | <u>UTS,</u><br><u>ksi</u> | <u>El., %</u> | <u>Charpy</u><br><u>V-Notch,</u><br><u>ft-lb</u> | <u>Reference</u>  |
|-----------|--------------------------------|-----------------------------|------------------------------------|---------------------------|---------------|--------------------------------------------------|-------------------|
| 0.41      | >98                            | 800                         | C35                                | 185.4                     | 6.8           | 9.5                                              | 17                |
| 0.46      | 98.6                           | 1100                        | C34-33                             | 152.2                     | 13            | -                                                | 10                |
| 0.40      | 99.89                          | 1050                        | -                                  | 155.7                     | 16.7          | -                                                | 14                |
| 0.40      | 99.24                          | 1100                        | -                                  | 157.5                     | 13.9          | -                                                | 14                |
| 0.51 (L1) | 98.2                           | 900                         | C34                                | 184                       | 4.3           | -                                                | } present<br>work |
| 0.51 (L1) | 98.2                           | 900                         | C34                                | 181                       | 6.6           | -                                                |                   |
| 0.41 (L2) | 98.6                           | 900                         | C35                                | 168                       | 7.3           | 18.0                                             |                   |
| 0.41 (L2) | 98.6                           | 900                         | C35                                | 152                       | 7.7           | 17.3                                             |                   |
| 0.41 (L2) | 98.6                           | 1100                        | C27                                | 149                       | 7.2           | 20.2                                             |                   |
| 0.41 (L2) | 98.6                           | 1100                        | C27                                | 148                       | 8.7           | 23.6                                             |                   |

## 7. CONCLUSIONS

P/M products made from a wide range of prealloyed steel powders can yield hardness and tensile strength values equal to their wrought counterparts if the products are processed to attain densities in the vicinity of 98% of theoretical. This was accomplished in the present program by hot repressing preforms and by HERF processing. The impact strength and ductility of the materials produced, however, were inferior to those of wrought products. In the case of the hot repressing operation (limited deformation forging) two major factors were thought to contribute to low impact strength and low ductility. Internal oxidation, during preform heating and transfer to the repressing dies, and lack of transverse metal flow during repressing, which would tend to further densify the material and help break up any continuous internal oxide films. With suitable attention to oxidation protection and steel composition, and if some transverse flow is permitted, there appears to be no insurmountable

barrier to routine attainment of properties closely approaching those of wrought materials in hot repressed P/M products. The present program was not intended to optimize procedures, processes, and materials, so that attainment of wrought properties was not generally expected.

The tensile properties of P/M products made from prealloyed steel powders by hot repressing or HERF processing are far superior to products made by cold pressing and sintering alone.

The HERF products tested exhibited unexpectedly low elongation and impact strength properties for material of such high density.

Individual prealloyed powders of essentially the same alloy composition were found to vary markedly from lot to lot, in ease of densification and resulting mechanical properties. The differences in mechanical properties tended to disappear when the various lots were processed to yield densities close to theoretical.

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**APPENDIX**

**DATA COMPILATION**

**Mechanical and Physical Properties  
of Powder Metallurgy Products Made  
From Prealloyed, Heat Treatable Steel Powders**

## 9. APPENDIX

### FOREWARD TO DATA COMPILATION

The purpose of the data compilation presented here is to bring together the major part of the data currently available on heat-treatable steel P/M materials. Though data from heat-treated material have been emphasized in this compilation, some data are presented on unalloyed and nonheat-treated ferrous materials. Data considered to be proprietary by the concerns responsible for its generation and ultimate use are of course not included. Unfortunately, a large amount of the most advanced data extant fall in this category, and so are unavailable. It must be emphasized that the data presented here do not ordinarily represent the optimum properties obtainable from a given P/M material or part. Data have not been excluded because inferior properties were obtained. It is hoped, however, that sufficient information on the materials, processing, and testing accompanies the particular data summary to permit the reader to satisfactorily judge its value.

A number of extensive programs are currently underway, in the United States and abroad, which will yield procedures for economical attainment of near-optimum P/M properties. It appears that forging of P/M preforms will be the procedure used for obtaining the highest quality parts. Pre-form design, a subject beyond the scope of this data compilation, is one of the most critical items which must be resolved before optimum properties can be obtained in any given P/M part.

The diversity of the fabrication and testing methods employed by various investigators makes it impossible to treat the data concisely except as "data groups". The data of each individual investigating team are treated as an independent unit. The Table of Contents (following page) lists, in arbitrary order, the investigator(s) responsible for the data group and the steel compositions studied.

No claim is made for completeness of this data compilation. Some data have been omitted for incompleteness or irrelevance, and some worthwhile data have been undoubtedly overlooked.

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|          | <b>8650 . . . . .</b>                            | <b>98</b>  |
|          | <b>9450 . . . . .</b>                            | <b>100</b> |
| <b>2</b> | <b>DATA GROUP B . . . . .</b>                    | <b>102</b> |
|          | <b>Reference: 10</b>                             |            |
|          | <b>Steels: 4645-4650</b>                         |            |
| <b>3</b> | <b>DATA GROUP C . . . . .</b>                    | <b>105</b> |
|          | <b>Reference: 17</b>                             |            |
|          | <b>Steels: 4620</b>                              |            |
|          | <b>4630</b>                                      |            |
|          | <b>4640</b>                                      |            |
| <b>4</b> | <b>DATA GROUP D . . . . .</b>                    | <b>109</b> |
|          | <b>Reference: 14</b>                             |            |
|          | <b>Steels: 1040</b>                              |            |
|          | <b>4640</b>                                      |            |
|          | <b>8640</b>                                      |            |
|          | <b>8650</b>                                      |            |
|          | <b>9440</b>                                      |            |
| <b>5</b> | <b>DATA GROUP E . . . . .</b>                    | <b>113</b> |
|          | <b>References: 1, 8</b>                          |            |
|          | <b>Steels: 1050</b>                              |            |
|          | <b>Mod. 4630 (low nickel)</b>                    |            |
|          | <b>4630</b>                                      |            |
|          | <b>8630</b>                                      |            |

## Section

|    |                                        |     |
|----|----------------------------------------|-----|
| 6  | DATA GROUP F . . . . .                 | 115 |
|    | R Reference: 11                        |     |
|    | Steel: 4640                            |     |
| 7  | DATA GROUP G . . . . .                 | 120 |
|    | Reference: 24                          |     |
|    | Steels: 1040                           |     |
|    | 4640                                   |     |
|    | 4665                                   |     |
|    | 1.35 Mn, 0.58 C                        |     |
| 8  | DATA GROUP H . . . . .                 | 125 |
|    | Reference: 18                          |     |
|    | Steels: 4625                           |     |
|    | 4635                                   |     |
|    | 4650                                   |     |
| 9  | DATA GROUP I . . . . .                 | 128 |
|    | Reference: 3                           |     |
|    | Steels: Unalloyed irons                |     |
|    | 9600 + C                               |     |
|    | 4600 + C                               |     |
|    | Fe-C, Fe-Ni-C, Fe-Ni-Mo-C,             |     |
|    | Fe-Cr-C, Fe-Cr-Ni-C Alloys             |     |
| 10 | OTHER SOURCES OF INFORMATION . . . . . | 136 |

## DATA COMPILATION

### 1. Data Group A

Reference: Summation of data presented in foregoing report.

#### Materials

| <u>Code</u> | <u>AISI Equivalent</u> | <u>Code</u> | <u>AISI Equivalent</u> |
|-------------|------------------------|-------------|------------------------|
| A           | 4130                   | H           | 8620                   |
| B1          | 4130                   | I           | 4100 + 0.3C            |
| B2          | 4130                   | J           | 4650                   |
| C           | 4130                   | K           | 4600 + 0.5C            |
| D           | 4130                   | L1          | 4600 + 0.5C            |
| E           | 4130                   | L2          | 4600 + 0.4C            |
| F           | 4130                   | M           | 8600 + 0.5C            |
| G           | 1040                   | N           | 9400 + 0.5C            |

The materials are described in detail in Figures 2 to 5, foregoing report.

#### Processing Notes

- All densities reported are bulk specimen densities, determined by measuring and weighing bars. These values are somewhat lower than the true specimen densities.
- All sintering was done in dissociated ammonia at either 1650°F or 2050°F, 1/2 hr.
- All austenitizing was done at 1575°F for 1/2 hr in endogas adjusted to the proper carbon potential.
- All austenitizing treatments ended with a water quench.
- All hot repressing operations (limited deformation forging) resulted in a lateral metal spread of  $\leq 10\%$ . In Task C, the die was preheated to 800°F.
- Hot repress preforms were not surface-protected in any way from oxidation during preheat (flowing argon) or transfer (in air) to the press.

### Definition of Terms Used in Group A Data Compilation

$P_1$  = Die press, 50 ksi

$P_2$  = Die press, 90 ksi

$P_3$  = Die press, 100 ksi

$I$  = Isostatic press, 50 ksi

$H_1$  = HERF, ~200 ksi

$H_2$  = HERF, ~300 ksi

$S_1$  = Sinter, 1650°F

$S_2$  = Sinter, 2050°F

$T_1$  = 1800°F

$T_2$  = 2000°F

$T_3$  = 2200°F

$F_1$  = Hot repress, 80 ksi

$F_2$  = Hot repress, 120 ksi

$F_3$  = Hot repress, 150 ksi

$F_4$  = Hot repress, 160 ksi

$R$  = Cold repress, 80 ksi

Examples:  $P_1S_2RS_2$  indicates an initial compaction at 50 ksi, followed by a 2050°F sinter, followed by a cold repress of 80 ksi and a 2050°F sinter

$P_3S_2F_4T_2$  indicates an initial compaction at 100 ksi, followed by a 2050°F sinter, followed by a hot repress operation: 160 ksi at 2000°F

$H_1T_3$  indicates a maximum pressure of about 200 ksi, with the powder at 2200°F

a = Compacts too fragile to handle

b = One or more samples broke during machining of tensile specimens, e.g., b(2) indicates two samples broke

c = Sample broke outside of reduced (gage) section during tensile test, e.g., within grips

# GROUP A DATA

## TYPE 4130

Nominal Composition: 0.3 C, 0.5 Mn, 1.0 Cr  
Mesh: -100 0.2 Mo, 0.3 Si

Austenitized at 1575°F, Water Quench, Tempered at 900°F

| Process                                       | Mat'l    | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch,<br>ft-lb | Remarks                                          |
|-----------------------------------------------|----------|-------------------------------|----------------------|-----------|--------------|---------------|-----------------------------|--------------------------------------------------|
| P <sub>1</sub>                                | B1       | 5.81                          |                      |           |              |               |                             | No machining attempted                           |
| P <sub>1</sub> S <sub>1</sub>                 | B1       | 5.83                          | B58                  |           |              |               |                             | b(2)                                             |
| P <sub>1</sub> S <sub>2</sub>                 | B1       | 5.97                          | B78                  |           | 21.7<br>35.0 | 0.3<br>0.2    |                             | c                                                |
| P <sub>2</sub>                                | B1       | 6.27                          |                      |           |              |               |                             | No machining attempted                           |
| P <sub>2</sub> S <sub>1</sub>                 | B1       | 6.31                          | B76                  |           |              |               |                             | b(2)                                             |
| P <sub>2</sub> S <sub>2</sub>                 | B1<br>B2 | 6.43<br>6.60                  | B85                  | 53.5      | 58.3         | 0.6           | 0.9                         | YS, UTS, TE<br>arithmetic average<br>of 11 spec. |
| P <sub>3</sub>                                | B1<br>B2 | 6.48<br>6.78                  |                      |           |              |               |                             | No machining attempted                           |
| P <sub>3</sub> S <sub>1</sub>                 | B1       | 6.52                          | B67                  |           |              |               |                             | b(2)                                             |
| P <sub>3</sub> S <sub>2</sub>                 | B1       | 6.65                          | B91                  |           | 61.0<br>57.3 | 0.5<br>0.4    |                             |                                                  |
| P <sub>3</sub> S <sub>2</sub>                 | B2       | 6.86                          | B85<br>B48           | 67.0<br>- | 73.0<br>53.0 | 0.7<br>0.4    | 1.2<br>1.2                  | 900°F temper<br>1100°F temper                    |
| P <sub>1</sub> S <sub>1</sub> RS <sub>2</sub> | B1       | 6.60                          | B99                  |           | 69.5<br>67.5 | 0.4<br>0.4    |                             |                                                  |
| P <sub>1</sub> S <sub>2</sub> RS <sub>2</sub> | B1       | 6.55                          | B99                  |           | 61.6<br>58.3 | 0.5<br>0.4    |                             |                                                  |
| P <sub>2</sub> S <sub>1</sub> RS <sub>2</sub> | B1       | 6.85                          | B99                  | 72.2      | 81.0<br>91.4 | 0.9<br>1.0    |                             |                                                  |
| P <sub>2</sub> S <sub>2</sub> RS <sub>2</sub> | B1       | 6.66                          | B94                  |           | 70.4         | 0.4           |                             | c(1)                                             |

# GROUP A DATA

## TYPE 4130

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch,<br>ft-lb | Remarks        |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|------------|--------------|---------------|-----------------------------|----------------|
| P <sub>3</sub> S <sub>1</sub> RS <sub>2</sub>               | B1    | 6.52                          | B94                  | 87.4       | 89.9<br>94.6 | 0.6<br>0.6    |                             |                |
| P <sub>3</sub> S <sub>2</sub> RS <sub>2</sub>               | B1    | 6.90                          | B98                  | 79.4       | 89.9<br>82.5 | 0.7<br>0.4    |                             |                |
|                                                             |       |                               |                      |            |              |               |                             |                |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | B1    | 7.05                          | C20                  |            | 13.8         | 0.1           |                             | c<br>b(1)      |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | B1    | 7.18                          | C27                  | 87.8       | 41.4<br>103  | 0.3<br>3.4    |                             | c              |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | B1    | 7.08                          | C23                  |            | 70.8<br>52.8 | 0.5<br>0.2    |                             |                |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | B1    | 6.98                          | C27                  | 114        | 126<br>67.6  | 2.5<br>0.3    |                             |                |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | B1    | 7.00                          | C25                  |            | 47.0<br>47.5 | 0.2<br>0.2    |                             |                |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | B1    | 7.29                          | C32                  |            | 126          | 0.4           |                             | b              |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | B1    | 7.11                          | C28                  |            | 97.5<br>96.5 | 0.4<br>0.4    |                             |                |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | B1    | 7.08                          | B99                  |            | 131<br>85.2  | 0.5<br>0.5    |                             |                |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | B1    | 7.16                          | C20                  |            | 41.4<br>54.5 | 0.1<br>0.2    |                             |                |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | B1    | 7.21                          | C29                  | 130        | 118<br>145   | 1.4           |                             | c              |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | B1    | 7.11                          | C27                  |            | 94.5<br>93.0 | 0.4<br>0.2    |                             |                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | B1    | 7.25                          | C31                  | 145<br>118 | 152<br>121   | 1.8<br>1.1    |                             | "Best Process" |
|                                                             | B2    | 7.49                          |                      |            |              |               | 3.2                         |                |
|                                                             |       |                               |                      |            |              |               |                             |                |
|                                                             |       |                               |                      |            |              |               |                             |                |

**GROUP A DATA**

**TYPE 4130**

| Process                                       | Mat'l    | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch,<br>ft-lb | Remarks        |
|-----------------------------------------------|----------|-------------------------------|----------------------|------------|--------------|---------------|-----------------------------|----------------|
| I                                             | B1<br>B2 | 5.90<br>6.23                  |                      |            |              |               |                             |                |
| IS <sub>1</sub>                               | B1<br>B2 | 6.06<br>6.28                  | B75                  |            |              |               |                             | b(2)           |
| IS <sub>2</sub>                               | B1       | 6.18                          | B81                  |            | 49.0<br>51.1 | 0.5<br>0.5    |                             |                |
| IF <sub>3</sub> T <sub>1</sub>                | B1       | 7.51                          | C33                  |            | 130          | 0.5           |                             | b(1)           |
| IF <sub>3</sub> T <sub>3</sub>                | B1       | 7.77                          | C37                  |            | 140          | 0.8           |                             | b(1)           |
| IS <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | B1       | 7.39                          | C32                  |            | 97.5<br>74.5 | 0.5<br>0.3    |                             |                |
| IS <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | B1       | 7.53                          | C39                  |            | 159<br>147   | 0.5<br>0.5    |                             | "Best Process" |
|                                               | B2       | 7.66                          |                      |            |              |               | 2.3                         |                |
| IS <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | B1       | 7.40                          | C36                  | 101        | 115<br>105   | 1.3<br>0.7    |                             |                |
| IS <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | B1       | 7.44                          | C37                  | 118<br>132 | 124<br>138   | 0.6<br>1.1    |                             |                |
|                                               |          |                               |                      |            |              |               |                             |                |
| H <sub>1</sub> T <sub>1</sub>                 | B1       | 7.70                          | C31                  |            | 84.5<br>92.8 | 0.3<br>0.3    |                             |                |
| H <sub>2</sub> T <sub>1</sub>                 | B1       | 7.74                          | C33                  | 116        | 116<br>120   | 0.4<br>0.6    |                             |                |
| H <sub>1</sub> T <sub>3</sub>                 | B1<br>B2 | 7.77<br>7.74                  | C24<br>C20           | 91.1       | 131<br>103   | 4.8           |                             |                |
| H <sub>2</sub> T <sub>3</sub>                 | B1       | 7.72                          | C35                  | 136        | 156<br>153   | 1.3<br>1.4    |                             | "Best Process" |
|                                               | B2       | 7.73                          | C23                  |            | 101          | 2.3           | 1.3                         |                |
|                                               |          |                               |                      |            |              |               |                             |                |
|                                               |          |                               |                      |            |              |               |                             |                |

**TYPE 4130**

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**GROUP A DATA**

**TYPE 4130**

Note that tempering temperature is a variable. Task C Data.

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Temper,<br>°F | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE,<br>percent | Charpy V-Notch<br>Impact Energy,<br>ft-lb |
|-------------------------------------------------------------|-------|-------------------------------|---------------|----------------------|--------------|--------------|----------------|-------------------------------------------|
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | B2    | 7.54                          | 900           | C20                  | 102<br>104   | 114<br>114   | 4.8<br>3.8     | 1.8 (duplicate<br>1.9 tests)              |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | B2    | 7.54                          | 1100          | B95                  | 90.5<br>90.5 | 100<br>98.4  | 5.0<br>5.0     | 2.2<br>2.4                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | B2    | 7.59                          | 900           | C21                  | 96.0<br>106  | 104<br>117   | 4.0<br>4.0     | 2.7<br>2.2                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | B2    | 7.59                          | 1100          | B95                  | 88.9<br>88.0 | 98.4<br>98.4 | 8.3<br>8.0     | 2.7<br>3.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | B2    | 7.65                          | 900           | C23                  | 99.2<br>100  | 113<br>114   | 5.1<br>4.4     | 3.3<br>2.9                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | B2    | 7.65                          | 1100          | B98                  | 92.0<br>89.6 | 102<br>99.2  | 8.8<br>7.5     | 2.3<br>4.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | B2    | 7.61                          | 900           | C23                  | 102<br>104   | 114<br>113   | 5.3<br>4.3     | 2.5<br>2.7                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | B2    | 7.61                          | 1100          | B92                  | 90.4<br>81.6 | 101<br>92.8  | 8.3<br>8.9     | 1.9<br>3.2                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | B2    | 7.65                          | 900           | C20                  | 96.0<br>84.0 | 107<br>95.0  | 4.7<br>4.0     | 3.2<br>2.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | B2    | 7.65                          | 1100          | B95                  | 81.6<br>90.4 | 90.4<br>100  | 8.3<br>7.3     | 4.3<br>4.6                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | B2    | 7.64                          | 900           | C21                  | 92.0<br>101  | 106<br>112   | 6.4<br>6.2     | 4.2<br>2.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | B2    | 7.64                          | 1100          | B97                  | 86.3<br>87.0 | 97.2<br>97.5 | 7.7<br>7.4     | 3.8<br>4.1                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>3</sub> | B2    | 7.64                          | 900           | B93                  | 95.0<br>84.0 | 108<br>88.0  | 3.8<br>4.4     | 3.3<br>2.9                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>3</sub> | B2    | 7.64                          | 1100          | B94                  | 80.9<br>82.4 | 91.2<br>92.4 | 7.4<br>10.4    | 4.8<br>4.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>3</sub> | B2    | 7.67                          | 900           | C20                  | 98.2<br>93.0 | 111<br>107   | 4.6<br>3.4     | 5.0<br>4.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>3</sub> | B2    | 7.67                          | 1100          | C20                  | 92.3<br>87.0 | 102<br>96.5  | 9.2<br>9.5     | 5.4<br>4.8                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | B2    | 7.64                          | 900           | C22                  | 88.9<br>85.0 | 99.0<br>101  | 6.9<br>4.1     | 4.5<br>4.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | B2    | 7.64                          | 1100          | B95                  | 89.0<br>105  | 89.0<br>105  | 6.5<br>7.7     | 5.5<br>4.9                                |

GROUP A DATA

TYPE 1040

Nominal Composition: 0.4 C, 0.8 Mn  
Mesh: -100

Austenitized at 1575 °F, Water Quench, Tempered at 900°F

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch,<br>ft-lb | Remarks                              |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|--------------|--------------|---------------|-----------------------------|--------------------------------------|
| P <sub>2</sub>                                              | G     | 6.69                          |                      |              |              |               |                             | Not machined                         |
| P <sub>2</sub> S <sub>2</sub>                               | G     | 6.72                          | B44                  | 31.5<br>32.5 | 40.0<br>40.0 | 5.1<br>5.1    | 2.0                         |                                      |
| P <sub>3</sub>                                              | G     | 6.90                          |                      |              |              |               |                             | Not machined                         |
| P <sub>3</sub> S <sub>2</sub>                               | G     | 6.94                          |                      |              |              |               |                             | Not machined                         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | G     | 7.67                          | B89                  | 74.8<br>80.0 | 93.9<br>94.6 | 15.1<br>13.6  | 31.9                        |                                      |
| I                                                           | G     | 6.60                          |                      |              |              |               |                             | Not machined                         |
| IS <sub>1</sub>                                             | G     | 6.62                          |                      |              |              |               |                             | Not machined                         |
| IS <sub>1</sub> F <sub>3</sub> T <sub>3</sub>               | G     | 7.79                          | B90                  | 70.8<br>74.0 | 85.3<br>87.3 | 19.7<br>18.4  | 35.5                        |                                      |
| H <sub>2</sub> T <sub>3</sub>                               | G     | 7.75                          | B86                  | 73.5         | 87.5         | 19.0          | 38.7                        | Only one sample<br>machined for test |
|                                                             |       |                               |                      |              |              |               |                             |                                      |
|                                                             |       |                               |                      |              |              |               |                             |                                      |
|                                                             |       |                               |                      |              |              |               |                             |                                      |
|                                                             |       |                               |                      |              |              |               |                             |                                      |
|                                                             |       |                               |                      |              |              |               |                             |                                      |

# GROUP A DATA

## TYPE 4640

Nominal Composition: 0.4 C, 0.2 Mn, 0.5 Mo, 2.0 Ni, 0.03 Si  
Mesh: -100

Austenitized at 1575 °F, Water Quench, Tempered at 900°F and 1100°F. Task C Data.

| Process                                                     | Mat'l | Density,<br>gm/cm <sup>3</sup> | Temper,<br>°F | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi | TE,<br>percent | Charpy V-Notch<br>Impact Energy,<br>ft-lb |
|-------------------------------------------------------------|-------|--------------------------------|---------------|----------------------|------------|------------|----------------|-------------------------------------------|
| P <sub>3</sub>                                              | L2    | 7.20                           |               |                      |            |            |                |                                           |
| P <sub>3</sub> S <sub>2</sub>                               | L2    | 7.21                           | 900           | B95                  | 119<br>122 | 129<br>131 | 2.4<br>1.4     | 1.9                                       |
| P <sub>3</sub> S <sub>2</sub>                               | L2    | 7.21                           | 1100          | B92                  | 111<br>110 | 112<br>119 | 0.7<br>2.9     | 2.3                                       |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | L2    | 7.64                           | 900           | C30                  | 145<br>151 | 157<br>163 | 3.6<br>5.8     | 3.3 (duplicate<br>3.7 tests)              |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | L2    | 7.64                           | 1100          | C29                  | 135<br>142 | 147<br>148 | 6.9<br>5.6     | 3.4<br>3.2                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | L2    | 7.69                           | 900           | C31                  | 157<br>159 | 170<br>171 | 4.1<br>5.6     | 5.9<br>5.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | L2    | 7.69                           | 1100          | C29                  | 146<br>157 | 157<br>145 | 9.2<br>9.7     | 6.4<br>6.9                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | L2    | 7.76                           | 900           | C33                  | 160<br>161 | 174<br>174 | 8.0<br>7.2     | 11.0<br>10.3                              |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | L2    | 7.76                           | 1100          | C31                  | 146<br>144 | 157<br>156 | 8.4<br>10.8    | 15.0<br>17.3                              |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | L2    | 7.67                           | 900           | C31                  | 153        | 171        | 5.5            | 3.5<br>4.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | L2    | 7.67                           | 1100          | C27                  | 140<br>140 | 152<br>153 | 8.5<br>10.0    | 5.8<br>5.0                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | L2    | 7.72                           | 900           | C31                  | 158<br>161 | 173<br>174 | 6.9<br>6.8     | 8.2<br>11.3                               |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | L2    | 7.72                           | 1100          | C29                  | 139<br>138 | 146<br>149 | 8.1<br>8.1     | 8.6<br>15.8                               |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | L2    | 7.75                           | 900           | C32                  | 150<br>152 | 162<br>163 | 7.6<br>7.1     | 15.0<br>12.7                              |

### GROUP A DATA

**TYPE 4640.** Note that the tempering temperature is a variable. Task C Data.

[illegible]

GROUP A DATA

TYPE 4650

Nominal Composition: 0.5 C, 0.2 - 0.5 Mn,  
Mesh: -100 0.2 - 0.5 Mo, 2.0 Ni  
0.02 - 0.5 Si

Austenitized at 1575°F, Water Quench, Tempered at 900°F

| Process                       | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi | UTS<br>ksi   | TE<br>Percent | Charpy<br>V-Notch,<br>ft-lb | Remarks                   |
|-------------------------------|-------|-------------------------------|----------------------|-----------|--------------|---------------|-----------------------------|---------------------------|
|                               | J     | 5.83                          |                      |           |              |               |                             |                           |
| P <sub>1</sub>                | K     | 6.10                          |                      |           |              |               |                             | No machining<br>attempted |
|                               | L1    | 6.46                          |                      |           |              |               |                             |                           |
|                               | J     | 5.78                          | B80                  |           |              |               |                             | b (2)                     |
| P <sub>1</sub> S <sub>1</sub> | K     | 6.03                          | B56                  |           |              |               |                             | b (2)                     |
|                               | L1    | 6.45                          | B43                  | †<br>†    | 36.5<br>33.8 | 0.2<br>0.4    |                             |                           |
|                               | J     | 5.95                          | B78                  |           |              |               |                             | b (2)                     |
| P <sub>1</sub> S <sub>2</sub> | K     | 6.17                          | B81                  | †         | 32.0         | 0.3           |                             | b (1)                     |
|                               | L1    | 6.43                          | B89                  | †<br>72.3 | 75.8<br>77.5 | 0.2<br>0.6    |                             |                           |
|                               | J     | 6.18                          |                      |           |              |               |                             |                           |
| P <sub>2</sub>                | K     | 6.58                          |                      |           |              |               |                             | No machining<br>attempted |
|                               | L1    | 6.89                          |                      |           |              |               |                             |                           |
|                               |       |                               |                      |           |              |               |                             |                           |
|                               |       |                               |                      |           |              |               |                             |                           |

\*Yield strength data unobtainable, due to extensometer problems.

†Yield strength data not obtainable due to characteristics of material.

GROUP A DATA

TYPE 4650

| Process                                       | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch<br>ft-lb | Remarks                   |
|-----------------------------------------------|-------|-------------------------------|----------------------|--------------|--------------|---------------|----------------------------|---------------------------|
|                                               | J     | 6.13                          | B85                  |              |              |               |                            | b (2)                     |
| P <sub>2</sub> S <sub>1</sub>                 | K     | 6.48                          | B62                  | †            | 8.0          | 0.2           |                            | b (1)<br>c                |
|                                               | L1    | 6.91                          | B54                  | 82.0<br>77.0 | 97.0<br>83.0 | 1.0<br>1.5    |                            |                           |
|                                               | J     | 6.31                          | B91                  | †<br>†       | 39.0<br>41.0 | 0.5<br>0.3    | 0.9                        |                           |
| P <sub>2</sub> S <sub>2</sub>                 | K     | 6.65                          | B93                  | †<br>†       | 68.5<br>69.7 | 0.5<br>0.4    | 1.0                        |                           |
|                                               | L1    | 6.93                          | B98                  | †<br>113     | 107<br>116   | 0.4<br>1.0    | 1.4                        |                           |
|                                               | J     | 6.33                          |                      |              |              |               |                            |                           |
| P <sub>3</sub>                                | K     | 6.79                          |                      |              |              |               |                            | No machining<br>attempted |
|                                               | L1    | 7.11                          |                      |              |              |               |                            |                           |
|                                               | J     | 6.38                          | B88                  |              |              |               |                            | b (2)                     |
| P <sub>3</sub> S <sub>1</sub>                 | K     | 6.69                          | B79                  | †            | 15.8         | 0.2           |                            | b (1)<br>c                |
|                                               | L1    | 7.08                          | B58                  | 33.0<br>31.5 | 36.0<br>35.0 | 1.4<br>1.0    |                            |                           |
|                                               | J     | 6.59                          | B92                  | †<br>†       | 55.3<br>59.0 | 0.3<br>0.4    | 3.2                        |                           |
| P <sub>3</sub> S <sub>2</sub>                 | K     | 6.85                          | B94                  | †<br>†       | 63.8<br>69.0 | 0.3<br>0.3    |                            |                           |
|                                               | L1    | 7.15                          | C21                  | 122<br>125   | 132<br>137   | 1.2<br>1.2    |                            |                           |
|                                               | J     | 6.40                          | B86                  | †<br>★       | 66.3<br>60.0 | 0.5<br>0.7    |                            |                           |
| P <sub>1</sub> S <sub>1</sub> RS <sub>2</sub> | K     | 6.82                          | B91                  | †<br>★       | 76.1<br>76.0 | 0.3<br>0.4    |                            |                           |
|                                               | L1    | 7.05                          | B99                  | 112<br>116   | 124<br>127   | 1.2<br>1.4    |                            |                           |

\*Yield strength data unobtainable, due to extensometer problems.

†Yield strength data not obtained because of material characteristics.

# GROUP A DATA

## TYPE 4650

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi   | TE<br>Percent | Charpy<br>V-Notch,<br>ft-lb | Remarks |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|------------|--------------|---------------|-----------------------------|---------|
|                                                             | J     | 6.31                          | B87                  | †<br>*     | 52.0<br>50.0 | 0.4<br>0.5    |                             |         |
| P <sub>1</sub> S <sub>2</sub> RS <sub>2</sub>               | K     | 6.44                          | B86                  | †<br>*     | 58.5<br>62.0 | 0.3<br>0.3    |                             |         |
|                                                             | L1    | 6.56                          | B83                  | †<br>82.5  | 88.0<br>87.8 | 0.2<br>0.6    |                             |         |
|                                                             | J     | 6.52                          | B90                  | †<br>8     | 64.7<br>57.8 | 0.4<br>0.3    |                             |         |
| P <sub>2</sub> S <sub>1</sub> RS <sub>2</sub>               | K     | 6.96                          | C24                  | *          | 87.0         | 0.4           |                             | b (1)   |
|                                                             | L1    | 7.33                          | C24                  | 135<br>137 | 145<br>150   | 2.2<br>1.7    |                             |         |
|                                                             | J     | 6.52                          | B92                  | *<br>†     | 65.0<br>64.0 | 0.5<br>0.4    |                             |         |
| P <sub>2</sub> S <sub>2</sub> RS <sub>2</sub>               | K     | 6.82                          | B97                  | *<br>†     | 78.0<br>91.9 | 0.5<br>0.4    |                             |         |
|                                                             | L1    | 7.00                          | C20                  | 108<br>110 | 128<br>120   | 0.7<br>1.3    |                             |         |
|                                                             | J     | 6.68                          | B96                  | †<br>*     | 65.7<br>67.5 | 0.3<br>1.0    |                             |         |
| P <sub>3</sub> S <sub>1</sub> RS <sub>2</sub>               | K     | 7.08                          | C26                  | †<br>*     | 41.6<br>101  | 1.0<br>0.5    |                             |         |
|                                                             | L1    | 7.38                          | C28                  | 138<br>143 | 152<br>157   | 2.0<br>2.3    |                             |         |
|                                                             | J     | 6.70                          | B96                  | †<br>*     | 72.0<br>66.3 | 0.4<br>0.7    |                             |         |
| P <sub>3</sub> S <sub>2</sub> RS <sub>2</sub>               | K     | 6.98                          | C23                  | *<br>†     | 90.0<br>105  | 0.6<br>1.0    |                             |         |
|                                                             | L1    | 7.19                          | C21                  | 127<br>126 | 138<br>133   | 1.5<br>1.8    |                             |         |
|                                                             | J     | 7.59                          | C43                  | †<br>*     | 89.0<br>96.0 | 0.3<br>0.9    |                             |         |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | K     | 7.60                          | C39                  |            |              |               |                             | b (2)   |
|                                                             | L1    | 7.70                          | C30                  | 152<br>135 | 159<br>143   | 2.8<br>3.1    |                             |         |

\*Yield strength data unobtainable, due to extensometer problems.

†Yield strength data not obtained because of material characteristics.

GROUP A DATA

TYPE 4650

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi   | TE<br>Percent | Charpy<br>V-Notch,<br>ft-lb | Remarks |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|------------|--------------|---------------|-----------------------------|---------|
|                                                             | J     | 7.67                          | C39                  | †<br>*     | 176<br>157   | 0.6<br>1.0    |                             |         |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | K     | 7.70                          | C39                  | 180<br>*   | 183<br>152   | 2.1<br>0.6    |                             | c       |
|                                                             | L1    | 7.65                          | C36                  | 168<br>169 | 177<br>177   | 4.8<br>4.9    |                             |         |
|                                                             | J     | 7.69                          | C41                  | †<br>*     | 145<br>193   | 0.5<br>2.0    |                             |         |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | K     | 7.64                          | C39                  | 185<br>*   | 189<br>188   | 2.6<br>1.9    |                             |         |
|                                                             | L1    | 7.84                          | C37                  | 168<br>171 | 180<br>182   | 6.5<br>5.2    |                             |         |
|                                                             | J     | 7.72                          | C39                  | 175<br>*   | 184<br>137   | 2.4<br>2.2    |                             |         |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | K     | 7.67                          | C38                  | 172<br>*   | 178<br>160   | 2.3<br>1.1    |                             |         |
|                                                             | L1    | 7.72                          | C36                  | 167<br>167 | 174<br>178   | 6.0<br>5.8    |                             |         |
|                                                             | J     | 7.53                          | C42                  | †<br>*     | 89.0<br>94.0 | 0.3<br>0.4    |                             |         |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | K     | 7.61                          | C39                  | †<br>*     | 163<br>155   | 2.3<br>0.6    |                             |         |
|                                                             | L1    | 7.77                          | C26                  | 148<br>113 | 151<br>125   | 3.2<br>3.2    |                             |         |
|                                                             | J     | 7.61                          | C43                  |            |              |               |                             | b (2)   |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | K     | 7.64                          | C40                  | *          | 150          | 0.8           |                             | b (1)   |
|                                                             | L1    | 7.60                          | C36                  | 174<br>151 | 184<br>152   | 5.1<br>0.7    |                             |         |
|                                                             | J     | 7.63                          | C39                  | †<br>*     | 168<br>162   | 0.5<br>1.3    |                             |         |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | K     | 7.67                          | C38                  | †<br>*     | 87<br>180    | 0.4<br>1.3    |                             |         |
|                                                             | L1    | 7.80                          | C38                  | 174<br>178 | 184<br>188   | 6.2<br>5.9    |                             |         |

\*Yield strength data unobtainable, due to extensometer problems.

†Yield strength data not obtained because of material characteristics.

# GROUP A DATA

## TYPE 4650

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi | TE<br>Percent | Charpy<br>V-Notch<br>ft-lb | Remarks |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|------------|------------|---------------|----------------------------|---------|
|                                                             | J     | 7.66                          | C38                  | †<br>*     | 177<br>146 | 1.0<br>1.2    |                            |         |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | K     | 7.68                          | C38                  | †<br>*     | 172<br>178 | 0.9<br>2.1    |                            |         |
|                                                             | L1    | 7.77                          | C35                  | 167<br>*   | 180<br>185 | 5.9<br>6.2    |                            |         |
|                                                             | J     | 7.60                          | C43                  | *          | 87.8       | 0.7           |                            | b (1)   |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | K     | 7.64                          | C35                  | *          | 128        | 0.6           |                            | b (1)   |
|                                                             | L1    | 7.76                          | C32                  | 153<br>156 | 158<br>160 | 3.6<br>2.6    |                            |         |
|                                                             | J     | 7.59                          | C39                  |            |            |               |                            | b (2)   |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | K     | 7.62                          | C41                  | †<br>*     | 153<br>142 | 1.6<br>1.2    |                            |         |
|                                                             | L1    | 7.67                          | C37                  | 173<br>175 | 180<br>185 | 3.4<br>4.0    |                            |         |
|                                                             | J     | 7.65                          | C38                  | †<br>*     | 177<br>158 | 1.1<br>1.7    |                            |         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | K     | 7.66                          | C40                  | †<br>*     | 177<br>171 | 2.0<br>0.7    |                            |         |
|                                                             | L1    | 7.81                          | C38                  | 173<br>178 | 185<br>189 | 6.2<br>5.6    |                            |         |
|                                                             | J     | 7.73                          | C41                  | †<br>*     | 197<br>150 | 0.5<br>1.2    |                            |         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | K     | 7.67                          | C39                  | 172<br>*   | 175<br>175 | 2.0<br>1.1    |                            |         |
|                                                             | L1    | 7.72                          | C34                  | 168<br>171 | 181<br>184 | 6.6<br>4.3    |                            |         |
|                                                             |       |                               |                      |            |            |               |                            |         |
|                                                             |       |                               |                      |            |            |               |                            |         |
|                                                             |       |                               |                      |            |            |               |                            |         |

\* Yield strength data unobtainable, due to extensometer problems.

† Yield strength data not obtained because of material characteristics.

# GROUP A DATA

TYPE 4650. Note that the tempering temperature is a variable. Task C Data.

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Temper<br>°F | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi | TE<br>Percent | Charpy V-Notch<br>Impact Energy,<br>ft-lb |
|-------------------------------------------------------------|-------|-------------------------------|--------------|----------------------|------------|------------|---------------|-------------------------------------------|
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | J     | 7.42                          | 900          | C34                  | -<br>-     | 148<br>144 | 0.6<br>0.5    | 1.8 (duplicate<br>1.5 tests)              |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | J     | 7.42                          | 1100         | C29                  | -<br>146   | 149<br>148 | 0.5<br>1.2    | 1.5<br>1.7                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | J     | 7.55                          | 900          | C35                  | -<br>-     | 159<br>165 | 0.4<br>0.5    | 2.1<br>2.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | J     | 7.55                          | 1100         | C32                  | 152<br>153 | 156<br>158 | 1.3<br>1.2    | 2.8<br>2.8                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | J     | 7.64                          | 900          | C39                  | 180<br>177 | 187<br>163 | 1.4<br>1.1    | 2.1<br>2.8                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | J     | 7.64                          | 1100         | C32                  | 148<br>152 | 149<br>157 | 0.9<br>1.1    | 1.8<br>2.4                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | J     | 7.52                          | 900          | C34                  | 163<br>164 | 163<br>166 | 0.6<br>0.7    | 2.5<br>2.2                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | J     | 7.52                          | 1100         | C31                  | 146<br>142 | 149<br>143 | 1.4<br>0.7    | 2.3<br>3.2                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | J     | 7.63                          | 900          | C36                  | 170<br>170 | 174<br>175 | 1.0<br>1.1    | 2.8<br>2.4                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | J     | 7.63                          | 1100         | C32                  | 148<br>147 | 150<br>152 | 0.8<br>1.1    | 2.9<br>3.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | J     | 7.67                          | 900          | C36                  | 172<br>173 | 173<br>181 | 0.9<br>1.3    | 2.2<br>2.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | J     | 7.67                          | 1100         | C33                  | 152<br>151 | 158<br>158 | 1.1<br>2.2    | 2.7<br>3.5                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>3</sub> | J     | 7.53                          | 900          | C34                  | 174<br>166 | 178<br>170 | 1.0<br>0.9    | 1.7<br>2.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>3</sub> | J     | 7.53                          | 1100         | C32                  | 151<br>151 | 154<br>159 | 0.9<br>1.7    | 3.0<br>-                                  |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>3</sub> | J     | 7.65                          | 900          | C36                  | -<br>172   | 181<br>182 | -<br>1.2      | 3.0<br>2.0                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>3</sub> | J     | 7.65                          | 1100         | C31                  | 147<br>147 | 151<br>161 | 1.0<br>5.7    | 3.5<br>4.4                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | J     | 7.69                          | 900          | C36                  | 170<br>170 | 170<br>174 | 0.8<br>1.0    | 3.2<br>3.1                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | J     | 7.69                          | 1100         | C34                  | 149        | 158        | 3.4           | 6.0<br>3.7                                |

# GROUP A DATA

## TYPE 8620

Nominal Composition: 0.2 C, 0.8 Mn, 0.2 Mo,

Mesh: -100 0.7 Ni, 0.4 Cr, 0.3 Si

Mechanical Properties Determined on Samples  
with 15-mil Carburized Case.

Austenitized at 1575°F, Water Quench, Tempered at 450°F

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch,<br>ft-lb | Remarks                          |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|------------|--------------|---------------|-----------------------------|----------------------------------|
| P <sub>2</sub>                                              | H     | 6.59                          |                      |            |              |               |                             | Not machined                     |
| P <sub>2</sub> S <sub>2</sub>                               | H     | 6.67                          | B74                  |            | 57.5<br>55.6 | 0.3<br>0.3    |                             |                                  |
| P <sub>3</sub>                                              | H     | 6.86                          |                      |            |              |               |                             | Not machined                     |
| P <sub>3</sub> S <sub>2</sub>                               | H     | 6.92                          | C39<br>C29           | -<br>-     | 145<br>111   | 0.7<br>0.5    | 1.3<br>1.2                  | Tempered 450°F<br>Tempered 900°F |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | H     | 7.65                          | C53                  | 188<br>188 | 214<br>201   | 1.1<br>2.2    | 1.8                         |                                  |
| I                                                           | H     | 6.25                          |                      |            |              |               |                             | Not machined                     |
| IS <sub>1</sub>                                             | H     | 6.35                          |                      |            |              |               |                             | Not machined                     |
| IS <sub>1</sub> F <sub>3</sub> T <sub>3</sub>               | H     | 7.73                          | C54                  | 191<br>160 | 196<br>173   | 1.1<br>1.6    | 2.0                         |                                  |
| H <sub>2</sub> T <sub>3</sub>                               | H     | 7.75                          | C53                  | 183<br>170 | 194<br>183   | 0.8<br>1.8    | 1.7                         |                                  |
|                                                             |       |                               |                      |            |              |               |                             |                                  |
|                                                             |       |                               |                      |            |              |               |                             |                                  |
|                                                             |       |                               |                      |            |              |               |                             |                                  |
|                                                             |       |                               |                      |            |              |               |                             |                                  |
|                                                             |       |                               |                      |            |              |               |                             |                                  |

# GROUP A DATA

TYPE 8620. Note that tempering temperature is a variable. Task C Data

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Temper,<br>°F | Rockwell<br>Hardness | YS<br>ksi  | UTS<br>ksi | TE<br>Percent | Charpy V-Notch<br>Impact Energy,<br>ft-lb |
|-------------------------------------------------------------|-------|-------------------------------|---------------|----------------------|------------|------------|---------------|-------------------------------------------|
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | H     | 7.55                          | 900           | C39                  | 164<br>163 | 165<br>165 | 0.7<br>0.9    | 1.5 (duplicate<br>- tests)                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>1</sub> | H     | 7.55                          | 450           | C52                  | -<br>193   | 202<br>201 | -<br>0.9      | 1.7<br>1.9                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | H     | 7.60                          | 900           | C40                  | 167<br>160 | 170<br>165 | 0.9<br>1.1    | 1.6<br>1.6                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>1</sub> | H     | 7.60                          | 450           | C53                  | 201<br>196 | 208<br>211 | 0.9<br>1.0    | 1.8<br>1.8                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | H     | 7.67                          | 900           | C40                  | -<br>164   | 173<br>167 | -<br>0.9      | 1.7<br>1.6                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | H     | 7.67                          | 450           | C54                  | 208<br>198 | 216<br>198 | 1.1<br>0.9    | 1.9<br>1.7                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | H     | 7.58                          | 900           | C40                  | -<br>164   | 165<br>170 | 0.6<br>0.9    | 1.7<br>1.6                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>2</sub> | H     | 7.58                          | 450           | C53                  | 196<br>192 | 201<br>207 | 0.8<br>1.0    | 1.8<br>1.9                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | H     | 7.66                          | 900           | C41                  | 166<br>169 | 171<br>175 | 0.9<br>1.0    | 1.7<br>1.6                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>2</sub> | H     | 7.66                          | 450           | C53                  | 207<br>192 | 209<br>206 | 0.9<br>1.1    | 1.8<br>1.8                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | H     | 7.66                          | 900           | C43                  | 169<br>169 | 177<br>174 | 1.0<br>0.9    | 1.7<br>1.7                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>2</sub> | H     | 7.66                          | 450           | C55                  | 193<br>196 | 214<br>219 | 1.0<br>1.3    | 1.8<br>1.8                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>3</sub> | H     | 7.63                          | 900           | C41                  | -<br>166   | 168<br>172 | -<br>0.9      | 1.5<br>1.6                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>1</sub> T <sub>3</sub> | H     | 7.63                          | 450           | C56                  | 201<br>204 | 206<br>216 | 1.0<br>1.0    | 2.0<br>2.1                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>3</sub> | H     | 7.66                          | 900           | C42                  | 166<br>163 | 171<br>169 | 1.1<br>1.0    | 1.7<br>1.7                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>2</sub> T <sub>3</sub> | H     | 7.66                          | 450           | C53                  | 187<br>193 | 212<br>208 | 1.2<br>1.1    | 1.9<br>2.3                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | H     | 7.65                          | 900           | C40                  | 164<br>163 | 171<br>169 | 1.1<br>1.1    | 1.7<br>1.9                                |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | H     | 7.65                          | 450           | C54                  | 184        | 212        | 1.2           | 2.0<br>2.0                                |

# GROUP A DATA

## TYPE 8650

Nominal Composition: 0.5 C, 0.6 Ni, 0.1 Mn,  
Mesh: -100 0.5 Mo, 0.6 Cr

Austenitized at 1575°F, Water Quench, Temperature at 900°F

| Process                                       | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch<br>ft-lb | Remarks                   |
|-----------------------------------------------|-------|-------------------------------|----------------------|--------------|--------------|---------------|----------------------------|---------------------------|
| P <sub>1</sub>                                | M     | 6.31                          |                      |              |              |               |                            | No machining<br>attempted |
| P <sub>1</sub> S <sub>1</sub>                 | M     | 6.30                          | B13                  |              | 23.9         | 0.2           |                            | b (1)                     |
| P <sub>1</sub> S <sub>2</sub>                 | M     | 6.32                          | B72                  | 45.0         | 46.0<br>40.2 | 0.6<br>0.3    |                            |                           |
| P <sub>2</sub>                                | M     | 6.81                          |                      |              |              |               |                            | No machining<br>attempted |
| P <sub>2</sub> S <sub>1</sub>                 | M     | 6.77                          | B31                  |              | 13.5<br>19.7 | 0.2<br>0.3    |                            |                           |
| P <sub>2</sub> S <sub>2</sub>                 | M     | 6.81                          | B88                  | 80.5<br>71.0 | 81.0<br>75.8 | 0.4<br>1.4    | 1.2                        |                           |
| P <sub>3</sub>                                | M     | 7.01                          |                      |              |              |               |                            | No machining<br>attempted |
| P <sub>3</sub> S <sub>1</sub>                 | M     | 6.97                          | B95                  | 80.5         | 88.5         | 0.7           |                            | b (1)                     |
| P <sub>3</sub> S <sub>2</sub>                 | M     | 7.00                          | B89                  | 81.3         | 86.0         | 0.5           |                            | b (1)                     |
| P <sub>1</sub> S <sub>1</sub> RS <sub>2</sub> | M     | 6.93                          | B91                  | 80.5         | 89.9<br>89.3 | 1.1<br>1.2    |                            |                           |
| P <sub>1</sub> S <sub>2</sub> RS <sub>2</sub> | M     | 6.88                          | B92                  | 85.0<br>77.7 | 91.6<br>89.5 | 1.4<br>0.8    |                            |                           |
| P <sub>2</sub> S <sub>1</sub> RS <sub>2</sub> | M     | 7.09                          | B96                  | 100<br>98    | 106<br>108   | 0.5<br>2.6    |                            |                           |
| P <sub>2</sub> S <sub>2</sub> RS <sub>2</sub> | M     | 7.06                          | B91                  | 90.0<br>96.0 | 96.0<br>103  | 0.5<br>1.6    |                            |                           |
|                                               |       |                               |                      |              |              |               |                            |                           |

**GROUP A DATA**

**TYPE 8650**

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch<br>ft-lb | Remarks |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|--------------|--------------|---------------|----------------------------|---------|
| P <sub>3</sub> S <sub>1</sub> RS <sub>2</sub>               | M     | 7.20                          | B96                  | 95.3<br>92.0 | 104<br>111   | 0.7<br>1.6    |                            |         |
| P <sub>3</sub> S <sub>2</sub> RS <sub>2</sub>               | M     | 7.16                          | B98                  | 93.3<br>94.0 | 107<br>103   | 0.9<br>1.0    |                            |         |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | M     | 7.64                          | B86                  | 55.8<br>64.5 | 62.3<br>62.0 | 1.8<br>1.4    |                            |         |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | M     | 7.82                          | C37                  | 155<br>163   | 157<br>170   | 0.8<br>4.2    |                            |         |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | M     | 7.68                          | C34                  | 157<br>160   | 166<br>168   | 3.4<br>2.5    |                            |         |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | M     | 7.83                          | C32                  | 154<br>153   | 163<br>167   | 4.8<br>5.0    |                            |         |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | M     | 7.74                          | B89                  | 61.3<br>58.0 | 64.0<br>59.6 | 2.2<br>0.9    |                            |         |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | M     | 7.70                          | C36                  | 168<br>113   | 173<br>124   | 1.1<br>1.1    |                            |         |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | M     | 7.83                          | C34                  | 167<br>160   | 173<br>171   | 2.4<br>3.8    |                            |         |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | M     | 7.83                          | C35                  | 157<br>158   | 166<br>165   | 4.2<br>5.0    |                            |         |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | M     | 7.68                          | B89                  | 64.7<br>65.1 | 68.5<br>68.6 | 2.1<br>1.4    |                            |         |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | M     | 7.90                          | C35                  | 151<br>150   | 160<br>161   | 3.8<br>2.6    |                            |         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | M     | 7.80                          | C32                  | 149<br>147   | 158<br>159   | 2.8<br>3.9    |                            |         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | M     | 7.81                          | C33                  | 145<br>123   | 155<br>156   | 3.7<br>5.0    |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |

# GROUP A DATA

## TYPE 9450

Nominal Composition: 0.5 C, 0.3 Ni, 0.2 Mn,  
Mesh: -100 0.3 Mo, 0.3 Cr

Austenitized at 1575°F, Water Quench, Tempered at 900°F

| Process                                       | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch<br>ft-lb | Remarks                   |
|-----------------------------------------------|-------|-------------------------------|----------------------|--------------|--------------|---------------|----------------------------|---------------------------|
| P <sub>1</sub>                                | N     | 6.33                          |                      |              |              |               |                            | No machining<br>attempted |
| P <sub>1</sub> S <sub>1</sub>                 | N     | 6.35                          | B5                   | 17.8<br>17.6 | 22.4<br>20.2 | 1.5<br>1.1    |                            |                           |
| P <sub>1</sub> S <sub>2</sub>                 | N     | 6.30                          | B70                  | 43.7<br>44.5 | 46.8<br>47.0 | 0.6<br>1.0    |                            |                           |
| P <sub>2</sub>                                | N     | 6.86                          |                      |              |              |               |                            | No machining<br>attempted |
| P <sub>2</sub> S <sub>1</sub>                 | N     | 6.86                          | B26                  | 54.5<br>23.1 | 75.8<br>29.4 | 3.8<br>2.6    |                            |                           |
| P <sub>2</sub> S <sub>2</sub>                 | N     | 6.85                          | B80                  | 61.1<br>59.0 | 66.0<br>65.4 | 0.6<br>1.0    | 1.5                        |                           |
| P <sub>3</sub>                                | N     | 7.05                          |                      |              |              |               |                            | No machining<br>attempted |
| P <sub>3</sub> S <sub>1</sub>                 | N     | 7.03                          | B40                  | 24.5<br>25.9 | 32.5<br>33.3 | 2.2<br>2.4    |                            |                           |
| P <sub>3</sub> S <sub>2</sub>                 | N     | 7.01                          | B83                  | 71.5<br>73.0 | 78.0<br>78.1 | 0.8<br>0.8    |                            |                           |
| P <sub>1</sub> S <sub>1</sub> RS <sub>2</sub> | N     | 7.01                          | B93                  | 83.0<br>75.0 | 93.5<br>93.0 | 0.8<br>2.0    |                            |                           |
| P <sub>1</sub> S <sub>2</sub> RS <sub>2</sub> | N     | 6.87                          | B78                  | 67.3<br>66.0 | 77.0<br>74.4 | 0.9<br>1.6    |                            |                           |
| P <sub>2</sub> S <sub>1</sub> RS <sub>2</sub> | N     | 7.18                          | B96                  | 88.5<br>83.5 | 103<br>93.3  | 1.4<br>1.6    |                            |                           |
| P <sub>2</sub> S <sub>2</sub> RS <sub>2</sub> | N     | 7.05                          | B91                  | 74.5         | 86.0<br>87.2 | 0.2<br>1.6    |                            |                           |
|                                               |       |                               |                      |              |              |               |                            |                           |

GROUP A DATA

TYPE 9450

| Process                                                     | Mat'l | Density<br>gm/cm <sup>3</sup> | Rockwell<br>Hardness | YS<br>ksi    | UTS<br>ksi   | TE<br>percent | Charpy<br>V-Notch<br>ft-lb | Remarks |
|-------------------------------------------------------------|-------|-------------------------------|----------------------|--------------|--------------|---------------|----------------------------|---------|
| P <sub>3</sub> S <sub>1</sub> RS <sub>2</sub>               | N     | 7.23                          | B91                  | 84.0<br>88.8 | 109<br>102   | 1.7<br>1.3    |                            |         |
| P <sub>3</sub> S <sub>2</sub> RS <sub>2</sub>               | N     | 7.17                          | B96                  | 75.0<br>84.5 | 94.9<br>95.5 | 2.2<br>0.9    |                            |         |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | N     | 7.64                          | B88                  | 65.6<br>67.9 | 80.6<br>82.0 | 7.4<br>7.5    |                            |         |
| P <sub>1</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | N     | 7.72                          | C30                  | 122<br>113   | 145<br>133   | 6.5<br>7.6    |                            |         |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | N     | 7.63                          | C31                  | 159<br>140   | 172<br>158   | 4.2<br>5.0    |                            |         |
| P <sub>1</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | N     | 7.72                          | C32                  | 153<br>138   | 166<br>153   | 5.7<br>6.2    |                            |         |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | N     | 7.70                          | B85                  | 65.8<br>70.5 | 76.5<br>84.8 | 7.0<br>7.8    |                            |         |
| P <sub>2</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | N     | 7.71                          | C30                  | 109<br>109   | 130<br>127   | 7.3<br>7.5    |                            |         |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | N     | 7.77                          | C30                  | 112<br>112   | 128<br>133   | 3.5<br>7.6    |                            |         |
| P <sub>2</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | N     | 7.83                          | C30                  | 131<br>130   | 145<br>146   | 6.1<br>6.4    |                            |         |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>1</sub> | N     | 7.70                          | B87                  | 68.0<br>74.0 | 80.3<br>87.3 | 7.4<br>8.0    |                            |         |
| P <sub>3</sub> S <sub>1</sub> F <sub>3</sub> T <sub>3</sub> | N     | 7.75                          | C30                  | 113<br>112   | 134<br>132   | 6.3<br>7.0    |                            |         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>1</sub> | N     | 7.80                          | C30                  | 124<br>105   | 142<br>137   | 5.5<br>4.3    |                            |         |
| P <sub>3</sub> S <sub>2</sub> F <sub>3</sub> T <sub>3</sub> | N     | 7.86                          | C30                  | 120<br>122   | 135<br>138   | 7.9<br>7.8    |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |
|                                                             |       |                               |                      |              |              |               |                            |         |

## 2. Data Group B

Reference: 10

### Materials

Steel: Type 4600, A. O. Smith-Inland EMP

See Table 1-A for powder composition and characteristics.

Carbon: Graphite, Southwestern No. 1651.

### Processing Summary

Preform Preparation: Preforms were made from steel admixed with 0.45 C plus 0.75% zinc stearate.

Three powder sizes were used: as-received (-28 +200) and fine (-200).

Preform sintering was done at 2100°F for 40 min in endogas at 40°F dewpoint.

Forging: Forging was limited-deformation type, with approximately 30% lateral flow (0.320 in. to 0.418 in.).

Preheat: Approximately five minutes in dissociated ammonia.

Ram speed: 2.6 ips.

No atmospheric protection was provided during transfer, forging, or cooling.

Heat treatment: Austenitizing was done at 1525°F for 45 min, followed by oil quenching. To complete the martensite transformation, forgings were held at -120°F for 12 hr. They were then stress relieved at 300°F for 30 min, and tempered at 1100°F.

### Group B Data

The tensile properties of the P/M steel forgings are presented in Table 2-A.

**TABLE 1-A**

**Properties of As-Received EMP 4600 Steel Powder<sup>a</sup>**

**Chemical Analysis, w/o**

|               |       |
|---------------|-------|
| Nickel        | 2.03  |
| Molybdenum    | 0.55  |
| Carbon        | 0.01  |
| Manganese     | 0.04  |
| Phosphorus    | 0.005 |
| Sulfur        | 0.009 |
| Silicon       | 0.010 |
| Oxygen        | 0.12  |
| Hydrogen Loss | 0.15  |

**Physical Properties**

|                             |          |      |
|-----------------------------|----------|------|
| Apparent Density,           | g/cc     | 2.92 |
| Flow,                       | sec/50 g | 25.4 |
| Green Density <sup>b</sup>  | g/cc     | 6.50 |
| Green Strength <sup>b</sup> | psi      | 1370 |

**Tyler Sieve Analysis, w/o**

|                |       |
|----------------|-------|
| - 28 + 35 mesh | trace |
| - 35 + 48      | 1.5   |
| - 48 + 60      | 6.2   |
| - 80 + 100     | 6.5   |
| -100 + 150     | 14.5  |
| -150 + 200     | 21.5  |
| -200 + 250     | 5.0   |
| -250 + 325     | 19.5  |
| -325           | 23.0  |

a - Lot No. 124. Values furnished by supplier.

b - At 30 tsi with 0.75% zinc stearate.

NOTE: Supplied at -28 mesh by request. This type is normally supplied at -80 mesh.

**TABLE 2-A**  
**Tensile Properties of P/M Steel Forgings**

| Experimental Variables |         |       |            | Properties of Forging |           |                       |                      |           |           |         |
|------------------------|---------|-------|------------|-----------------------|-----------|-----------------------|----------------------|-----------|-----------|---------|
| Powder Size            | Preform |       | Preheat, F | Density, %            | Carbon, % | Hard., R <sub>C</sub> | Tensile <sup>b</sup> |           |           |         |
|                        | Den., % | Cond. |            |                       |           |                       | T.S., ksi            | Y.S., ksi | Elong., % |         |
|                        |         |       |            |                       |           |                       |                      |           |           | R.A., % |

|          |    |       |      |      |      |       |       |       |    |    |
|----------|----|-------|------|------|------|-------|-------|-------|----|----|
| As-Rec'd | 75 | Sint. | 1750 | 98.5 | 0.48 | 34-33 | 156.5 | 145.3 | 14 | 43 |
| Coarse   | 81 |       |      | 98.9 | 0.46 | 34-33 | 152.2 | 140.0 | 13 | 42 |
| Fine     | 81 |       |      | 98.6 | 0.51 | 35-35 | 153.4 | 142.0 | 14 | 43 |

a - Portion tested was probably >99%.

b - Round specimen with 0.18 in. gage diameter; elongation in 0.9 in; 0.1 in./min crosshead speed; 0.2%-offset Y.S.

### 3. Data Group C

Reference: 17

#### Materials

Steel - 4600, prealloyed, A. O. Smith-Inland

Iron - EMP 300, A. O. Smith-Inland

Molybdenum - Fansteel P/M, 200 mesh

Nickel - International Nickel, Type 123

Carbon - Southwestern Graphite, No. 1651

Compositions of the steels investigated are given in Table 3-A.

TABLE 3-A  
Composition of Steels Used in Study

| <u>Steel Type</u>         |             | <u>Alloy Element, wt%</u> |           |           |           |           |
|---------------------------|-------------|---------------------------|-----------|-----------|-----------|-----------|
|                           |             | <u>C</u>                  | <u>Mn</u> | <u>Si</u> | <u>Ni</u> | <u>Mo</u> |
| Wrought Control Materials | 4620        |                           |           |           |           |           |
|                           | 4640        |                           |           |           |           |           |
| Prealloy                  | 4600 + 0.2C | Added                     | 0.20      | --        | 2.00      | 0.50      |
|                           | 4600 + 0.3C |                           |           |           |           |           |
|                           | 4600 + 0.4C |                           |           |           |           |           |
| Elemental                 | 4640        | Added                     | --        | --        | 1.85      | 0.50      |

#### Processing Summary

Preform Preparation: The preform compacts made from the various blends had green densities in the range 6.5 to 6.7 gm/cm<sup>3</sup>. Each preform was simultaneously sintered and preheated for forging in one of two ways, viz., by furnace heating in hydrogen for 15 min at 2000°F, or by induction heating, in air, to 2000°F. The hot samples were then immediately forged.

Forging Procedure: Not described in detail. Forgings had density of >98% of theoretical.

Heat Treatment: All material, wrought and otherwise, was normalized at 1650°F prior to further heat treatment. Material tested in both normalized condition, as well as austenitized, quenched, and tempered. Heat treatment was done by a commercial heat-treating concern.

Group C Data

Mechanical properties resulting from furnace heating and induction heating of 4620 and 4630 preforms are given in Table 4-A. The comparison between furnace heating and induction heating of elemental and prealloyed 4640 is presented in Tables 5-A and 6-A, respectively.

TABLE 4-A  
Furnace Heating versus Induction Heating  
of Prealloyed 4620 and 4630

|                                    |           | <u>4620</u> | <u>4630</u> |
|------------------------------------|-----------|-------------|-------------|
| Hardness (Rockwell)                | Wrought   | B-91        | -           |
|                                    | Furnace   | B-90        | B-92        |
|                                    | Induction | B-89        | B-92        |
| Ultimate Tensile<br>psi            | Wrought   | 92,500      | -           |
|                                    | Furnace   | 89,300      | 95,300      |
|                                    | Induction | 88,400      | 96,300      |
| Yield Strength<br>psi, 0.2% Offset | Wrought   | 72,100      | -           |
|                                    | Furnace   | 68,600      | 72,300      |
|                                    | Induction | 70,500      | 80,100      |
| Elongation<br>% in 1 in.           | Wrought   | 21.4        | -           |
|                                    | Furnace   | 19.3        | 18.1        |
|                                    | Induction | 15.6        | 14.5        |
| Charpy Impact<br>ft-lb             | Wrought   | 122.0       | -           |
|                                    | Furnace   | 65.0        | 42.0        |
|                                    | Induction | 32.0        | 28.0        |

**TABLE 5-A**  
**Furnace Heating versus Induction Heating**  
**of Elemental 4640**

|                                    |           | Normalized | Temper  |         |
|------------------------------------|-----------|------------|---------|---------|
|                                    |           |            | 400°F   | 800°F   |
| Hardness (Rockwell)                | Wrought   | B-86       | C-45    | C-36    |
|                                    | Furnace   | B-69       | C-43    | C-27    |
|                                    | Induction | B-54       | C-25    | B-88    |
| Ultimate Strength<br>psi           | Wrought   | 115,400    | 274,000 | 182,200 |
|                                    | Furnace   | 82,800     | 257,000 | 143,800 |
|                                    | Induction | 75,500     | 180,300 | 113,400 |
| Yield Strength<br>psi, 0.2% Offset | Wrought   | 73,500     | 206,600 | 173,200 |
|                                    | Furnace   | 37,400     | 185,600 | 120,700 |
|                                    | Induction | 36,400     | 115,900 | 80,200  |
| Elongation<br>% in 1 in.           | Wrought   | 17.1       | 11.0    | 12.0    |
|                                    | Furnace   | 20.0       | 4.6     | 8.1     |
|                                    | Induction | 24.0       | 3.5     | 9.2     |
| Charpy Impact<br>ft-lb             | Wrought   | 39.0       | 25.0    | 39.0    |
|                                    | Furnace   | 11.0       | 9.0     | 7.0     |
|                                    | Induction | 10.0       | 9.0     | 9.0     |

**TABLE 6-A**  
**Furnace Heating versus Induction Heating**  
**of Prealloyed 4640**

|                                    |           | Normalized | Temper  |         |
|------------------------------------|-----------|------------|---------|---------|
|                                    |           |            | 400°F   | 800°F   |
| Hardness (Rockwell)                | Wrought   | B-86       | C-45    | C-36    |
|                                    | Furnace   | B-86       | C-43    | C-35    |
|                                    | Induction | B-86       | C-47    | C-35    |
| Ultimate Tensile<br>psi            | Wrought   | 115,400    | 274,000 | 182,200 |
|                                    | Furnace   | 100,300    | 276,100 | 185,400 |
|                                    | Induction | 110,200    | 295,300 | 198,500 |
| Yield Strength<br>psi, 0.2% Offset | Wrought   | 73,500     | 206,600 | 173,200 |
|                                    | Furnace   | 68,000     | 203,500 | 167,700 |
|                                    | Induction | 82,400     | 210,000 | 185,000 |
| Elongation<br>% in 1 in.           | Wrought   | 17.1       | 11.0    | 12.0    |
|                                    | Furnace   | 14.3       | 6.1     | 6.8     |
|                                    | Induction | 12.4       | 3.2     | 4.2     |
| Charpy Impact<br>ft-lb             | Wrought   | 39.0       | 25.0    | 39.0    |
|                                    | Furnace   | 19.0       | 9.0     | 9.5     |
|                                    | Induction | 8.0        | 8.5     | 5.0     |

#### 4. Data Group D

Reference: 14

##### Materials

A. O. Smith Inland materials:  
1040 carbon steel, resulfurized;  
8600, 9400, and 4600 with graphite additions.

##### Processing Summary

Two processes were employed to yield mechanical property data:  
high-energy-rate-forming (Dynapak) and forging.

##### High-Energy-Rate-Forming

Blanks 1 1/2 in. thick were forged at 1700°F in one blow to 1 in. thick sections by Dynapak. The resulting densities were 98 - 99%. The samples were oil quenched from 1650°F and tempered. The pre-form density was 6.7 gm/cm<sup>3</sup>.

##### Forging

In order to determine the optimum properties of alloyed steel powder, slugs of -80 mesh alloy powder mixed with 0.5 wt % graphite were prepared without admixed lubricant.

The slugs were pressed to a density of 7.05 - 7.40 gm/cm<sup>3</sup>, double sintered in cracked ammonia at 2050°F, and encapsulated in 2 in. diameter steel tubing. The resulting encapsulated preforms were then either hot forged into 1 in. x 10 in. bars, with an approximate hot reduction of 5:1, or upset forged into 5/8 in. thick discs with an approximate hot reduction of 3.2:1. The final composition of the forgings is given in Table 7-A.

**TABLE 7-A**  
**Compositions of Final Forgings**

|         | <u>C</u> | <u>Mn</u> | <u>Si</u> | <u>Cr</u> | <u>Ni</u> | <u>Mo</u> | <u>O<sub>2</sub></u> | <u>N<sub>2</sub></u> | <u>H<sub>2</sub></u> |
|---------|----------|-----------|-----------|-----------|-----------|-----------|----------------------|----------------------|----------------------|
| Blend A | 0.37     | 0.17      | 0.020     | 0.080     | 1.73      | 0.44      | 0.030                | 0.003                | 0.0001               |
| Blend B | 0.41     | 0.29      | 0.13      | 0.58      | 0.63      | 0.40      | 0.185                | 0.001                | 0.0007               |

The mechanical properties of samples cut from P/M crankshaft forgings are also presented.

**Group D Data**

The mechanical properties of the P/M products resulting from the study are presented in Tables 8-A through 11-A.

**TABLE 8-A**  
**Tensile Properties**  
**of High-Energy-Rate-Formed Material**

| <u>Type</u> | <u>Tempering<br/>Temp.<br/>°F</u> | <u>Yield<br/>Strength<br/>psi</u> | <u>Ultimate<br/>Strength<br/>psi</u> | <u>Elongation<br/>%</u> | <u>Reduction<br/>of Area<br/>%</u> |
|-------------|-----------------------------------|-----------------------------------|--------------------------------------|-------------------------|------------------------------------|
| 1040        | 400                               | 68,000                            | 90,000                               | 27.5                    | 18.3                               |
| 4640        | 700                               | 185,000                           | 203,000                              | 7.0                     | 7.7                                |
| 4640        | 1000                              | 155,000                           | 167,000                              | 9.0                     | 18.1                               |
| 8650        | 700                               | 96,000                            | 122,000                              | 5.0                     | 3.9                                |
| 9440        | 700                               | 79,000                            | 108,000                              | 14.0                    | 25.8                               |

**TABLE 9-A**  
**Tensile Properties**  
**of "Optimized Properties" Forgings**

| Type            | Forged Density % | Forging Temp. °F | Forging Ratio | Yield Strength 0.2% Offset ksi | Ultimate Yield Strength ksi | Elongation % | Reduction of Area % |
|-----------------|------------------|------------------|---------------|--------------------------------|-----------------------------|--------------|---------------------|
| Blend A<br>4640 | 99.63            | 1700             | 5:1           | 138.9                          | 148.8                       | 16.4         | 46.5                |
|                 | 99.63            | 1950             | 5:1           | 145.3                          | 157.2                       | 16.5         | 45.9                |
|                 | *99.76           | 1950             | 5:1           | 151.5                          | 163.9                       | 12.0         | 33.0                |
|                 | 99.89            | 2100             | 5:1           | 144.7                          | 155.7                       | 16.7         | 48.8                |
|                 | 99.11            | 1700             | 3.2:1         | 143.8                          | 157.0                       | 13.6         | 46.0                |
|                 | 99.24            | 2100             | 3.2:1         | 142.4                          | 157.5                       | 13.9         | 46.0                |
| Blend B<br>8640 | 98.60            | 1700             | 5:1           | 144.8                          | 151.0                       | 7.0          | 11.8                |
|                 | 98.73            | 1950             | 5:1           | 155.4                          | 164.1                       | 9.0          | 22.6                |
|                 | *98.73           | 1950             | 5:1           | 146.6                          | 155.0                       | 5.6          | 7.4                 |
|                 | 98.98            | 2100             | 5:1           | 152.0                          | 155.5                       | 11.3         | 26.5                |
|                 | 98.22            | 1700             | 3.2:1         | 153.7                          | 161.2                       | 10.3         | 28.0                |
|                 | 98.60            | 2100             | 3.2:1         | 144.0                          | 160.6                       | 9.7          | 20.5                |

\* Homogenized, 2300°F - 3 hr prior to heat treatment.

Test specimens cut from encapsulated hammer forged bars. 5:1 ratio are 0.505 in. diameter tensile bars, 1650°F water quenched + 1050°F.  
3.2:1 ratio are 0.180 in. diameter Hounsfield bars, 1650°F oil quenched + 1000°F.

**TABLE 10-A**

**Impact Data from 4640 Forging  
Hot Reduced 3.2:1 at 1950°F**

Density 7.84 g/cc (99.76%)

Heat Treated            1650°F water quench  
                             1100°F temper  
                             30 Rockwell C

Chemical Analysis: Percent by weight

| <u>C</u> | <u>Mn</u> | <u>Si</u> | <u>Ni</u> | <u>Mo</u> | <u>Cr</u> | <u>O<sub>2</sub></u> |
|----------|-----------|-----------|-----------|-----------|-----------|----------------------|
| 0.36     | 0.17      | 0.02      | 1.82      | 0.47      | 0.08      | 0.030                |

Half-standard Charpy notched bars tested at room temperature.

|                         | <u>U Notch</u> | <u>Vee Notch</u> |
|-------------------------|----------------|------------------|
| Energy ft-lb            | 20.8           | 11.4             |
| Contraction Under Notch | 11.2%          | 7.6%             |
| Fracture Appearance     | 100% Shear     | 100% Shear       |

**TABLE 11-A**

**Longitudinal Tensile Properties of Crankshaft Core**

| <u>Type</u> | <u>Forged<br/>Density<br/>g/cc</u> | <u>Tempering<br/>Temp.<br/>°F</u> | <u>Tempered<br/>Hardness<br/>R - C</u> | <u>Yield<br/>Strength<br/>ksi</u> | <u>Tensile<br/>Strength<br/>ksi</u> | <u>Elonga-<br/>tion %<br/>in 1 in.</u> | <u>Reduction<br/>of Area<br/>%</u> |
|-------------|------------------------------------|-----------------------------------|----------------------------------------|-----------------------------------|-------------------------------------|----------------------------------------|------------------------------------|
| 4645        | 7.86                               | 700                               | 44/46                                  | 187.4                             | 204.9                               | 9                                      | 42.5                               |
| 8650        | 7.81                               | 700                               | 45/47                                  | 203.6                             | 231.4                               | 5                                      | 5.0                                |
| *1150       | 7.83                               | 400                               | 20/24                                  | 72.3                              | 100.1                               | 16                                     | 47.0                               |

\* 0.2% Sulfur

Test specimens cut from forged crankshaft. Forged in conventional closed die from 1 7/8 in. diameter preforms. Forging temperature 1600°F. Oil quenched from 1650°F and tempered.

## 5. Data Group E.

References: 1 and 8

### Materials

Steels: "Commercially available" types 1050, 4630, modified 4630 (low nickel), and 8630 steel powders.

### Processing Summary

The powder was admixed with the appropriate amount of graphite, a lubricant added, and briquettes pressed to 80% of theoretical density. The briquettes were then sintered at 2050°F for 20 minutes. After sintering, the bars were heated to 1800°F under a controlled atmosphere. The bars were then transferred in air into a rectangular die cavity where they were hot densified (hot repressed) to 98% of theoretical density. The samples were then annealed, machined, heat treated, and tested.

### Group E Data

The tensile and impact properties of the four P/M steel products studied are presented in Tables 12-A and 13-A, respectively.

### Additional Comments

Standard R. R. Moore fatigue tests showed the modified 4630 alloy to have the highest endurance limit of the four steels chosen for study, viz., 60,000 psi.

**TABLE 12-A**  
**Tensile Properties of Hot Densified Powder Metal Alloys**

| <u>Material</u>    | <u>Yield Stress<br/>0.2% Offset<br/>psi</u> | <u>Ultimate<br/>Strength<br/>psi</u> | <u>Elongation<br/>% in 1 in.<br/>gage length</u> | <u>Reduction<br/>of Area<br/>%</u> | <u>Modulus of<br/>Elasticity<br/>×10<sup>6</sup></u> | <u>Hard-<br/>ness<br/>R<sub>c</sub></u> |
|--------------------|---------------------------------------------|--------------------------------------|--------------------------------------------------|------------------------------------|------------------------------------------------------|-----------------------------------------|
| <b>400°F Draw</b>  |                                             |                                      |                                                  |                                    |                                                      |                                         |
| 1050               | 83,000                                      | 100,000                              | 11.3                                             | 17.8                               | 32.0                                                 | 28                                      |
| Mod 4630           | 193,000                                     | 215,000                              | 6.5                                              | 10.5                               | 28.0                                                 | 42                                      |
| 4630               | 178,000                                     | 214,000                              | 6.5                                              | 22.0                               | 25.5                                                 | 42                                      |
| 8630               | 174,000                                     | 233,000                              | 7.0                                              | 18.0                               | 26.0                                                 | 42                                      |
| <b>800°F Draw</b>  |                                             |                                      |                                                  |                                    |                                                      |                                         |
| Mod 4630           | 163,000                                     | 173,000                              | 9.0                                              | 22.0                               | 29.5                                                 | 34                                      |
| 4630               | 146,000                                     | 171,000                              | 10.5                                             | 22.0                               | 25.5                                                 | 35                                      |
| 8630               | 151,000                                     | 174,000                              | 11.0                                             | 24.0                               | 26.5                                                 | 35                                      |
| <b>1000°F Draw</b> |                                             |                                      |                                                  |                                    |                                                      |                                         |
| Mod 4630           | 157,000                                     | 167,000                              | 11.0                                             | 23.0                               | 27.7                                                 | 30                                      |
| 4630               | 148,000                                     | 167,000                              | 14.0                                             | 22.5                               | 28.0                                                 | 32                                      |
| 8630               | 143,000                                     | 166,000                              | 12.5                                             | 30.0                               | 27.5                                                 | 34                                      |

**TABLE 13-A**  
**Room Temperature Impact Strength**

| <u>Alloy</u> | <u>V-Notched Charpy<br/>ft-lb</u> | <u>Unnotched Charpy<br/>ft-lb</u> | <u>Hardness R<sub>c</sub></u> |
|--------------|-----------------------------------|-----------------------------------|-------------------------------|
| 1050         | 6.5                               | -                                 | 28                            |
| Mod 4630     | 6.0                               | -                                 | 42                            |
| 4630         | 6.5                               | 80.0                              | 42                            |
|              | 9.0                               | -                                 | 39                            |
|              | 11.0                              | -                                 | 32                            |
| 8630         | 8.5                               | 68.0                              | 42                            |
|              | 10.5                              | -                                 | 37                            |
|              | 17.5                              | -                                 | 30                            |
| 8615         | 70.0                              | -                                 | 18                            |

## 6. Data Group F

Reference: 11

### Materials

Steel of a nominal 4640 composition was studied.

Description of the prealloyed 4600 and elemental powders is given in Table 14-A.

### Processing Summary

Atomized and mixed elemental powders, prepared to a nominal 4640 steel composition (2.0 Ni, 0.25 Mo - 0.40 C - balance iron) were pressed and sintered to comparable density levels in the range 6.45 to 7.25 gm/cm<sup>3</sup>. Sintering was carried out at either 2050°F for 30 minutes or 2400°F for 60 min, in dissociated ammonia. The specimens were subsequently heat treated and tested.

### Group F Data

The mechanical properties of sintered atomized and sintered elemental 4640 powder compacts is given in Table 15-A. The heat-treated properties of the atomized and mixed elemental 4640 powders sintered at 2050°F and 2400°F are given in Tables 16-A and 17-A, respectively.

**TABLE 14-A**  
**Raw Powders Used**

| Alloy or Element               | 4600     | Iron     | Nickel   | Molybdenum   | Graphite |
|--------------------------------|----------|----------|----------|--------------|----------|
| Type                           | Atomized | Atomized | Carbonyl | Electrolytic | Natural  |
| Apparent Density,<br>g/cc      | 3.28     | 2.95     | 2.17     | 1.50         | -        |
| Flow, sec.                     | 22.2     | 25.0     | No Flow  | No Flow      | No Flow  |
| Avg. Particle Size,<br>Microns | -        | -        | 5.1      | 3.90         | 0.7      |
| Screen Analysis, %             |          |          |          |              |          |
| - 80 + 100                     | 0.1      | 3.0      | -        | -            | -        |
| -100 + 150                     | 15.6     | 14.0     | 0.1      | -            | -        |
| -150 + 200                     | 25.5     | 22.0     | 2.3      | -            | -        |
| -200 + 250                     | 9.4      | 10.0     | 1.5      | -            | -        |
| -250 + 325                     | 14.9     | 21.0     | 5.0      | -            | -        |
| -325                           | 34.5     | 30.0     | 91.1     | 100.0        | 100.0    |
| Chemical Analysis, %           |          |          |          |              |          |
| Fe                             | Bal      | 99.5     | 0.003    | 0.01         | -        |
| Ni                             | 1.90     | 0.03     | 99.6     | 0.005        | -        |
| Mo                             | 0.25     | -        | -        | 99.8         | -        |
| Carbon                         | 0.15*    | 0.01     | 0.10     | 0.01         | Bal      |
| Oxygen                         | 0.20     | 0.08     | 0.125    | 0.150        | -        |

\* Additional graphite added to get 4640 composition.

**TABLE 15-A**  
**Mechanical Properties of Sintered Atomized and Mixed Elemental 4640 Powder**

| Powder Origin                                     | Compacting Pressure<br>tsi | Sintered Density<br>g/cc | Ultimate Tensile Strength<br>ksi | Yield Strength<br>0.2% Offset<br>ksi | Tensile Elongation<br>% | Transverse Rupture Strength<br>ksi | Hardness<br>R <sub>h</sub> | Combined Carbon Content<br>% |
|---------------------------------------------------|----------------------------|--------------------------|----------------------------------|--------------------------------------|-------------------------|------------------------------------|----------------------------|------------------------------|
| <u>Sintered 2050°F 30 min/Dissociated Ammonia</u> |                            |                          |                                  |                                      |                         |                                    |                            |                              |
| Atomized                                          | 26.6                       | 6.51                     |                                  | A                                    |                         | 77.8                               | 50.6                       | 0.35                         |
|                                                   | 40.7                       | 6.91                     | 62.6                             | 45.5                                 | 2.0                     | 110.9                              | 66.3                       | 0.34                         |
|                                                   | 60.0                       | 7.21                     |                                  | B                                    |                         | 138.0                              | 77.4                       | 0.35                         |
| Mixed Elemental                                   | 20.0                       | 6.48                     | 33.1                             | 19.7                                 | 4.0                     | 67.6                               | 32.1                       | 0.34                         |
|                                                   | 30.0                       | 6.87                     | 52.4                             | 31.3                                 | 6.0                     | 95.0                               | 46.5                       | 0.34                         |
|                                                   | 42.5                       | 7.15                     | 58.8                             | 33.2                                 | 7.0                     | 122.7                              | 60.4                       | 0.35                         |
| <u>Sintered 2400°F/60 min/Dissociated Ammonia</u> |                            |                          |                                  |                                      |                         |                                    |                            |                              |
| Atomized                                          | 26.6                       | 6.59                     |                                  | A                                    |                         | 96.7                               | 55.2                       | 0.34                         |
|                                                   | 40.7                       | 6.97                     | 64.8                             | 54.1                                 | 2.0                     | 132.3                              | 70.1                       | 0.34                         |
|                                                   | 60.0                       | 7.28                     |                                  | B                                    |                         | 165.9                              | 78.3                       | 0.35                         |
| Mixed Elemental                                   | 20.0                       | 6.58                     | 44.7                             | 31.0                                 | 6.0                     | 91.8                               | 44.6                       | 0.34                         |
|                                                   | 30.0                       | 6.98                     | 54.5                             | 40.4                                 | 6.0                     | 119.6                              | 21.8                       | 0.32                         |
|                                                   | 42.5                       | 7.22                     | 70.8                             | 44.5                                 | 7.0                     | 149.9                              | 72.5                       | 0.38                         |

A - Grain strength of these atomized bars too low to permit adequate handling and sintering.

B - Excessive lamination occurred in the atomized bars at this compacting pressure.

**TABLE 16-A**  
**Heat-Treated Properties**  
**of Atomized and Mixed Elemental**  
**4640 Steel Powders**

Sintered: 2050°F/30 min/Dissociated Ammonia  
Heat Treated: 1550°F/1 hr/Oil Quenched  
+ Tempered 1 hr/Air Cooled

**Atomized Powder**

|                                   |      |       |       |
|-----------------------------------|------|-------|-------|
| Density, g/cc                     | 6.50 | 6.91  | 7.20  |
| Tempering Temperature, °F         | 600  | 600   | 500   |
| Ultimate Tensile Strength, ksi    | A    | 64.1  | C     |
| Yield Strength (0.2% Offset), ksi | A    | B     | C     |
| Tensile Elongation, %             | A    | Nil   | C     |
| Transverse Rupture Strength, ksi  | 85.7 | 127.5 | 180.0 |
| Hardness, R <sub>B</sub>          | 88.3 | 98.3  | 106.7 |
| Combined Carbon Content, %        | 0.38 | 0.37  | 0.40  |

**Mixed Elemental Powder**

|                                   |       |       |       |
|-----------------------------------|-------|-------|-------|
| Density, g/cc                     | 6.48  | 6.87  | 7.15  |
| Tempering Temperature, °F         | 600   | 600   | 500   |
| Ultimate Tensile Strength, ksi    | 73.4  | 101.1 | 143.6 |
| Yield Strength (0.2% Offset), ksi | 67.6  | 88.1  | 119.5 |
| Tensile Elongation, %             | 1.0   | 1.5   | 1.0   |
| Transverse Rupture Strength, ksi  | 124.1 | 176.4 | 239.5 |
| Hardness, R <sub>B</sub>          | 80.2  | 91.7  | 101.2 |
| Combined Carbon Content, %        | 0.38  | 0.37  | 0.40  |

A - Green strength of these atomized bars too low to permit adequate handling and sintering.

B - Bars broke before 0.2% offset.

C - Excessive lamination occurred in atomized bars.

**TABLE 17-A**  
**Heat-Treated Properties**  
**of Atomized and Mixed Elemental**  
**4640 Steel Powders**

Sintered: 2400°F/60 min/Dissociated Ammonia  
Heat Treated: 1550°F/1 hr/Oil Quenched  
+ Tempered 1 hr/Air Cooled

**Atomized Powder**

|                                   |       |       |       |
|-----------------------------------|-------|-------|-------|
| Density, g/cc                     | 6.59  | 6.97  | 7.27  |
| Tempering Temperature, °F         | 600   | 600   | 400   |
| Ultimate Tensile Strength, ksi    | A     | 92.0  | C     |
| Yield Strength (0.2% Offset), ksi | A     | B     | C     |
| Tensile Elongation, %             | A     | N11   | C     |
| Transverse Rupture Strength, ksi  | 107.2 | 153.9 | 219.3 |
| Hardness, R <sub>B</sub>          | 91.7  | 99.7  | 109.0 |
| Combined Carbon Content, %        | 0.38  | 0.39  | 0.38  |

**Mixed Elemental Powder**

|                                   |       |       |       |
|-----------------------------------|-------|-------|-------|
| Density, g/cc                     | 6.59  | 6.95  | 7.23  |
| Tempering Temperature, °F         | 600   | 500   | 400   |
| Ultimate Tensile Strength, ksi    | 96.1  | 145.5 | 186.7 |
| Yield Strength (0.2% Offset), ksi | 85.7  | 127.4 | 155.6 |
| Tensile Elongation, %             | 1.0   | 1.0   | 1.0   |
| Transverse Rupture Strength, ksi  | 176.5 | 252.5 | 317.1 |
| Hardness, R <sub>B</sub>          | 90.5  | 100.0 | 108.3 |
| Combined Carbon Content, %        | 0.38  | 0.39  | 0.38  |

A - Green strength of these atomized bars too low to permit adequate handling and sintering.

B - Bars broke before 0.2% offset.

C - Excessive lamination occurred in atomized bars.

## 7. Data Group G

Reference: 24

### Materials

Data is presented on the following steel compositions: 1040, 4640, 4665, and 1.35 Mn, 0.58 C. The material characteristics are given in Table 18-A.

### Processing Summary

The powder blends were compacted into square bars approximately  $0.44 \times 0.44 \times 3.0$  in. long. The density of the compacts was  $6.5 - 6.7 \text{ gm/cm}^3$ . The compacting pressure used depended on the powder blend, but was approximately 80 ksi. The preforms were then preburned at 1200°F, sintered at 2000°F for 15 min in hydrogen, removed from the furnace and "hot forged" within 5 sec, and allowed to cool in air. The resulting samples were 97% minimum density.

### Group G Data

Tensile properties of 1040 steel are presented in Table 19-A. Properties of as-forged 4640 and 4665 materials are given in Table 20-A. Some tensile properties of heat-treated primary and prealloyed 4665 and 1.35 Mn, 0.58 C steels are presented in Tables 21-A, 22-A and 23-A, respectively.

**TABLE 18-A**  
**Composition of Steels**

| <u>Type</u>     | <u>Alloy Element, wt%</u> |           |           |          |
|-----------------|---------------------------|-----------|-----------|----------|
|                 | <u>Ni</u>                 | <u>Mn</u> | <u>Mo</u> | <u>C</u> |
| SAE 4640        | 1.85                      | 0.7       | 0.25      | 0.40     |
| Prealloyed 4600 |                           |           |           |          |
| A. O. Smith     | 2.00                      | 0.2       | 0.5       | Added    |
| Hoeganaes       | 1.85                      | 0.2       | 0.5       | Added    |
| 1.35 Mn, 0.58 C | -                         | 1.35      | -         | 0.58     |

**Elemental Powders**

|               |                                |
|---------------|--------------------------------|
| Iron Powder   | A. O. Smith E P 300 (Atomized) |
| Graphite      | Southwestern Graphite #1651    |
| Molybdenum    | Fansteel P/M - 200 mesh        |
| Nickel        | International Nickel type 123  |
| Zinc Stearate | Nopco P M G                    |

**TABLE 19-A**  
**1040 Carbon Steel**  
**Primary Blend**

|                                                           | <u>Sintered Only</u> | <u>Hot Forged</u> |
|-----------------------------------------------------------|----------------------|-------------------|
| Density, g/cc                                             | 6.60                 | 7.67              |
| Tensile Strength, psi                                     | 24,200               | 74,000            |
| Yield Strength, psi                                       | 17,700               | 51,100            |
| Elongation, % in 1 in.                                    | 1.8                  | 25                |
| <u>Oil Quench from 1550°F and tempered at 350°F, 1 hr</u> |                      |                   |
| Tensile Strength, psi                                     | 44,800               | 107,000           |
| Yield Strength, psi                                       | 38,000               | 72,000            |
| Elongation, % in 1 in.                                    | 0.8                  | 10                |

**TABLE 20-A**  
**Effect of Alloying Elements**  
**on Hot Forged Properties**

| <u>Carbon Content</u>            | <u>Tensile<br/>Strength<br/>psi</u> | <u>Yield<br/>Strength<br/>psi</u> | <u>Elongation<br/>% in 1 in.</u> | <u>Hardness<br/>Rockwell</u> |
|----------------------------------|-------------------------------------|-----------------------------------|----------------------------------|------------------------------|
| <b><u>0.40 - 0.45 Carbon</u></b> |                                     |                                   |                                  |                              |
| 1040 Forged                      | 74,000                              | 51,000                            | 25                               | B-60                         |
| Primary 4600 (No Mo)             | 91,000                              | 44,000                            | 23                               | B-78                         |
| Primary 4600 (0.5 Mo)            | 96,000                              | 52,000                            | 20                               | B-82                         |
| Prealloyed                       | 107,000                             | 80,000                            | 8                                | B-90                         |
| <b><u>0.65 - 0.70 Carbon</u></b> |                                     |                                   |                                  |                              |
| Primary 4600 (No Mo)             | 114,000                             | 56,000                            | 15                               | B-89                         |
| Primary 4600 (0.5 Mo)            | 125,000                             | 61,000                            | 14                               | B-92                         |
| Prealloyed                       | 144,000                             | 102,000                           | 5                                | B-96                         |

NOTE: Forged Densities -- 7.65 g/cc

**TABLE 21-A**  
**Properties of Primary 4665**

| <u>Type</u>                 | <u>UTS, psi</u> | <u>YS, psi</u> | <u>El, %</u> | <u>Density, gm/cm<sup>3</sup></u> |
|-----------------------------|-----------------|----------------|--------------|-----------------------------------|
| <b><u>Sintered:</u></b>     |                 |                |              |                                   |
| 4665, No Mo                 | 47,300          | 22,800         | 2.4          | 6.8                               |
| <b><u>As Forged:</u></b>    |                 |                |              |                                   |
| 4665, No Mo                 | 114,000         | 56,000         | 15           | 7.65                              |
| 4665, 0.5 Mo                | 125,000         | 61,000         | 14           | 7.65                              |
| <b><u>Heat Treated:</u></b> |                 |                |              |                                   |
| 4665, No Mo                 |                 |                |              |                                   |
| Tempered 350°F              | 285,000         | 185,000        | 1.5          |                                   |
| 500°F                       | 275,000         | 221,000        | 2.6          |                                   |
| 650°F                       | 212,000         | 178,000        | 5.1          |                                   |
| 800°F                       | 189,000         | 162,000        | 7.8          |                                   |
| 4665, 0.5 Mo                |                 |                |              |                                   |
| Tempered 350°F              | 276,000         | 215,000        | 1.0          |                                   |
| 500°F                       | 282,000         | 229,000        | 2.2          |                                   |
| 650°F                       | 220,000         | 192,000        | 4.5          |                                   |
| 800°F                       | 208,000         | 180,000        | 5.0          |                                   |

**TABLE 22-A**  
**Properties of Prealloyed 4665**

| <u>Temperature, °F</u> | <u>UTS, psi</u> | <u>YS, psi</u> | <u>El, %</u> |
|------------------------|-----------------|----------------|--------------|
| 350                    | 283,000         | 239,000        | 0.7          |
| 500                    | 290,000         | 250,000        | 1.3          |
| 650                    | 242,000         | 220,000        | 2.1          |
| 800                    | 213,000         | 145,000        | 4.3          |

**TABLE 23-A**  
**Properties of Prealloyed Manganese Steel**

|                                  | <u>1.35 Mn</u>                      | <u>0.58 Carbon</u>                |                                  |                              |
|----------------------------------|-------------------------------------|-----------------------------------|----------------------------------|------------------------------|
|                                  | <u>Tensile<br/>Strength<br/>psi</u> | <u>Yield<br/>Strength<br/>psi</u> | <u>Elongation<br/>% in 1 in.</u> | <u>Hardness<br/>Rockwell</u> |
| As Forged                        | 135,000                             | 78,000                            | 6.5                              | C-18                         |
| <u>Tempering<br/>Temperature</u> |                                     |                                   |                                  |                              |
| 500°F                            | 272,000                             | 252,000                           | 0.4                              | C-45                         |
| 650°F                            | 238,000                             | 216,000                           | 0.75                             | C-42                         |
| 800°F                            | 216,000                             | 198,000                           | 1.7                              | C-36                         |
| 1000°F                           | 147,000                             | 136,000                           | 6.0                              | C-34                         |

## 8. Data Group H

Reference: 18

### Materials

- AISI 460C + 0.25% C  
4600 + 0.35% C  
460G + 0.5% C
- Carbon steels ranging from 0 to 0.5% C

### Processing Summary

Preforms were protected from oxidation/decarburization by graphite coating or by an endothermic gas atmosphere. The other processing details which are available accompany the data tables.

### Group H Data

The mechanical properties of normalized and carburized 4600 + 0.25 C steel are listed in Table 24A. Data for heat-treated 4600 + graphite are given in Table 25-A. Mechanical properties of some forged mild and carbon steels are shown in Table 26-A. Mechanical properties of steels using raw powders manufactured by different methods are presented in Table 27-A. Notes on fatigue resistance follow Table 27-A.

**TABLE 24-A**  
**Mechanical Properties**  
**of AISI 4600 + 0.25% Added Graphite**

| <u>Treatment</u>             | <u>UTS, ksi</u> | <u>Elongation, %</u> | <u>R.A., %</u> | <u>Hardness, Case</u> | <u>HV 30 Core</u> |
|------------------------------|-----------------|----------------------|----------------|-----------------------|-------------------|
| Normalized                   | 67.6            | 15                   | 25             | -                     | 150/150           |
| Carburized and Oil-Quenched* | 115.8           | 10                   | 20             | 750/772               | 260/264           |

\* Material gas-carburized 2 hr at 1688°F; oil-quenched direct.  
Subzero treatment 1 1/2 hr at -22°F.  
Total case depth: 0.032 in.  
Effective case depth: 0.028 in.

**TABLE 25-A**  
**Mechanical Properties**  
**of Heat-Treated AISI 4600 + Graphite**

| <u>Added Graphite, %</u> | <u>Final C %</u> | <u>Austenitizing Temperature, °F</u> | <u>Temper. °F</u> | <u>UTS ksi</u> | <u>Elong. %</u> | <u>R.A. %</u> | <u>HV 30</u> |
|--------------------------|------------------|--------------------------------------|-------------------|----------------|-----------------|---------------|--------------|
| 0.25                     | 0.24             | 1688                                 | -22               | 116.2          | 12              | 25            | 200          |
| 0.35                     | 0.32             | 1580                                 | 1220              | 95.0           | 23              | 38            | 240/250      |
|                          |                  |                                      | 1157              | 123.2          | 12              | 20            | 300/320      |
| 0.50                     | 0.45             | 1562                                 | 1022              | 147.0          | 12              | 20            | 353          |

**TABLE 26-A****Mechanical Properties  
of Some Forged Mild and Carbon Steels**

Starting material: 0.02% C, 0.03% Mn, 0.018 Si, 0.12% P

| <u>Added Graphite</u>   | <u>Final C %</u> | <u>UTS, ksi</u> | <u>Elastic Limit, ksi</u> | <u>Elongation %</u> | <u>R.A. %</u> |
|-------------------------|------------------|-----------------|---------------------------|---------------------|---------------|
| 0                       | 0.02             | 49.6            | -                         | 28                  | 43            |
| 0.5                     | 0.12             | 54.4            | 46.4                      | 33                  | 62            |
| 1.0                     | 0.44             | 86.4            | 53.2                      | 21                  | 35            |
| En-2 wrought,<br>0.4 Mn | 0.13             | 52.0            | 36.0                      | 40                  | 67            |

**TABLE 27-A****Mechanical Properties of Mild and Carbon Steels  
Using Powders Manufactured by Different Methods**

| <u>Material Origin</u> | <u>Final C %</u> | <u>UTS, ksi</u> | <u>Elastic Limit, ksi</u> | <u>Elongation %</u> | <u>R.A. %</u> |
|------------------------|------------------|-----------------|---------------------------|---------------------|---------------|
| Electrolytic iron      | 0.04             | 44.4            | 38.4                      | 46.4                | 76.5          |
|                        | 0.37             | 69.2            | 43.8                      | 31.0                | 52.3          |
| Water-atomized iron    | 0.017            | 50.2            | 40.0                      | 39.5                | 69.5          |
|                        | 0.460            | 82.6            | 48.0                      | 20.3                | 35.3          |
| Air-Atomized iron      | 0.020            | 49.0            | -                         | 29.0                | 45            |
|                        | 0.440            | 86.4            | -                         | 21.0                | 35            |
| Wrought Steel          | 0.03             | 40              | 23.0                      | 43                  |               |
|                        | 0.40             | 85.0            | 60.0                      | 21                  |               |

Note the good approximation of P/M products to wrought materials in the case of the Fe-C alloys listed in the preceding table.

**Notes on Fatigue Testing**

Bending fatigue curves of powder-forged and wrought Mn-Mo and AISI 4632 connecting rods were determined. The wrought material exhibited somewhat better fatigue properties in all cases. The fatigue strength curves tend to converge with increasing cycles, however, attaining similar values at  $10^7$  cycles. GKN endurance test programs have shown powder-forged rods to be comparable to their wrought counterparts.

## 9. Data Group I

Reference: 3

### Materials

A wide range of steel compositions was investigated, including unalloyed irons, EN 18A, SAE 8600 + C, SAE 4600 + C, and Fe-C, Fe-Ni-C, Fe-Ni-Mo-C, Fe-Cr-C, and Fe-Cr-Ni-C alloys. Both blended and atomized alloys were studied. The material properties are given in Tables 28-A and 29-A.

### Processing Summary

- The forging method used throughout is "sinter-forging" (synonymous with hot repressing, hot densification, hot coining, or hot restriking).
- All samples were initially compacted at 50 ksi, in a 2.30 in. diameter die. Sintering was done in a hydrogen atmosphere generally at 2102°F. Atomized alloys were sintered for 1/2 hr, blended alloys for 1 hr.
- Preforms were preheated prior to forging in an inert atmosphere in the range 1830°F - 2010°F. By the start of pressing the temperature of the samples had fallen to 1740°F - 1830°F. The hot pressing die was 2.38 in. in diameter. The hot pressing pressure was 50 ksi.
- Low carbon samples were generally given a normalizing treatment of air cooling from 1650°F. Samples containing >0.2% C were heat treated by oil quenching from temperatures in the range 1530°F - 1650°F, followed by tempering at 570°F or 1112°F.

### Group I Data

- Examples of densities obtained at different stages of the processing are shown in Table 30-A.
- Mechanical properties of normalized sinter/forged iron and iron-carbon samples are shown in Table 31-A.
- Tensile properties of sinter/forged blended alloys of Fe-Ni-C, Fe-Ni-Mo-C, Fe-Cr-C and Fe-Cr-Ni-C are shown in Table 32-A.

- Mechanical properties of sinter/forged samples made from atomized En 18A and SAE 8600 powders are shown in Table 33-A.
- Mechanical properties of sinter/forged SAE 4600 alloys, both normalized and heat treated, are given in Table 34-A.
- The effect of different sintering treatments on the mechanical properties of blended and atomized alloys is shown in Table 35-A.
- The effect of different iron powders on the mechanical properties of a blended alloy of nominal composition 2% Ni, 0.5% Mo, 0.5% C is shown in Table 36-A.

**TABLE 28-A**  
**Iron Powder Characteristics**

| <u>Powder</u> | <u>Manufacturing Process</u> | <u>Grade</u>         | <u>Apparent Density, g/cm<sup>3</sup></u> | <u>Compressibility*, g/cm<sup>3</sup></u> | <u>Flow Rate, s/50 g</u> |
|---------------|------------------------------|----------------------|-------------------------------------------|-------------------------------------------|--------------------------|
| A             | Chloride reduction           | Normal - 100 mesh    | 2.44                                      | 6.21                                      | 34                       |
| B             | Chloride reduction           | High compressibility | 2.96                                      | 6.40                                      | 27                       |
| C             | Oxide reduction              | Normal - 100 mesh    | 2.39                                      | 6.49                                      | 32                       |
| D             | Oxide reduction              | High compressibility | 2.54                                      | 6.30                                      | 32                       |
| E             | Oxide reduction              | High compressibility | 2.68                                      | 6.45                                      | 29                       |
| F             | Water atomization            | Normal - 100 mesh    | 2.96                                      | 6.44                                      | 35                       |
| G             | Electrolysis                 | -300 mesh            | 2.49                                      | 6.40                                      | -                        |
| H             | Oxide reduction              | -300 mesh            | 2.49                                      | 6.17                                      | -                        |

\* 50 ksi; no lubricant

**TABLE 29-A**  
**Composition and Properties of Water-Atomized Alloy Powders**

| <u>Powder</u> | <u>Composition, wt%</u> |           |           |          |          |           |           |           | <u>Apparent Density, g/cm<sup>3</sup></u> | <u>Compressibility*, g/cm<sup>3</sup></u> | <u>Flow Rate, s/50 g</u> |
|---------------|-------------------------|-----------|-----------|----------|----------|-----------|-----------|-----------|-------------------------------------------|-------------------------------------------|--------------------------|
|               | <u>C</u>                | <u>Si</u> | <u>Mn</u> | <u>S</u> | <u>P</u> | <u>Ni</u> | <u>Cr</u> | <u>Mo</u> |                                           |                                           |                          |
| En 18A        | 0.26                    | 0.32      | 0.75      | 0.02     | 0.01     | 0.24      | 1.2       | -         | 2.84                                      | 5.30                                      | 33                       |
| SAE 8600      | 0.01                    | 0.02      | 0.09      | 0.012    | 0.007    | 0.59      | 0.60      | 0.49      | 3.33                                      | 6.14                                      | 23                       |
| SAE 4600      | 0.01                    | 0.03      | 0.12      | 0.015    | 0.008    | 1.70      | -         | 0.42      | 3.08                                      | 6.30                                      | 25                       |

\* 50 ksi; no lubricant.

**TABLE 30-A**  
**Densities of Iron and Alloy Samples**  
**at Various Stages in Processing, gm/cm<sup>3</sup>**

| <u>Powder/Alloy</u> | <u>Pressed</u> | <u>Sintered</u> | <u>Hot-Pressed</u> | <u>Calculated<br/>Absolute<br/>Density</u> |
|---------------------|----------------|-----------------|--------------------|--------------------------------------------|
| A                   | 6.21           | 6.25            | 7.82               | 7.835                                      |
| C                   | 6.19           | 6.25            | 7.76               | 7.80                                       |
| D                   | 6.30           | 6.32            | 7.79               | 7.83                                       |
| F                   | 6.44           | 6.53            | 7.84               | 7.855                                      |
| G                   | 6.40           | 6.41            | 7.85               | 7.865                                      |
| SAE 4600            | 6.30           | 6.34            | 7.85               | 7.875                                      |
| SAE 4600 + 1/2% C   | 6.30           | 6.35            | 7.83               | 7.870                                      |
| EN 18A + 0.3% C     | 5.30           | 5.70            | 7.75               | 7.775                                      |
| SAE 8600            | 6.14           | 6.16            | 7.77               | 7.825                                      |
| SAE 8600 + 1/2% C   | 6.15           | 6.17            | 7.81               | 7.845                                      |

**TABLE 31-A**  
**Mechanical Properties of Sinter/Forged Iron**  
**and Iron-Carbon Samples**

(Samples with 0.5% C added were normalized  
from 1562°F, other samples from 1652°F)

| <u>Powder</u> | <u>Carbon<br/>Added,<br/>%</u> | <u>Yield<br/>Stress,<br/>ksi</u> | <u>UTS, ksi</u> | <u>Elongation,<br/>%</u> | <u>Reduction<br/>in Area,<br/>%</u> | <u>Charpy<br/>Impact<br/>Value,<br/>ft-lb</u> |
|---------------|--------------------------------|----------------------------------|-----------------|--------------------------|-------------------------------------|-----------------------------------------------|
| A             | 0                              | 32                               | 42              | 25                       | 40                                  | 26                                            |
| C             | 0                              | 30                               | 42              | 29                       | 35                                  | 14                                            |
| C             | 0.5                            | 42                               | 58              | 19                       | 22                                  | 3                                             |
| D             | 0                              | 28                               | 43              | 25                       | 47                                  | 14                                            |
| D             | 0.5                            | 40                               | 58              | 20                       | 28                                  | 3                                             |
| F             | 0                              | 38                               | 48              | 38                       | 71                                  | 22                                            |
| F             | 0.25                           | 40                               | 56              | 30                       | 57                                  | 10.5                                          |
| F             | 0.5                            | 60                               | 80              | 22                       | 51                                  | 10.5                                          |
| G             | 0                              | 28                               | 43              | 43                       | 79                                  | 19                                            |
| G             | 0.5                            | 23                               | 64              | 24                       | 45                                  | 2.5                                           |

**TABLE 32-A**  
**Tensile Properties of Sinter/Forged Blended Alloys**  
**made from Chloride-Reduced Iron**  
**(Powder A)**

| Nominal Composition<br>wt%    | Tempering<br>Temp., °F | Yield<br>Strength,<br>ksi | UTS,<br>ksi | Elonga-<br>tion,<br>% | R.A.,<br>% | HV  |
|-------------------------------|------------------------|---------------------------|-------------|-----------------------|------------|-----|
| 1 1/4% Ni, 1/4% C             | 572                    | 52                        | 76          | 15                    | 28         | 182 |
|                               | 1112                   | -                         | 68          | 24                    | 45         | 146 |
| 1 1/4% Ni, 1/2% C             | 572                    | 64                        | 94          | 18                    | 38         | 277 |
|                               | 1112                   | -                         | 88          | 20                    | 49         | 198 |
| 1 1/4% Ni, 0.8% C             | 572                    | 94                        | 136         | 9                     | 25         | 342 |
|                               | 1112                   | 94                        | 118         | 12                    | 38         | 279 |
| 2% Ni, 1/2% Mo,<br>1/4% C     | 572                    | 52                        | 80          | 16                    | 32         | 171 |
|                               | 1112                   | -                         | 72          | 22.5                  | 40         | 160 |
| 2% Ni, 1/2% Mo,<br>1/2% C     | 572                    | 66                        | 110         | 5                     | 7.5        | 279 |
|                               | 1112                   | -                         | 96          | 16                    | 35         | 249 |
| 2% Ni, 1/2% Mo,<br>0.8% C     | 572                    | 106                       | 144         | 9                     | 20         | 330 |
|                               | 1112                   | 74                        | 116         | 13                    | 28         | 255 |
| 1 1/4% Cr, 1/2% C             | 572                    | -                         | 126         | 4                     | 11         | 306 |
|                               | 1112                   | -                         | 86          | 14                    | 26         | 237 |
| 1 1/4% Cr, 1/2% Ni,<br>1/2% C | 572                    | 64                        | 124         | 6                     | 10         | 292 |
|                               | 1112                   | -                         | 90          | 10                    | 17         | 222 |
| 1 1/4% Cr, 1/2% Ni,<br>0.8% C | 572                    | 84                        | 134         | 5                     | 4          | 330 |
|                               | 1112                   | 76                        | 110         | 10                    | 12         | 274 |

**TABLE 33-A****Mechanical Properties of Sinter/Forged Samples  
made from Atomized En 18A and SAE 8600 Powders****(All samples oil-quenched and tempered as indicated)**

| <u>Powder</u> | <u>Nominal<br/>%<br/>Carbon</u> | <u>Tempering<br/>Temp., °F</u> | <u>0.2%<br/>Yield<br/>Stress,<br/>ksi</u> | <u>UTS, ksi</u>   | <u>Elonga-<br/>tion<br/>%</u> | <u>R.A.,<br/>%</u> | <u>Charpy<br/>Impact<br/>Value,<br/>ft-lb</u> |
|---------------|---------------------------------|--------------------------------|-------------------------------------------|-------------------|-------------------------------|--------------------|-----------------------------------------------|
| En 18A        | 0.26                            | 572                            | 64                                        | 92                | 6                             | 7                  | -                                             |
|               |                                 | 1112                           | 60                                        | 82                | 6                             | 6                  | -                                             |
| En 18A        | 0.56                            | 572                            | 100                                       | 134               | 4.5                           | 6                  | -                                             |
|               |                                 | 1112                           | 80                                        | 96                | 12.5                          | 26                 | 3                                             |
| En 18A        | 0.76                            | 572                            | 148                                       | 160<br>(unbroken) |                               |                    | -                                             |
|               |                                 | 1112                           | 92                                        | 110               | 15                            | 29                 | -                                             |
| SAE 8600      | 0                               | 1112                           | 46*                                       | 56                | 10                            | 10                 | 8                                             |
| SAE 8600      | 0.25                            | 1112                           | 50                                        | 70                | 14                            | 19                 | 7                                             |
| SAE 8600      | 0.375                           | 1112                           | 66*                                       | 84                | 10                            | 16                 | 4                                             |
| SAE 8600      | 0.5                             | 1112                           | 78*                                       | 96                | 11                            | 20                 | 6                                             |

\* Upper yield point.

**TABLE 34-A**  
**Mechanical Properties of Sinter/Forged SAE 4600 Alloys**

| <u>% Carbon Added</u> | <u>Heat Treatment*</u> | <u>0.2% Yield Stress, ksi</u> | <u>UTS, ksi</u> | <u>Elongation, %</u> | <u>R.A., %</u> |
|-----------------------|------------------------|-------------------------------|-----------------|----------------------|----------------|
| 0                     | AC                     | -                             | 54              | 48                   | 74             |
| 0.1                   | AC                     | -                             | 55              | 45.5                 | 68             |
| 0.125                 | AC                     | -                             | 60              | 30                   | 55             |
| 0.2                   | AC                     | -                             | 68              | 20                   | 27             |
| 0.3                   | AC                     | -                             | 75              | 21                   | 55             |
| 0.325                 | AC                     | 53                            | 76              | 22                   | 51             |
| 0.4                   | AC                     | 62                            | 90              | 19.5                 | 51             |
| 0.5                   | AC                     | 66                            | 93              | 16                   | 47             |
| 0.6                   | AC                     | 66                            | 96              | 14.5                 | 32             |
|                       |                        |                               |                 |                      |                |
| 0                     | 1112                   | -                             | 60              | 31                   | 68             |
| 0.1                   | 1112                   | -                             | 71              | 25                   | 69             |
| 0.2                   | 1112                   | 73                            | 88              | 20                   | 57             |
| 0.25                  | 572                    | 76                            | 94              | 18                   | 46             |
| 0.25                  | 1112                   | 74                            | 92              | 20                   | 60             |
| 0.4                   | 572                    | 101                           | 136             | 9                    | 35             |
| 0.4                   | 1112                   | 76                            | 100             | 17.5                 | 47             |
| 0.5                   | 752                    | 164                           | 180             | 10                   | 38             |
| 0.5                   | 1112                   | 82                            | 111             | 18                   | 54             |
| 0.6                   | 572                    | 211                           | 276             | 3.5                  | 3              |
| 0.6                   | 752                    | 177                           | 199             | 5                    | 10             |
| 0.6                   | 1112                   | 120                           | 144             | 5.5                  | 15             |

\* AC - Air-cooled (normalized).

T572 - 011 quenched and tempered at 572°F, etc.

**TABLE 35-A**

**Effect of Different Sintering Treatments  
on the Tensile and Impact Properties  
of Blended and Atomized Alloys**

(All samples oil quenched, tempered at 1112°F)

| Alloy        | Temp.,<br>°F | Sintering<br>time, hr | 0.2%<br>Yield<br>Stress,<br>ksi | UTS,<br>ksi | Elonga-<br>tion<br>% | R.A.,<br>% | Charpy<br>Impact<br>Value<br>ft-lb |
|--------------|--------------|-----------------------|---------------------------------|-------------|----------------------|------------|------------------------------------|
| Powder A     | 2100         | 0.5                   | -                               | 66          | 26                   | 47         | 27.5                               |
| + 2 1/2% Ni, | 2100         | 1                     | -                               | 70          | 25                   | 47         | 28                                 |
| 1/2% Mo,     | 2370         | 1                     | -                               | 73          | 22                   | 35         | 26.5                               |
| 1/4% C       | 2370         | 2                     | -                               | 83          | 19                   | 30         | 29.5                               |
| SAE 4600     | 2100         | 0.5                   | 74                              | 108         | 15                   | 45         | 8                                  |
| + 1/2% C     | 2370         | 1                     | 82                              | 115         | 15                   | 49         | 11.5                               |
|              | 2370         | 2                     | 82                              | 110         | 19                   | 58         | 13.5                               |

**TABLE 36-A**

**Effect of Different Iron Powders on the Mechanical Properties  
of a Blended Alloy of Nominal Composition 2% Ni, 0.5% Mo, 0.5% C**

(All samples were sintered at 2370°F, then oil-quenched and tempered at 1112°F)

| Powder | Type                        | UTS,<br>ksi | Elonga-<br>tion,<br>% | R.A.,<br>% | Charpy<br>Impact<br>Value<br>ft-lb | Oxygen<br>Content,<br>wt% |
|--------|-----------------------------|-------------|-----------------------|------------|------------------------------------|---------------------------|
| A      | Chloride reduction          | 96          | 16                    | 35         | 11.5                               | 0.14                      |
| B      | Chloride reduction HC*      | 90          | 15                    | 41         | 14.5                               | 0.036                     |
| C      | Reduced Iron                | 91          | 10                    | 17         | 8                                  | 0.32                      |
| D      | Reduced Iron HC             | 80          | 15                    | 22         | 10.5                               | 0.24                      |
| E      | Reduced Iron HC             | 84          | 13.5                  | 24         | 9                                  | 0.24                      |
| F      | Atomized Iron               | 94          | 16                    | 38         | 13                                 | 0.032                     |
| G      | Electrolytic<br>(-300 mesh) | 103         | 14                    | 30         | 13.5                               | 0.09                      |
| H      | Reduced Iron<br>(-300 mesh) | 77          | 16                    | 23         | 9.5                                | 0.34                      |

\* HC - High compressibility.

### Other Sources of Information

There are a number of other extensive sources of information available on ferrous P/M products which have not been incorporated into the present data compilation, either because the subject matter was not considered strictly relevant (e.g., data presentations concerned with only sintered material, or only nonheat-treatable material, would generally not be included), because the processing, test, or sample data are not presented in sufficiently specific detail, or because inclusion of the data in this compilation was considered to be unnecessary duplication of readily available sources. Data sources which are particularly useful in that they present a broad spectrum of P/M material properties in a reasonably condensed form are referenced below.

1. "P/M Materials Standards and Specifications," MPIF Standard No. 35, published by Metal Powder Industries Federation, 201 East 42nd St., New York, N.Y., 10017, copyright 1969.

This work contains a large quantity of mechanical property data on nickel-steel P/M products, heat treated and otherwise, arranged as a function of composition (range) and density (range). In addition, data on brasses, bronzes, Fe-Cu alloys, carbon steels, infiltrated steels, and stainless steels are presented.

2. "Properties and Applications of Powder Metallurgy Parts," data sheets compiled by S. W. McGee, Burgess-Norton Mfg. Co., reported in Metal Progress, April 1971, pp. 80-81.

3. ASTM Standard Specifications.

- ASTM B310: Standard Specification for Sintered Carbon-Steel Structural Parts.

The typical mechanical properties which can be expected from as-sintered and heat-treated carbon-steel P/M specimens as a function of carbon content and density.

- **ASTM B426**: Standard Specification for Sintered Copper-Steel Structural Parts.

The typical mechanical properties which can be expected from as-sintered and heat treated carbon steel P/M specimens as a function of amount of copper added and specimen density.

- **ASTM B308**: Standard Specification for Sintered Carbon-Steel Structural Parts.

The tensile and compressive properties which can be expected from sintered iron infiltrated parts are presented as a function of combined carbon.

- **ASTM B484**: Standard Specification for Sintered Nickel-Steel Structural Parts.

The mechanical properties which can be expected from as-sintered and heat-treated nickel specimens are presented as a function of nickel, combined carbon, and density.