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WARM EXTRUSION OF TRIP STEELS

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ABSTRACT

TRIP steel rods were warm extruded to reductions of area of 40%, 60%, and 80%. Temperature increases on the order of 300 F were compensated for by selecting a lower initial billet temperature than the optimum of 850 F used for warm rolling. The billet preheat temperature was selected to produce a maximum extrusion temperature (at the die exit) of 850 F. The 40% and 60% reductions were each performed in one extrusion pass. The 80% reduction required a two-step sequence (60% followed by 50%). This procedure was necessary to avoid the excessively low preheat temperature required for a single reduction to 80%. The extrusion constants are approximately 50 ksi for hot extrusion, 150 ksi for single-pass warm extrusion, and 300 ksi for the second (50%) warm reduction. With the procedures established, the material was successfully extruded to hardness levels equivalent to those obtained by warm rolling.

CONTENTS

INTRODUCTION

There has been a continual interest in the development and utilization of steels with higher strength and higher toughness. Increases in these properties have been achieved by the use of thermomechanical treatments of selected steel compositions.[1] During thermomechanical treatments plastic deformation is introduced into the heat-treatment cycle to obtain properties not obtainable by heat treatments alone. However, as the steels are processed to higher yield strengths, there is a corresponding decrease in ductility and toughness. As a result, high yield strength steels often lack adequate toughness for most applications. In alleviating this problem, a major advance has been made by the application of thermomechanical treatments to certain metastable austenitic steels called TRIP (TRansformation Induced Plasticity) steels.[2] The critical processing of TRIP steels involves a severe warm-working treatment to produce a high yield strength material. At room temperature, the material is metastable with respect to deformation, i.e., on straining there is a strain-induced transformation from the severely worked austenitic phase to the higher strength martensitic phase. This phase transformation strengthens the material so that the onset of unstable flow (necking) is delayed. The result is both a high yield strength, due to the warm deformation, and high ductility, due to the strain-induced transformation. Like conventional high-strength steels, TRIP steels also experience an inverse relationship between strength and ductility. However, this strength-ductility base is significantly higher. At a yield strength of 230 ksi, elongations of 35% are typical.[2]

High-strength TRIP steels are inherently difficult to process since the achievement of high austenite strength levels requires extensive deformation at moderate (warm) temperatures. This material behavior, therefore, imposes equipment requirements not currently available in terms of load capacity and rigidity for the production of high-strength TRIP steel components. Extrusion, though subjected to the same equipment limitations, does offer significant advantages over rolling in that it provides a technique capable of producing high-strength TRIP steel of intricate profiles. These extruded shapes would require little or no additional machining other than "cut-off." There are, however, certain problems associated with warm extrusion that are unimportant in warm rolling. This report will discuss, in detail, the aspects of warm extrusion for producing TRIP steel components.

BACKGROUND

A number of factors determine the optimum temperature for warm-working TRIP steels. Obviously, the working temperature must remain above the M_d even as the M_d increases during deformation.[3,4] (M_d is the maximum temperature for a

1. RADCLIFFE, S. V., and KULA, E. B. *Deformation, Transformation, and Strength* in Fundamentals of Deformation Processing, W. A. Backofen, J. J. Burke, F. L. Coffin, Jr., N. L. Reed, and V. Weiss, ed., Syracuse University Press, Syracuse, New York, 1964, p. 321-363.
2. ZACKAY, V. F., PARKER, E. R., FAHR, D., and BUSCH, R. *The Enhancement of Ductility in High-Strength Steels.* Trans. ASM, v. 60, 1967, p. 252-259.
3. ZACKAY, V. F., BHANDARKAR, M. D., and PARKER, E. R. *Role of Diffusionless Phase Transformations in the Plasticity of Some Iron-Base Alloys* in Advances in Deformation Processing. Syracuse University Press, Syracuse, New York, to be published.
4. GERBERICH, W. W., THOMAS, G., PARKER, E. R., and ZACKAY, V. F. *Metastable Austenites: Decomposition and Strength.* University of California, Berkeley, California, UCRL-20308, August 1970.

strain-induced austenite-to-martensite transformation; this temperature is approximately 300 F for the composition studied here, Reference 5.) This consideration sets a lower limit to the warm-working temperature. The upper limit is set to produce the desired rate of carbide precipitation from the solid solution and at the same time avoid simultaneous annealing of the cold-worked austenitic structure.

The control of warm-working temperature is relatively simple for rolling where the temperature drop of the workpiece after removal from the furnace is partially restored by adiabatic heating during rolling. Large perturbations are avoided by returning the workpiece to the furnace prior to additional passes. This is in contrast to the large temperature increases possible during extrusion. If a substantial temperature rise is expected, then the initial or preheat temperature must be correspondingly lowered. The composition used here has optimum strength-ductility properties after rolling at 850 F to reductions of area of 80%. It was, therefore, decided to fix the maximum extrusion temperature (at the die exit) at 850 F. There is a limit to which the preheat temperature can be reduced to obtain 850 F at the die exit. Obviously, even for very large temperature increases, the preheat temperature must not be below the M_d.

With a large temperature rise occurring during extrusion, it is expected that the resulting austenite stability and mechanical properties would be different from that for rolling to the same final reduction. In addition, even for equivalent strains or reductions of area, it is entirely possible that different strain states during warm working could produce different levels of austenite hardening. Evidence does exist for the influence of strain state on hardening during cold working of various sheet materials.[6,7] If this were true during the warm working of TRIP steels, then a given reduction would produce different levels of austenite strength and austenite stability during rolling as compared to swaging even though both processes are essentially isothermal. In extrusion, where a large temperature rise is anticipated, the differences could be even more pronounced. The effect of extrusion parameters on austenite stability and mechanical properties will be the subject of a later report.

MATERIALS AND EXPERIMENTAL PROCEDURES

Materials

Forty-pound heats (Table 1) were produced by both air-melting (under an argon blanket) and vacuum-melting techniques with solidification in cast iron molds. The nominal composition is similar to the A-2 alloy designation reported by Zackay et al.[2] This composition was selected because it is one of the higher strength TRIP steels. All ingots were homogenized at 2300 F for 6 hours (in vacuum) followed by a fast argon cool, press forged at 2100 F to 3-3/8-inch diameter, then machined to 3-1/8-inch diameter in preparation for hot extrusion.

5. AZRIN, M., GAGNE, R. A., HOLMES, K. D., QUIGLEY, F. C., and SHEPARD, L. *Development of TRIP Steels for Army Applications.* Army Materials and Mechanics Research Center, AMMRC TR 71-57, December 1971.
6. AZRIN, M. *The Deformation and Failure of a Biaxially Stretched Sheet.* Ph.D. Thesis, MIT, Department of Metallurgy and Materials Science, Cambridge, Massachusetts, 1970.
7. GHOSH, A. K. *Strain Hardening and Instability in Biaxially Stretched Sheets.* Ph.D. Thesis, MIT, Department of Metallurgy and Materials Science, Cambridge, Massachusetts, 1972.

Hot Extrusion

Hot extrusion* was performed on a 700-ton vertical hydraulic press instrumented to measure load and displacement. The process parameters are listed in Table 2. The pressures required to extrude the vacuum-melted material differed little from those required for the air-melted material. Thus, the extrusion pressures and extrusion constant in Table 2 are representative of all hot extrusion trials. Following hot extrusion, the rods were heated to 1500 F and straightened by flattening between parallel dies, then solution treated at 2250 F for one hour and water quenched.

Warm Extrusion

Warm extrusion* was performed on an instrumented 500-ton mechanical press. The press rating was 90 strokes per minute with a 10-inch stroke. A schematic of the warm extrusion tooling is shown in Figure 1. The container-and-die assembly was heated to the desired temperatures using strip heaters attached to the surface of the outer ring.

Table 1. CHEMICAL COMPOSITION (Wt%)

Melt	C	Mn	Si	Ni	Cr	Mo	P	S	Al	N	O*	H*
Air	0.25	2.16	2.11	7.73	8.86	4.08	0.003	0.010	0.05	0.060	25	8.5
Air	.26	2.18	2.02	6.81	8.90	4.09	.003	.010	.06	.044	63	3.9
Air	.27	2.17	2.14	7.75	8.87	4.04	.003	.010	.04	.065	47	7.3
Air	.27	2.16	1.93	7.79	8.96	4.06	.003	.010	.06	.054	49	3.7
Vacuum	.33	2.25	2.06	7.56	9.06	3.97	.003	.009	.08	.004	2.2	6.0
Vacuum	.33	2.32	1.77	7.71	8.98	4.14	.002	.009	.10	.003	0.3	5.5
Vacuum	.33	2.27	2.03	7.68	8.90	3.96	.003	.009	.09	.003	1.1	5.8

*Parts per million

Table 2. HOT EXTRUSION PROCESS PARAMETERS

Billet Size: 3-1/8 in. diam. × 7 to 8 in. long

Billet Temperature: 2100 F

Extrusion Ratio, R: 6.6/1

Extrusion Ram Speed: 80 in./min

Extruded Rod Size (Nominal): 1.29 in. diam.

Extrusion Pressures (Nominal)

- Breakthrough: 124 ksi
- Runout (P): 96 ksi

Extrusion Constant, K: 51 ksi
(from P = K lnR)

Lubrication

- Billet: Glass Powder (-100 mesh)
- Container: Fiske BMI-4 Hot Die Lube
- Die: Glass Pad and Glass Wool

*Performed at Battelle Memorial Institute, Columbus Laboratories, under AMMRC Contract DAAG-46-73-C-0092.

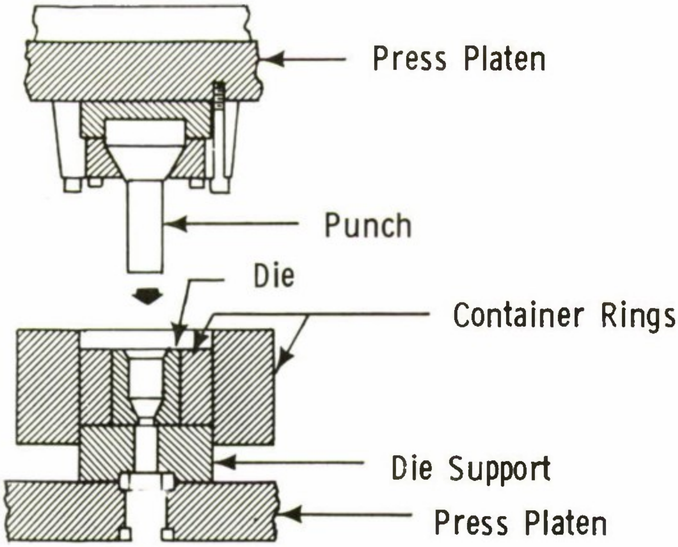

Figure 1. Schematic tooling used in warm extrusion of TRIP steel.

Hydrafilm Versus Conventional

Initial warm extrusion runs were made using the hydrafilm* extrusion process to minimize die wear and improve surface quality of the extruded material. Hydrafilm is a hydrostatic extrusion technique which simplifies the extrusion process by using a minimum of pressurizing fluid in combination with proper lubrication. With this technique it is possible to use conventional tooling and equipment and operate at cycle rates near those encountered in conventional extrusion. The hydrafilm process was used in conjunction with a mechanical press to warm extrude high-strength TRIP steel. However, due to the relatively short billet length and modest extrusion ratios, it was found that the extrusion loads were not excessively high and, therefore, there was no need for the continued use of this technique. Thus, the material was processed using conventional warm extrusion practice, i.e., without stem seals and pressurization of a hydrostatic fluid.

Calculated Warm Extrusion Loads

Design of the warm extrusion tooling was based on flow stress data obtained by an isothermal compression test at 850 F. A TRIP steel cylinder was enclosed in an insulated container and placed between hardened tool steel platens. The entire assembly was heated to the test temperature and then upset between the platens of the mechanical press. Top and bottom surfaces of the specimens were lubricated with a low shear strength sheet material (1100 Al) to permit uniform upsetting (i.e., without barreling).

The flow stress $\bar{\sigma}$ for the solution-treated material is shown in Figure 2. Also included is the curve for the as-forged material. It is clear that solutionizing is beneficial since reduced deformation loads are required for subsequent warm working.

The use of the flow stress data obtained at 850 F (Figure 2) resulted in lower bound calculated values of the warm extrusion loads since deformation occurred

*Patented process.

during a temperature rise, reaching 850 F only during the final stages of extrusion (i.e., at the die exit). The result is that for equivalent strains more strengthening occurred during extrusion than is indicated in Figure 2. The curve for solutionized material can be approximated by the parabolic strain-hardening equation:

$$\bar{\sigma} = k\bar{\varepsilon}^{n}, \qquad (1)$$

where $\bar{\sigma}$ = true flow stress
k = strain-hardening coefficient
$\bar{\varepsilon}$ = logarithmic strain
n = strain-hardening exponent

The constants for the solutionized material are: n = 0.56 and k = 203.6 ksi. Extrusion loads at 850 F were calculated using Siebel's relationship:[8]

$$F = A_o\bar{\sigma}_a(\ln R) + [(2\alpha A_o\bar{\sigma}_a)/3] + A_o\bar{\sigma}_a\mu(\ln R)/(\cos\alpha\cdot\sin\alpha) = \pi DL\bar{\sigma}_a\mu, \qquad (2)$$

where F = extrusion load
A_o = cross-sectional area of the container
$\bar{\sigma}_a$ = average true flow stress of billet material
α = half die angle
μ = coefficient of friction
D = container diameter
L = billet length

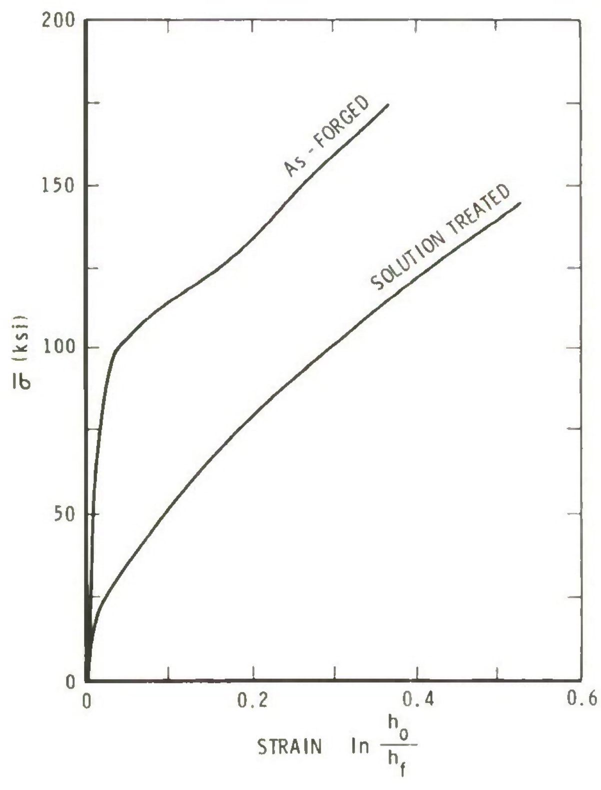

Figure 2. Flow stress (σ) versus strain for TRIP steel at 850 F. Conditions of starting material: (1) as-forged, and (2) solution treated at 2250 F for 1 hour and water quenched.

8. SIEBEL, E. *Fundamentals and Concepts in Forming.* Werkstattechnik and Maschinenbau, v. 40, 1950, p. 373 (in German).

The average true flow stress value is determined from

$$\bar{\sigma}_a = k(\ln R)^n/n+1. \tag{3}$$

Based on Equations 2 and 3 and the flow stress data obtained, it was possible to predict extrusion punch stresses for each extrusion ratio used (Table 3). This information was used to design the tooling for warm extrusion.

Estimated Temperature Increase During Warm Extrusion

Estimates were made of the maximum temperature increase that could occur during warm extrusion. It was assumed that all mechanical energy required to extrude the billet is converted to thermal energy in the form of a temperature rise:

$$\Delta T = E/JC\rho, \tag{4}$$

where ΔT = temperature rise
E = mechanical energy required to extrude the material
J = conversion factor for converting mechanical energy to thermal energy
C = billet heat capacity
ρ = billet density

The calculated temperature increases are given in Table 4 for 40%, 60%, and 80% reductions. The extrusions of 40% and 60% were approximately 65% efficient in

Table 3. CALCULATED EXTRUSION PRESSURE AT 850 F

Reduction (%)	Flow Stress, $\bar{\sigma}_a$ (ksi)	Calculated Punch Stress* (ksi)
40	90	80
60	124	165
80	170	352

*Based on α = 22-1/2 degrees and μ = 0.1

Table 4. WARM EXTRUSION PARAMETERS

Reduction % (R)	Size (in.) Billet diam./length	Size (in.) Extrusion diam./length	Calculated Temperature Increase (deg F)	Measured Temperatures (deg F) Initial	Measured Temperatures (deg F) Final	Measured Temperatures (deg F) Increase	Measured Extrusion Pressure, P (ksi)	Extrusion Constant, K* (ksi)
40 (1.67)	1.25/2.40	0.96/3.25	257	700	820-860	120-160	81	158
60 (2.5)	1.25/2.00	0.78/3.25	518	500	800-850	300-350	134	146
80 (5)	-	-	1130	-	-	(700)†	-	-
50‡ (2)	0.78/2.37	0.56/3.25	-	400	790-850	390-450	210	303

*From P = K (lnR)

†Corrected calculated temperature rise, based on 40% and 60% reductions being only 60 to 70 percent efficient in converting mechanical energy to a temperature rise.

‡A total reduction of 80% was obtained by performing a 60% reduction, followed by a 50% reduction.

converting mechanical energy into a temperature rise in the extruded product.* Assuming that this situation would also exist at the 80% reduction, it could be expected that the temperature increase in this case would be about 700 F. Billets would then need to be preheated to only 150 F, thereby producing an austenite-to-martensite transformation during extrusion. This transformation was prevented by performing the 80% reduction in two steps, using a preheat temperature for each step that is significantly higher than that required for a single step reduction. Table 4 contains a summary of the billet and extrusion dimensions (diameter/length) and preheat and final extrusion temperatures.

RESULTS AND DISCUSSION

Temperature Increase During Warm Extrusion

The 40% and 60% warm extrusions were performed in one step. The 80% final reduction was obtained by giving the 60% specimen an additional 50% reduction. The measured temperature increases are given in Table 4 and represented schematically in Figure 3, which shows that it is possible to maintain nearly constant hot- and warm-working temperatures only during rolling. Short extrusion times produce large temperature-time slopes (Figures 3b and 3c). The temperature rise is a function of the flow stress (or extrusion pressure) for the material undergoing deformation. Therefore, in Figure 3c the 50% reduction produces a larger temperature rise than the 60% reduction (Table 4).

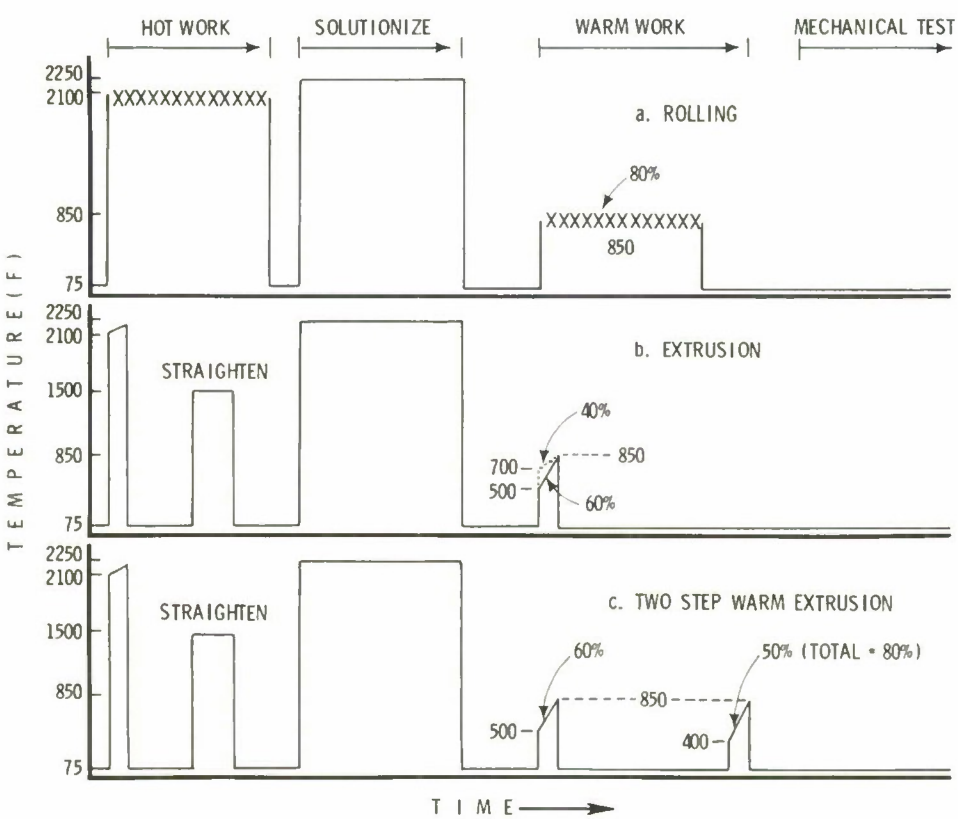

Figure 3. Temperature-time diagram for hot and warm working. XXXX indicates repeated rolling operations with furnace reheat between each pass. Temperature coordinate is to scale, while time coordinate is drawn only to indicate large difference between rolling and extrusion operations.

*A Leeds and Northrup fast-response contact pyrometer was used to measure temperatures on the extruded samples.

The temperature-time representation for swaging would be similar to that for rolling (Figure 3a). It is only where processing occurs at high deformation rates in a single uninterrupted straining, as in extrusion, that a rapid temperature rise will result.

Extrusion Constants

There are a number of expressions, including Equation 2, that can be used to predict the difficulty in extruding a material. Often these relationships are cumbersome to use and more importantly they require information that is rarely known. This information includes billet friction, die angle, appropriate average yield stress, cross-sectional configuration, nonuniform deformation of the billet, billet dimensions, as well as possible strain rate and strain-hardening effects.

The importance of each factor varies with extrusion conditions. For example, extrusions carried out above the recrystallization temperature would be significantly influenced by strain rate with strain hardening having little effect. However, deformation below the recrystallization temperature would be conversely affected. Fortunately, the influence of these process parameters can be represented by an extrusion constant K, where K is equal to the extrusion pressure divided by the natural log of the reduction ratio:

$$K = P/\ln R. \qquad (5)$$

Figure 4 shows four extrusion constants for TRIP steel; two for hot extrusion and two for warm extrusion of solutionized material. Also included are typical curves for a number of selected materials.[9] It is apparent that hot extrusion of TRIP steel compares in difficulty to that of other high-strength materials; warm extrusion values are another matter. The high K value of 303 ksi (Table 4) to complete sequential processing would limit this approach to small reductions on the second step. Even for one-step extrusion, a very high K value exists. The straight line drawn between the hot extruded and single-step extrusion values is meant only to emphasize the relative values at the end locations and not the shape

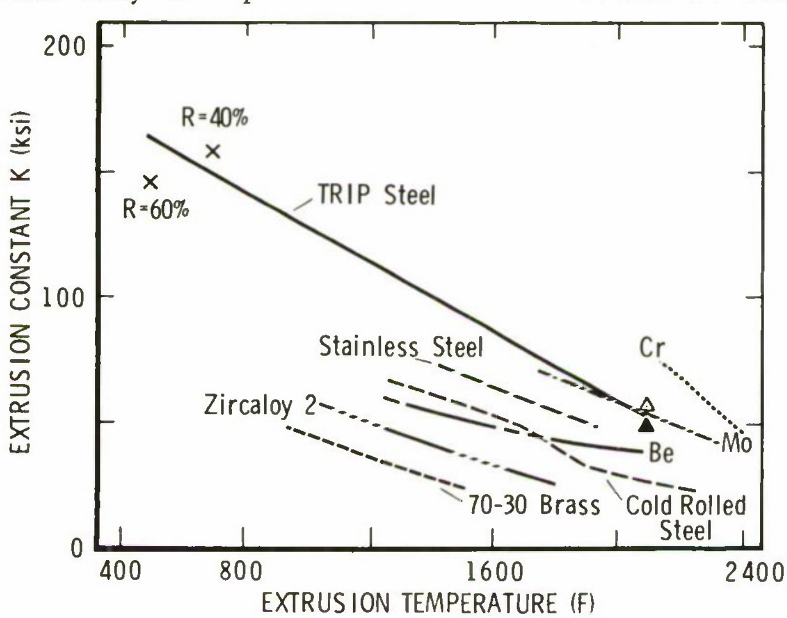

Figure 4. Extrusion constants for TRIP steel.

9. LOWENSTEIN, P. *Space-Age Materials Extruded by New Techniques.* Tool and Manufacturing Engineer, v. 50, no. 5, 1963, p. 85-91.

of the connecting curve. Extrusions are limited to the lower temperature range to avoid excessive carbide precipitation and/or simultaneous annealing of the cold-worked austenitic structure.

The K values observed in Figure 4 indicate that the maximum warm reductions feasible for TRIP steels would be much less than those possible for other materials. For example, with the equipment and procedures described in this study, the extrusion pressures encountered suggest a 1-3/4 inch upper limit for the final diameter of the bar which could be warm extruded 80%. This would require an initial billet diameter of 3.9 inches.

Conventional warm extrusion practice was used in this study. However, by utilizing the more complex hydrafilm process, up to 50% reduction in extrusion pressure is possible, depending on the length/diameter ratio of the starting materials.[10] The hydrafilm process essentially minimizes the die-workpiece-container surface friction, and therefore requires reduced extrusion pressures.

Microstructure and Hardness

Figure 5 shows the equiaxed structure (A-A) of the solutionized material, and the elongated structure after warm extrusion (60% at B-B and then an additional 50% at C-C). At the 50% die exit, the elongated grains are nearly 100% austenite, indicating that the initial billet temperature was sufficiently high to avoid the occurrence of a strain-induced transformation.

Rockwell C hardness readings are shown at their respective locations. As expected, the hardness increases with increasing reduction from A-A to C-C. The lower hardness observed at the surface region is attributed to the lower redundant work in this region.[11]

The Rockwell C hardness after 60% reduction is 45 to 46, and with an additional 50% is 47 to 50. These hardness values are similar to those obtained after warm rolling 60% and 80%. Therefore, it is possible to obtain hardness levels by warm extrusion equivalent to those obtained by rolling.

SUMMARY AND CONCLUSIONS

1. Loads for warm extrusion were predicted from flow stress measurements at 850 F. Also, estimates were made of the temperature increase during warm extrusion to determine the level of preheat temperature necessary to attain a temperature of 850 F at the die exit.

2. The moderate temperature increases for the 40% and 60% reductions permitted these reductions to be performed in one pass. It was not possible, however, to perform the 80% reduction in a single pass since the large temperature increase would have required a preheat temperature below the M_d. Therefore, a two-step reduction sequence was used: 60% followed by an additional 50% (total reduction

10. FIORENTINO, R. J., MEYER, G. E., and BYRER, T. G. *Thick Film Hydrostatic Extrusion Process.* SME Paper No. MF71-103.
11. AVITZUR, B. *A Survey of the Study of Flow Through Conical Converging Dies.* Department of Metallurgy and Materials Science, Lehigh University, Bethlehem, Pennsylvania, February 1968.

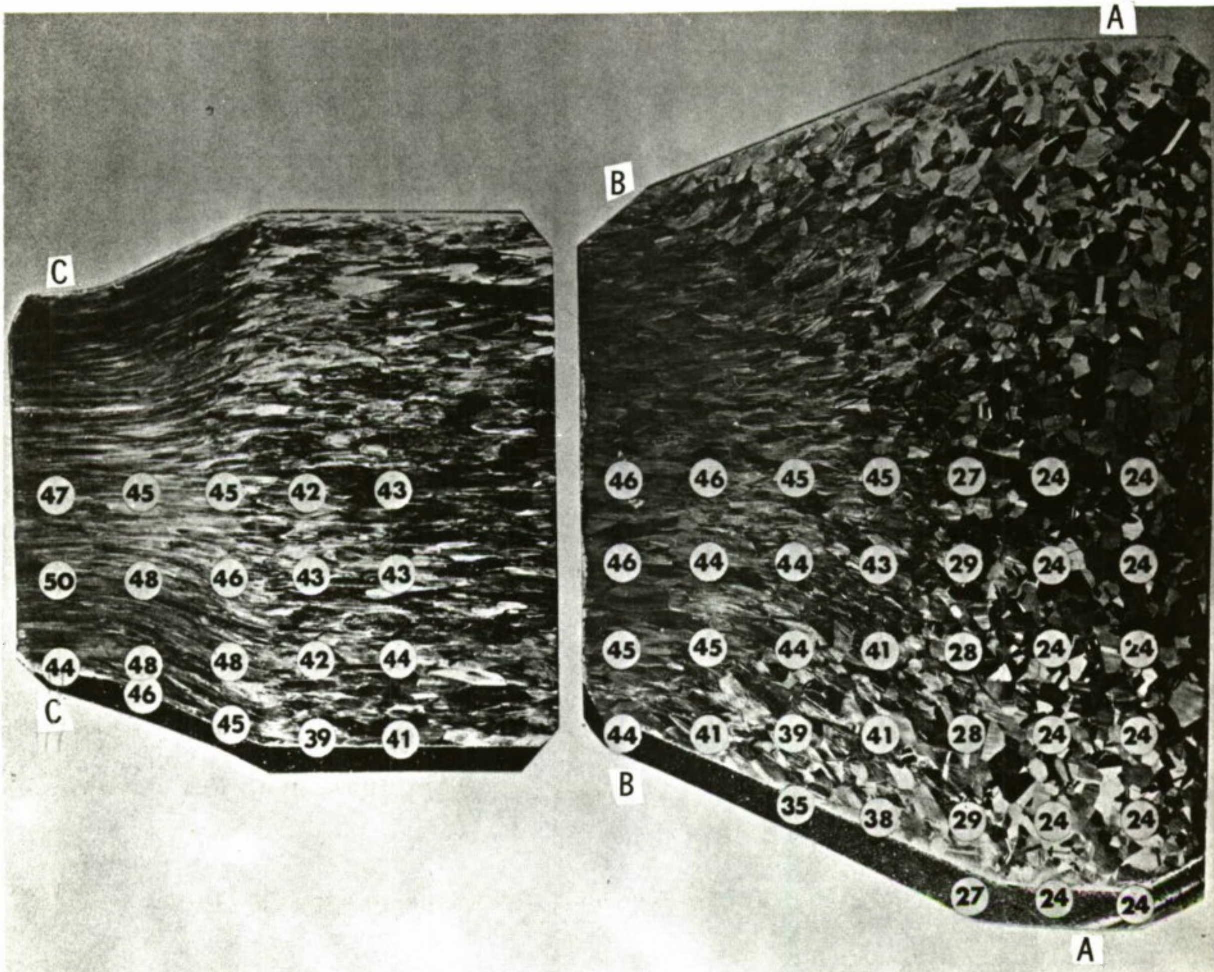

Figure 5. Rockwell C hardness distribution and microstructure of warm-extruded TRIP steel (4-1/2X). Starting material at (A-A), first reduction 60% (B-B), and second reduction 50% (C-C).

of 80%). Each reduction was performed at a significantly higher preheat temperature than would be required for a single reduction of 80%.

3. The hot extrusion constants of approximately 50 ksi are not significantly different from other high-strength materials. This value increased to about 150 ksi for warm extrusion. Extruding material previously warm extruded 60% resulted in an extrusion constant of 303 ksi. The high constants for warm extrusion severely limit the TRIP steel sizes producible by this technique. It is expected that hydrostatic extrusion would permit larger section sizes of TRIP steel which are not currently attainable with conventional techniques.

4. It was demonstrated that standard extrusion practice and tooling concepts could be used in processing high-strength TRIP steels by warm extrusion. The hardness of 45 to 46 R_c after 60% reduction and 47 to 50 R_c after 80% reduction (60% followed by 50%) indicates that for equivalent total reductions, the same level of strengthening can be obtained by warm rolling or extrusion.

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WARM EXTRUSION OF TRIP STEELS -
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Technical Report AMMRC TR 76-2, January 1976, 13 pp -
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Key Words

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Extrusion

TRIP steel rods were warm extruded to reductions of area of 40%, 60%, and 80%. Temperature increases on the order of 300 F were compensated for by selecting a lower initial billet temperature than the optimum of 850 F used for warm rolling. The billet preheat temperature was selected to produce a maximum extrusion temperature (at the die exit) of 850 F. The 40% and 60% reductions were each performed in one extrusion pass. The 80% reduction required a two-step sequence (60% followed by 50%). This procedure was necessary to avoid the excessively low preheat temperature required for a single reduction to 80%. The extrusion constants are approximately 50 ksi for hot extrusion, 150 ksi for single-pass warm extrusion, and 300 ksi for the second (50%) warm reduction. With the procedures established, the material was successfully extruded to hardness levels equivalent to those obtained by warm rolling.

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