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TECHNICAL REPORT
69-32-GP

A FORMING TECHNIQUE FOR SOLDIERS TITANIUM HELMETS

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U. S. Army Natick Laboratories

Contract No. DA19-129-AMC-940 (N)

July 1968

UNITED STATES ARMY
NATICK LABORATORIES
Natick Massachusetts 01760

General Equipment & Packaging Laboratory

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FOREWORD

This report covers the work conducted under U. S. Army Natick Laboratories Contract No. DA19-129-AMC-940(N). The project was initiated in October, 1965 as a product improvement in support of Southeast Asia. The scope of this project was further expanded at the request of Headquarters, U. S. Army Materiel Command in July, 1966.

The authors wish to thank Mr. Walter Greer, Greer Products, Los Angeles, California, for his unending efforts and cooperation. Mr. Greer made many significant contributions to this program without which it could not have succeeded.

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ABSTRACT

The 5Al-2.5 Sn, 6Al-4 V, 4Al-3 Mn, and commercially pure grades of titanium were investigated for use in infantry helmets.

The 5Al-2.5 Sn grade of titanium alloy was found to be the best commercially available grade for this application. This selection was based upon a combination of ballistic performance and formability using the "Greer" process.

The forming and intermediate stress-relieving operations were found to improve the ballistic properties of the titanium.

A total of 500 helmets were fabricated, and the feasibility of mass-producing titanium alloy helmets at room temperature, using the "Greer" forming process, was demonstrated.

It was determined that up to a one-pound weight reduction could be achieved in a titanium helmet without significantly reducing the ballistic protection as compared to the standard M-1 Hadfield manganese steel helmet. A significant increase in ballistic protection could also be achieved with a titanium helmet of equivalent weight to the M-1 steel helmet.

A FORMING TECHNIQUE FOR SOLDIERS TITANIUM HELMET

1. Introduction.

The standard M-1 Hadfield steel soldiers helmet dates back to 1940 and is undoubtedly one of the best-known pieces of personnel equipment to millions of United States servicemen. Approximately 30,000,000 of these helmets have been fabricated over the years, and they have been credited with saving thousands of lives during World War II and the Korean conflict.[1] The M-1 helmet is also the standard infantry helmet currently used by combat personnel in Southeast Asia. The unusual life span of the M-1 helmet can be largely attributed to the good ballistic performance of the Hadfield manganese steel with which it is made.

The only known metallic armor material capable of providing a significant improvement in ballistic protection over the M-1 manganese steel helmet (with no increase in weight) is titanium alloy. This superior ballistic performance has been known for many years. However, all previous efforts to form helmets with titanium alloy were unsuccessful.[2] A recent breakthrough in forming technology now makes it practical to consider titanium alloy for mass production.

This report covers the work conducted under the U. S. Army Natick Laboratories Contract No. DA19-129-AMC-940(N)[3] with Titanium Metals Corporation of America, West Caldwell, New Jersey. The forming of the helmets was performed by Greer Products, Inc., Los Angeles, California, a subsidiary of Garrett Corporation. A total of 500 titanium helmets were formed during the program.

2. Objectives.

The objectives of this program were to determine the feasibility of mass-producing titanium alloy helmets and the optimum commercially available alloy for this application. The following variables were investigated:

a. Titanium alloy chemical composition.

b. Effect of helmet thickness on ballistic performance.

c. Effect of hand mill and continuous rolled sheet on helmet formability.

d. Effect of stress relieving on ballistic performance of formed helmets.

e. Effect of stress concentrations on formed helmets.

3. Helmet Descriptions.

Three types of titanium helmets were developed under this program. The configuration of these helmets was identical to the standard M-1 manganese steel helmet so that they could be worn with the standard nylon helmet liner. The following is a description of the three experimental types and the current standard helmet.

a. Type I - 5Al-2.5 Sn titanium alloy; 0.048-inch nominal thickness; shell weight including paint and hardware, 23 ounces (Figure 1).

b. Type II - 5Al-2.5 Sn titanium alloy; 0.055-inch nominal thickness; shell weight including paint and hardware, 27 ounces.

c. Type III - 5Al-2.5 Sn titanium alloy; 0.078-inch nominal thickness; shell weight including paint and hardware, 38 ounces.

d. Helmet, Steel, Soldiers', M-1, Hadfield steel, 0.039-inch nominal thickness; shell weight including paint and hardware, 38 ounces (Figure 1).

In addition, other titanium alloy helmets were evaluated. Their characteristics are identified in sections 4 and 8.

4. Alloy Selection.

The following considerations were included in selecting the titanium alloy:

a. Commercial availability.

b. Formability in shaping the helmet.

c. Ballistic properties.

The economics involved with the titanium helmet will be an overriding factor in any decision to initiate mass production. Therefore, an alloy was selected that could be mass-produced, thereby permitting large production runs and lower material cost. Several alloys, including the 6Al-4 V alloy and the 5Al-2.5 Sn alloy, were evaluated.

The second requirement for formability has been explored over a period of years on several previous Army sponsored programs

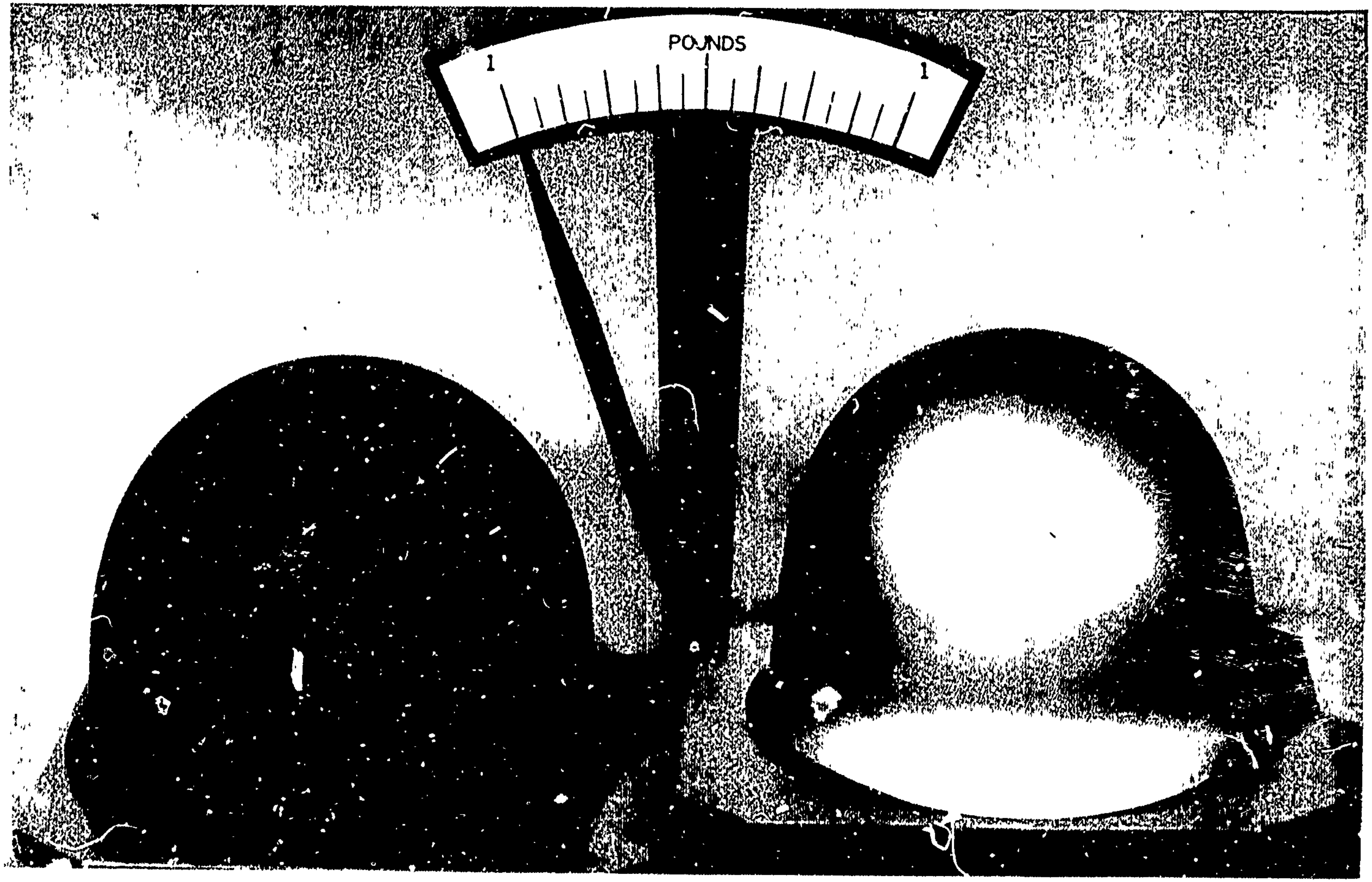

Figure 1. Left: Current Standard Manganese Steel Helmet.
Right: Experimental Type I, Titanium Alloy Helmet.

using the 6Al-4 V and 4Al-3 Mn alloys as well as commercially pure titanium. Both hot, deep-drawing and high-energy-rate forming were evaluated. None of these programs resulted in acceptable titanium helmets.

The alloy selected for the current program had to exhibit good ballistic properties. The 6Al-4 V and 5Al-2.5 Sn alloys were both considered acceptable. However, the 5Al-2.5 Sn was chosen for most of the work, primarily for ballistic advantages; and satisfactory forming procedures were developed.

During development several additional materials were formed with varying degrees of success. Examples of alloy experimentation are as follows:

a. Four helmets were made from commercially pure titanium, grades 50A and 75A.

b. Ten helmets were made from the 6Al-4 V alloy.

c. Three helmets were made from the 4Al-3 Mn complex alloy.

In the formed helmets, the 5Al-2.5 Sn alloy had a slightly better overall ballistic performance than 6Al-4 V.

In addition, Battelle Memorial Institute previously examined seven titanium alloys for use in personnel armor.[4] Based on the results of this study, the 5Al-2.5 Sn alloy has also been selected for fragmentation protective armor vests. However, the best ballistic performance during the Battelle program was achieved by the 4Al-3 Mn complex alloy. As this is an experimental alloy, no attempt has been made to strip-roll the product.

In the course of titanium alloy development, it has become very evident that both chemistry and processing are important in providing optimum ballistic protection and suitability for fabrication. The 5Al-2.5 Sn alloy, with a low oxygen level and moderate iron content, has provided the best combination of good ballistic properties and formability. This alloy conformed to Military Specification MIL-T-9046F. However, from the progress thus far on the 5Al-2.5 Sn alloy, iron content approaching 0.5% maximum has been found to be beneficial to strip-rolling and formability. A maximum oxygen content of 0.12% is desirable for best ballistic performance; however, it is very costly to achieve this oxygen level. A satisfactory compromise between cost and ballistic performance would be 0.18% maximum oxygen. These chemical compositions represent slight modifications to the military specification for the 5Al-2.5 Sn alloy.

Although 5Al-2.5 Sn titanium alloy provides good ballistic performance, there is little doubt that further work in this area will result in improved ballistic performance.

5. Production and Fabrication Techniques.

a. Metal production. The production process for making titanium metal is well documented in available literature. The area pertinent to the helmet program involves hand-mill sheet and continuous rolled sheet. The first sheets formed into helmets were made on hand mills. They were produced from heavy gauge sheets of titanium, which were stacked together and welded into sandwiches between steel cover sheets. The sandwich packs were then cross-rolled to finish gauge, disassembled, and cleaned. The hand-mill product was used initially since continuous strip was not formable when processed conventionally. Because of this, emphasis has been directed to the development of a continuous strip-rolling process specifically for the helmet application. The strip product has greater directionality than hand-mill sheet. However, directionality has not been a problem with the Greer forming process. During the course of this program, much effort has been applied in developing a strip product amenable to the Greer forming technique. An area still being investigated is the effect of a surface macro-structure pattern on the formability of the titanium for helmets. Appendix I covers part of the metallurgical work associated with helmet fractures encountered during the early phase of the program.

b. Fabrication techniques. The Greer process has been referred to by a number of different terminologies such as modified hydro-forming, compression forming, and step drawing. As a number of aspects in the forming technique are novel, existing titles do not descriptively apply. The technique was developed primarily to form titanium fuel bottles for missiles. Greer products has been producing components from difficult-to-form metals for several years using these techniques. The following covers the details of the forming process that are not proprietary:

(1) Fabrication of blanks. The circular blank (16 1/2-inch diameter) of titanium sheet required for forming can be easily stamped from sheet stock, using a conventional mechanical press and a class "A" sheet-metal die. The blanks must be deburred and lubricated prior to forming.

(2) Forming.

(a) The helmets are formed using a four-stage cycle on a conventional hydraulic press. The skills required for forming are typical of those required for conventional draw forming. Tooling costs for the forming operations are comparable to conventional deep-draw tooling.

(b) Stress relieving. Since an intermediate stress relieving operation during the forming cycle results in improved resistance to fragment penetration, the helmets are heated to 1250°F. for two hours after the second forming operation. However, stress relieving is not necessary for the forming of complete helmets. This operation is performed in a conventional, thermostatically controlled furnace.

(3) Trimming. The periphery of the formed helmet can be die-trimmed using a class "A" sheet-metal die and a standard mechanical press.

(4) Deburring. Belt-sanding can accomplish the necessary deburring of the inside and outside peripheral edges of the helmets. The operation can be performed on a conventional belt sander without special tooling.

The unit cost of a titanium helmet will consist of approximately 70% material and 30% for fabrication. Conversely, the Hadfield steel helmet cost consists of approximately 30% for the material and 70% for the fabrication.

Appendix II covers stress analysis of a formed helmet that was performed by the Titanium Metals Corporation of America. The stress analysis was run on an as-formed, unannealed helmet that had several microcracks on one side. The intent was to determine the amount of residual stress and its effect on a completed helmet. The investigator determined that stresses were not evenly distributed nor equal in symmetrically opposite sections, and this was due to variations in forming techniques. The investigator concluded that residual stresses were not high enough to justify an anneal for metallurgical stability alone.

c. Welding. The spot-welding techniques developed for joining the chinstrap hardware to the 5Al-2.5 Sn helmets were straightforward. An essential step in making high integrity spot welds is that the metal be completely clean. The presence of fingerprints, oily films, dust, can grossly degrade the strength of the joint. A Taylor-Winfield 100 K.V.A. spot welder was used. A 150-pound force was applied with 3,400 amps nominal recorded with a Du-trol current monitor, and the electrodes were contoured to fit the helmet. Three spots were made on each clip. The setting for heat control was 70 cycles, and heat time was 12 cycles. Both squeeze time and weld time were controlled by the operator.

d. Chinstrap hardware. The chinstrap hardware used on the types I, II, and III helmets was of standard design. The chinstrap hinges were made from commercially pure titanium grades 50A and 35A. North & Judd Manufacturing Company of New Britain, Connecticut, found that microcracks developed in the tight bends on the 50A and that the more ductile 35A grade was completely satisfactory.

6. <u>Finishing</u>.

Painting and finishing techniques were developed to take advantage of titanium's inherent resistance to corrosion with a minimum addition of weight.

Since a titanium helmet would not be affected by environmental corrosion, there is no reason to apply a primer coat or to paint the inside. Consequently, a technique was used where both inner and outer surfaces of the helmet were anodized for camouflage purposes with paint subsequently applied only to the outer surface. The anodizing process yielded a dull-brown color, added no measurable weight, and provided a base for the final outer coat of paint.

a. <u>Anodizing procedure</u>.

(1) <u>Roughening surface</u>. To achieve a dull-brown color, the outer surface of the hel[illegible]ust be roughened by shot-peening or sandblasting prior to anodi[illegible]

(2) <u>Pickling</u>. After roughening, it is critical to remove iron traces from the helmet surface before anodizing. This is done by pickling the helmet in 15 percent HNO_3, 1 percent HF, and 1 percent $FeSo_4$ solution for 30 seconds at a temperature of 80°F.

(3) <u>Electrolyte</u>. The electrolyte is a 5-percent solution of NaOH in tap water. Other solutions may be used. The main limitation is the exclusion of halogen ions.

(4) <u>Cathode</u>. The cathode is commercially pure titanium with the cathode-to-anode surface area ratio held close to 1.

(5) <u>Anodizing</u>. The anodizing process is done in two steps: the outer surface of the helmet first, and then the inner surface.

Both the current and cell voltage are monitored with the voltage regulated by a large variable resistor. Electrical contact to the helmet is made, the helmets are immersed in the solution, and the voltage is brought to 10.5 volts. Initially, the current is approximately 20 amps, but as the titanium dioxide film forms, the current drops. The final value of the current is about 3 amps.

The desired color of the coating is achieved by controlling both the anodizing voltage and the surface finish of the helmets. Anodizing smooth 5Al-2.5 Sn at 10 volts produces a gold color, but when the surface is roughened and then anodized to 10 volts, the resulting color is dull brown. To consistently produce this color, both the voltage and surface finish must be carefully controlled. A slightly higher voltage will turn the helmet to a red color.

The surface coating achieved by the above process is easily scratched if left unprotected. This shortcoming is of no consequence for the inner surface of the helmet which is anodized nor on the outer surface which is both anodized and painted.

b. <u>Painting procedure</u>. A new paint was specifically developed for the titanium helmet.

(1) The formula of Olive Drab Enamel containing sand was:

(a) Paint* - 1 gallon

(b) #70 Sand - 6 pounds

(c) Mineral spirits - 1/4-gallon.

(2) Application process consisted of:

(a) Spray (exterior only): One wet coat.

(b) Allow paint to set for 20 minutes.

(c) Bake helmet at 250°F. for 45 minutes.

Since the titanium helmet offers a great reduction in weight, one further specification was that the paint and attendant techniques of application contribute minimum weight increase to the helmet. Tests indicated that one coat of the paint mixed with sand met all specifications. Environmental exposure tests have been underway for one year and will continue longer.

7. <u>Ballistic Data</u>.

Table I contains V_{50} ballistic data of the standard M-1 steel helmet and three types of experimental titanium helmets. Table II contains V_{50} ballistic data of titanium alloy helmets that have been stress-relieved. These helmets were tested without the nylon liner. Table III contains helmet V_{50} ballistic data of several different alloys of titanium which were considered under this program. Figure 2 shows the variation in ballistic performance as a function of areal density for the titanium alloys evaluated.

*National Lead Company Paint No. T-15843.

Table I

V_{50} BALLISTIC LIMITS (feet/sec) OF THREE TYPES

OF TITANIUM HELMETS AND M-1 STEEL HELMET*

Missile	Obliquity	M-1 Steel	Type I	Type II	Type III
A	0°	2991	2880	2984	4237
	30°	3410	3385	3573	4700**
	45°	3852	3920	4250**	5600**
B	0°	2070	2040	2262	2533
	30°	2335	2308	2472	2762
	45°	2855	2922	3115	3863
	60°	3220	3224	3420	4550
C	0°	1310	1295	1386	1843
	30°	1613	1441	1558	2024
	45°	1819	1894	1961	2574
	60°	2076	2112	2411	3365
D	0°	1052	1061	1107	1432
	30°	1123	1093	1197	1570
	45°	1174	1101	1206	1714
	60°	1264	1225	1338	1889
E	0°	2757	2680	2792	3610
F	0°	966	1400	1700	2275

*All helmets were tested with standard nylon liners.

**The actual V_{50} could not be determined since the V_{50} was in excess of the maximum velocity obtainable with the test weapon.

Table II

V_{50} BALLISTIC LIMITS OF TITANIUM ALLOY HELMETS

(STRESS RELIEVED) WITHOUT LINER

Type I

Helmet No.	Helmet Weight (oz)	V_{50} (ft/sec)
87	23.7	982
63	22.5	902
47	23.6	992
97	21.9	917
83	22.8	941
79	22.6	930

Average of six V_{50} tests - 945 ft/sec

Type II

206	25.7	1049
140	25.8	1009
138	25.8	1092
307	25.7	1068
204	25.9	1052

Average of five V_{50} tests - 1055 ft/sec

Type III

174	37.2	1583
175	36.9	1565
176	37.8	1556
386	37.5	1566
348	36.5	1578

Average of five V_{50} tests - 1570 ft/sec

M-1*

	40 (max)	900 (min)

*Military Specification MIL-H-1988.

Table III

V_{50} BALLISTIC LIMITS OF TITANIUM ALLOY HELMETS

Alloy Designation	Helmet Weight (oz)	Intermediate Stress Relief*	V_{50} (ft/sec)
6Al-4 V	37.1	Yes	1394
6Al-4 V	38.2	Yes	1450
6Al-4 V	19.2	Yes	844
6Al-4 V ELI	18.2	Yes	827
6Al-4 V ELI	22.0	Yes	1000
6Al-4 V ELI	22.5	Yes	1067
6Al-4 V ELI	20.7	Yes	945
4Al-3 Mn	39.0	No	1699
4Al-3 Mn	38.0	Yes	1750
Commercially Pure 50A	16.7	No	747
Commercially Pure 50A	30.3	No	1064
Commercially Pure 75A	15.5	No	708
5Al-2.5 Sn	21.0	No	883
5Al-2.5 Sn	20.0	No	785
5Al-2.5 Sn	21.3	No	852
5Al-2.5 Sn	21.2	No	889
5Al-2.5 Sn	25.5	No	994
5Al-2.5 Sn	25.5	No	944
5Al-2.5 Sn	36.0	No	1370

*1250°F. for 2 hours.

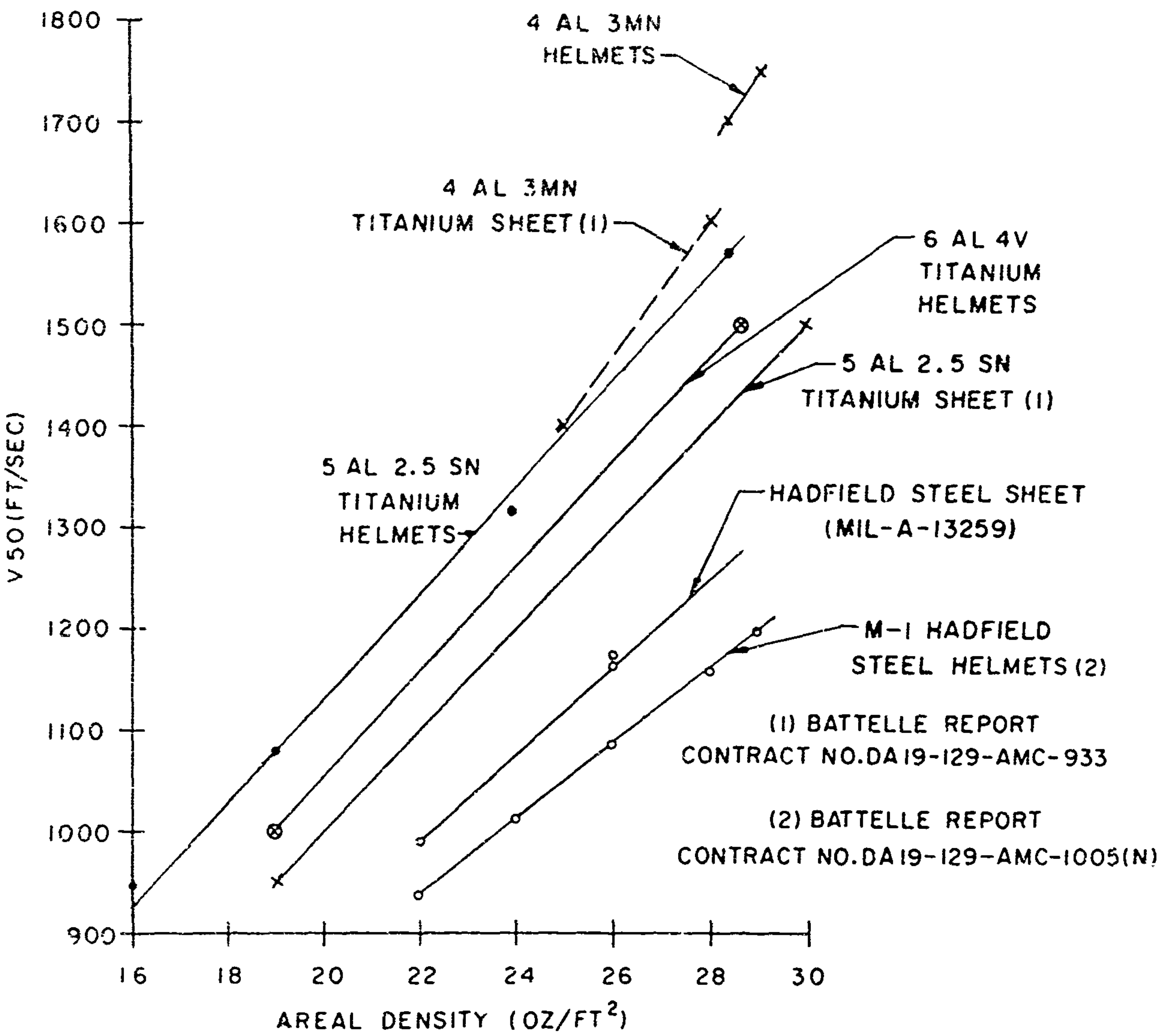

Figure 2. V_{50} Ballistic Limit Plots.
0-Degree Obliquity.

8. Mechanical Property Data.

Table IV shows the thickness variations in the types I, II, and III titanium helmets. All thickness measurements were made with an ultrasonic thickness measuring device. Figure 3 shows the helmet locations where thickness and hardness measurements were taken.

Table V shows typical hardness values of all three types of titanium helmets. Hardness measurements were determined with a Rockwell tester, and all readings are on the "C" scale. There was no difference in hardness levels among the three types of helmets.

Table VI indicates the strength of the spot welds of the chinstrap hinged loop assembly. The strength of these welds was found to far exceed service requirements (100 pounds).

9. Production Cost Estimates.

Table VII contains the estimated production costs for the types I, II, and III titanium helmets. Costs are shown for quantities varying between 100,000 and 1,000,000 helmets. The costs are categorized as material cost, manufacturing cost, and unit cost. This table points out the significant differences between the helmet cost as a function of quantity and amount of titanium in the helmet.

10. Results.

The following results were obtained under this program:

a. A total of 500 titanium helmets were successfully fabricated.

b. Both continuous strip and hand-mill titanium alloy are suitable for helmet fabrication.

c. Commercially pure grades of titanium are ballistically inferior to the 5Al-2.5 Sn and 6Al-4V titanium alloys.

d. The 4Al-3 Mn experimental alloy is ballistically superior to the 5Al-2.5 Sn alloy. However, this alloy is not commercially available at present.

e. The forming operation and intermediate stress relieving improve the ballistic characteristics of the titanium.

f. The thickness uniformity of the titanium helmet is within plus or minus 5 percent of the helmet blank.

Table IV

TYPICAL THICKNESS MEASUREMENTS (inch)

Type I

Helmet Area

Location Point (Zone)	Front	Rear	Right Side	Left Side
1	0.0435	0.0435	0.0435	0.0435
2	0.0440	0.0440	0.0440	0.0440
3	0.0445	0.0465	0.0450	0.0445
4	0.0470	0.0490	0.0490	0.0485
Type II				
1	0.0490	0.0490	0.0490	0.0490
2	0.0510	0.0515	0.0520	0.0510
3	0.0515	0.0535	0.0530	0.0525
4	0.0545	0.0560	0.0555	0.0550
Type III				
1	0.0730	0.0730	0.0730	0.0730
2	0.0750	0.0755	0.0745	0.0750
3	0.0775	0.0780	0.0770	0.0775
4	0.0815	0.0830	0.0810	0.0815

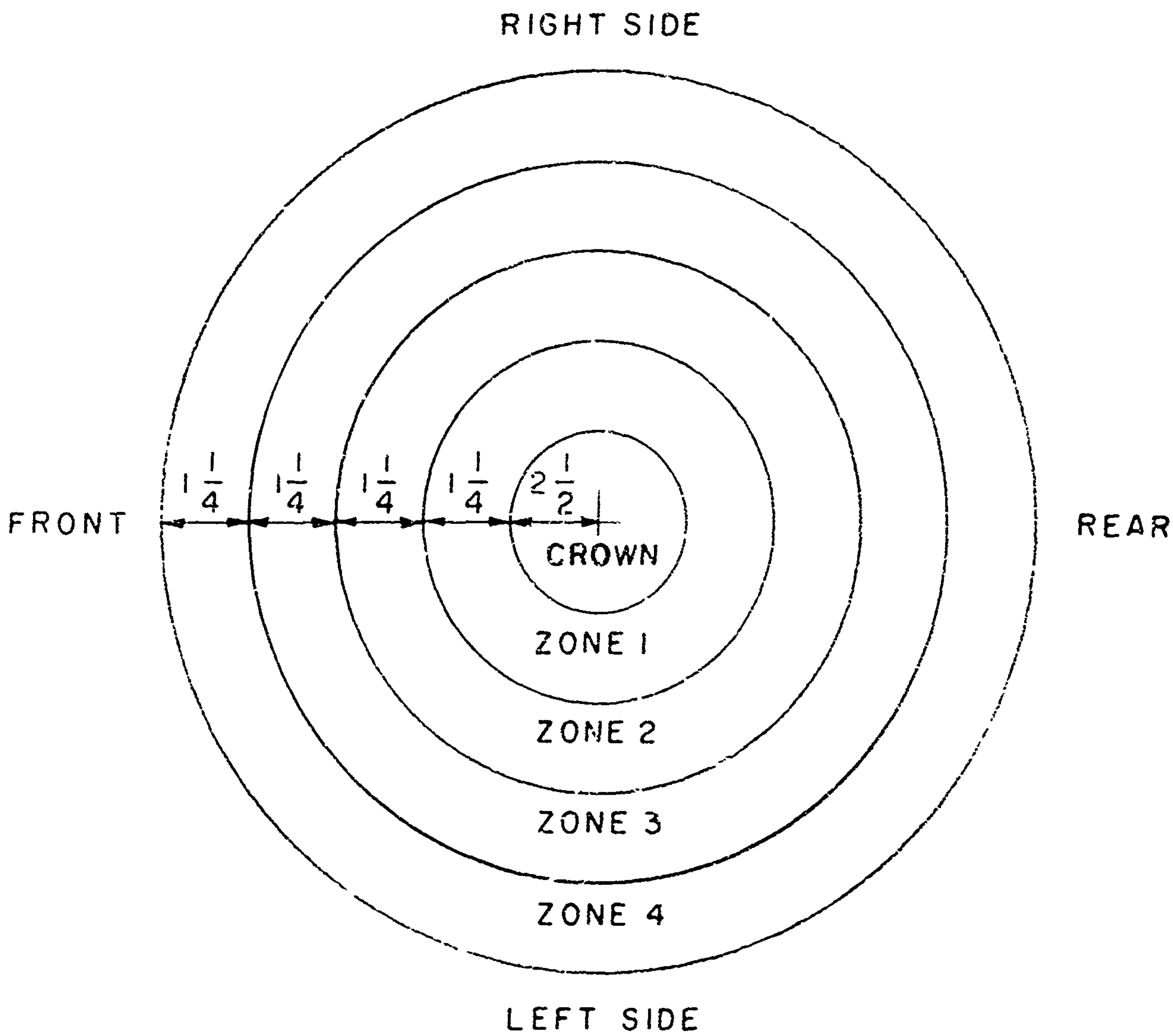

Figure 3. Diagram for Helmet Thickness and Hardness Measurements.

Table V

TITANIUM HELMET HARDNESS MEASUREMENTS (TYPICAL)

(Rockwell "C" Scale)

Location Point (Zone)	Helmet Area			
	Front	Rear	Right Side	Left Side
1	38	39	40	39
2	41	42	42.5	42
3	43	42	42	42
4	41	42	41.5	41.5

Table VI

TENSILE TEST RESULTS OF SPOT WELD CHINSTRAP HARDWARE* (Pounds)

Type I Helmet

Helmet No.	Right Side	Left Side
41	975	900
48	725	770
52	715	795
54	930	885

*Tensile load required to cause failure.

Table VII

ESTIMATED PRODUCTION COSTS OF TITANIUM HELMETS

Quantity of Helmets	Material Cost	Manufacturing* Cost	Unit Cost
		Type I	
100,000	$12.40	$12.56	$24.96
1,000,000	9.30	9.50	18.80
		Type II	
100,000	13.30	12.90	26.20
1,000,000	9.95	9.75	19.70
		Type III	
100,000	20.80	13.6[illegible]	34.47
1,000,000	15.60	10.10	25.70
		M-1	
1,000,000	1.20	2.60	3.80

*Includes fabrication, inspection, testing, packaging, general and administrative, and profit.

g. The control of chemistry and processing parameters at the mill was found to have a significant effect on the formability of the titanium alloy.

h. The Greer process does not contribute to high residual stress in the formed helmet.

Conclusions.

The successful fabrication of 500 titanium helmets conclusively demonstrates the feasibility of mass-producing titanium helmets using the Greer process. The 5Al-2.5 Sn titanium alloy is the best commercially available alloy for the helmet application. The use of titanium alloy in a helmet provides significant reductions in weight with no significant loss in ballistic protection or significant increases in ballistic protection with no increase in weight.

12. <u>References</u>.

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APPENDIX I

INVESTIGATION OF FAILURES OF
5Al-2.5 Sn SHEET FORMABILI_Y

by

H. A. Russell
Titanium Metals Corporation of America

Case Study M-110

March 1967

APPENDIX I

INVESTIGATION OF FAILURES OF 5Al-2.5 Sn SHEET FORMABILITY

SUMMARY

Under subcontract to Titanium Metals Corporation of America, Greer Products, Incorporated, has been successful in forming helmets from titanium. All of the material applied to the program has not exhibited the same formability, and a failure rate of approximately 20 percent has been encountered.

An encompassing laboratory investigation at the TMCA Application Development Center was initiated to determine the cause of failures in the 5Al-2.5 Sn material. A common denominator for all of the failures that were studied was a microstructure exhibiting preferred grain orientation. Material which has formed well in this operation had an equiaxed microstructure. Small variations were noted in chemistry, grain size, and surface finish. However, any subtle effect which these may have had on failure initiation was masked by the microstructural conditions.

RECOMMENDATIONS

Due to the observed detrimental effect on formability of a microstructure that is not totally recrystallized, it is recommended that maximum annealing schedules be specified for material to be applied to helmet production.

Material containing a minimum of 0.25 weight per iron, 7-8 ASTM grain size, and high surface finish quality for drawing should be applied to obtain the optimum forming response with an equiaxed microstructure.

INTRODUCTION

Ballistic fragment penetration tests have indicated that titanium alloy helmets have considerably better resistance than M-1 Hadfield steel helmets. Under previous government contracts[1, 2] deep-drawing of 5Al-2.5 Sn and 6Al-4 V for mass-production of helmets has been shown to be either unsuccessful or economically unfeasible. In the first case 5Al-2.5 Sn could not be drawn by conventional cold-drawing techniques to the required depth without a rupture failure in the crown of the blanks. Drawing of 6Al-4V by conventional techniques was accomplished under another contract; however, forming temperatures in excess of 1200°F. were found to be required. This method was not implemented due to the obvious cost disadvantage attendant with hot-forming.

Under subcontract to Titanium Metals Corporation of America, Greer Products, Incorporated, has been successful in cold-forming 5Al-2.5 Sn into helmets using a processing method similar in principle to hydroforming. It was found, however, that all of the 5Al-2.5 Sn material which was applied to this program did not exhibit the same formability with this process. Failures of material in different stages of the multi-operation process were encountered. An anomaly of these failures seemed to be that individual sheets of material exhibited a "go" or "no-go" behavior. It was the object of this case study to determine the metallurgical or processing variables which led to these failures.

Several titanium alloy grades, 5Al-2.5 Sn, 5Al-2.5 Sn ELI, 6Al-4 V ELI, and commercially pure (Ti-50A), have been formed under the subcontract by Greer Products. Hand-mill sheet and strip product of several thicknesses have been formed and were used in the Army investigation of the ballistic resistance effect. This case study has been concerned with a specific analysis of forming 5Al-2.5 Sn, as the majority of the helmets have been formed from this grade.

Failures in forming may occur for a variety of reasons, many of which may not directly relate to the material itself. Due to the fact, however, that different heats or sheets of material have exhibited a "go" or "no-go" formability behavior in the helmet-forming sequence, the laboratory effort has been focused on discerning material conditions which might explain this anomaly.

MATERIALS AND PROCEDURES

The Application Development Center received several failed helmets from which tensile and metallographic specimens were taken.

Uniform elongation tests were conducted on both as-received, undeformed material, and adjacent specimens which were given stress relief treatments. Uniform elongation was determined by measuring the elongation over 0.400 inch in the reduced section away from the localized yielding near the tensile failure. Small pieces of trim stock, which had been cut from either formed or cracked blanks, were used for tensile tests, surface finish examination, and metallographic examination. The Henderson Technical Laboratory conducted an X-ray diffraction analysis for texture on these specimens.

As several of the initial failures received at the ADC illustrated different stages of the forming process, a quantitative measure of the plastic forming deformation was also made by taking incremental thickness readings of successive forming stages.

The Toronto Process Laboratory conducted several chemical analyses on both formable and unformable material. TPL also conducted an examination on a failed helmet from strip product in order to determine the cause of a visible surface effect associated with the failure.

A residual stress analysis investigation is in progress on a finished helmet. Experimentally mill-processed material has been shipped to Greer for forming. The results of the continuing work will be issued as an addendum to this report when it is completed.

RESULTS AND DISCUSSION

Visual Examination.

The typical failure by cracking in the forming of helmets is shown in Figure 1 through 6. Figures 1, 4, 5, and 6, which are different views of the same helmet, show the normal sequence of the forming operations to achieve the final configuration. It may be noted that in all instances the crack exhibits a 45° orientation to the material edge; this is typical of a shear induced failure.

A few other failed blanks were received at the ADC which contained bulges in the pan stage, or vertical cracks associated with wrinkles at the material edge. The wrinkles occurred during the operation of coining the helmet brim to final configuration. These atypical failures appear to be due to a tooling misalignment, or incomplete pressure application from the die.

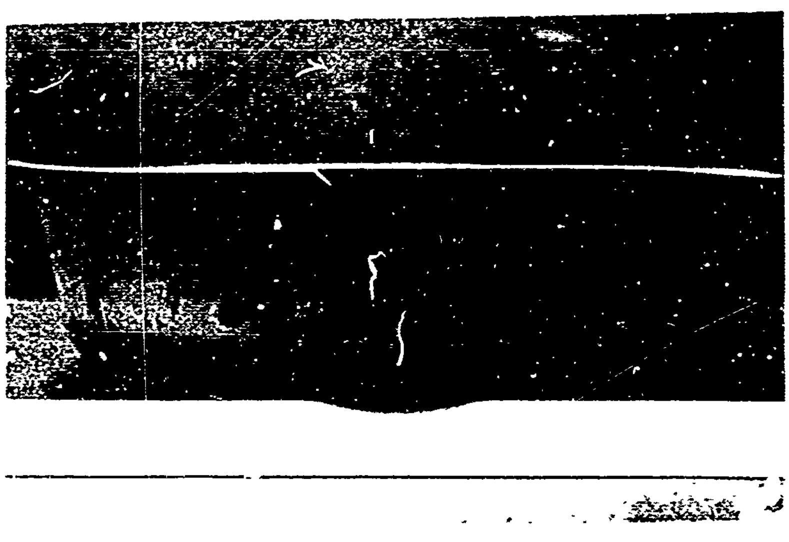
In order to understand the forming process, the incremental thickness measurements of each partially formed blank in the normal sequence are shown in Figure 7. Figure 8 shows the thickness of material along a longitudinal section after the final drawing operation. This operation incorporates the oval shape and starts the brim formation in the helmet. The increased thickening of the edge material with successive forming is readily seen. Although the original thickness of the sheet is not known, it is surmised that very little thinning of the crown material has taken place.

State of Stress.

The state of stress is essentially biaxial resulting from the free sinking of the blank. In the horizontal direction it is an

3/8X

Figure 1. Failure of 5Al-2.5 Sn Sheet in the Initial Forming Operation.



3/8X

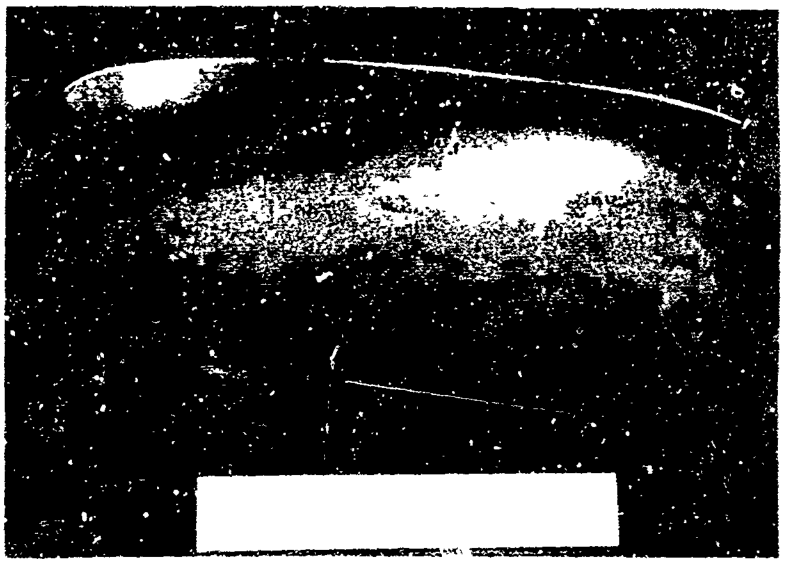
Figure 2. Failure of 5Al-2.5 Sn Sheet in the Early Stages of the Second Forming Operation.

3/8X

Figure 3. Failure of 5Al-2.5 Sn Sheet during the Second Forming Operation.

3/8X

Figure 4. Failure of 5Al-2.5 Sn Sheet Shown at the Completion of the Second Forming Operation.



5/16X

Figure 5. Failure of 5Al-2.5 Sn Sheet Showing Side View of the Third Forming Operation. Note the Scrap Allowance at the Highly Stressed Rear Compound Curve.

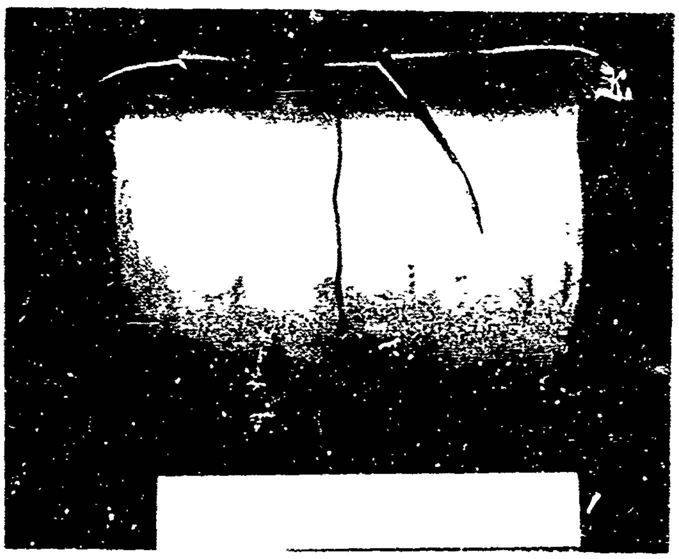


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Figure 6. Failure of 5Al-2.5 Sn Sheet Showing Rear View of the Third Forming Operation.

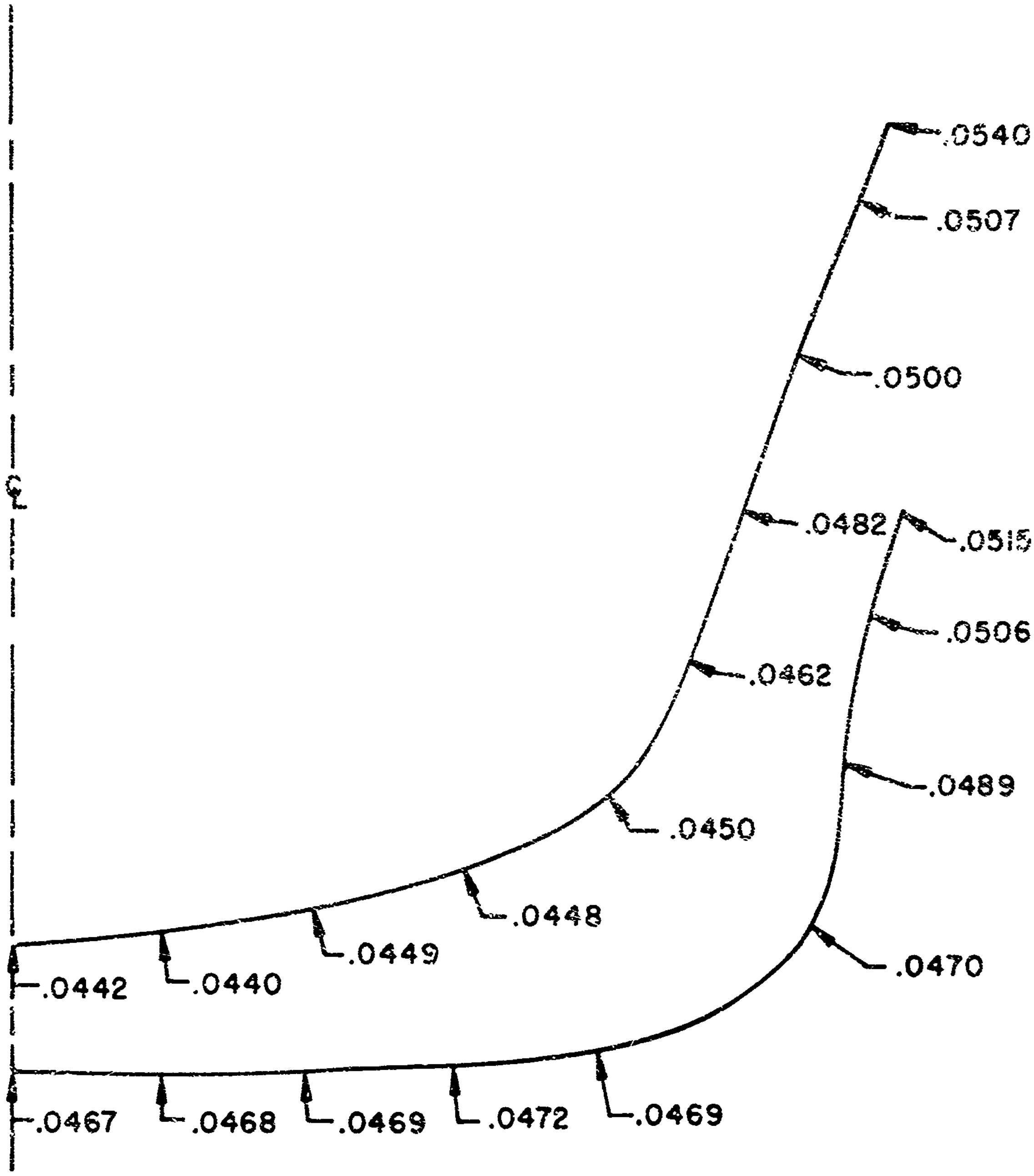


Figure 7. Thickness Measurements of 5Al-2.5 Sn Sheet Shown in the First and Second Operations of the Forming Process.

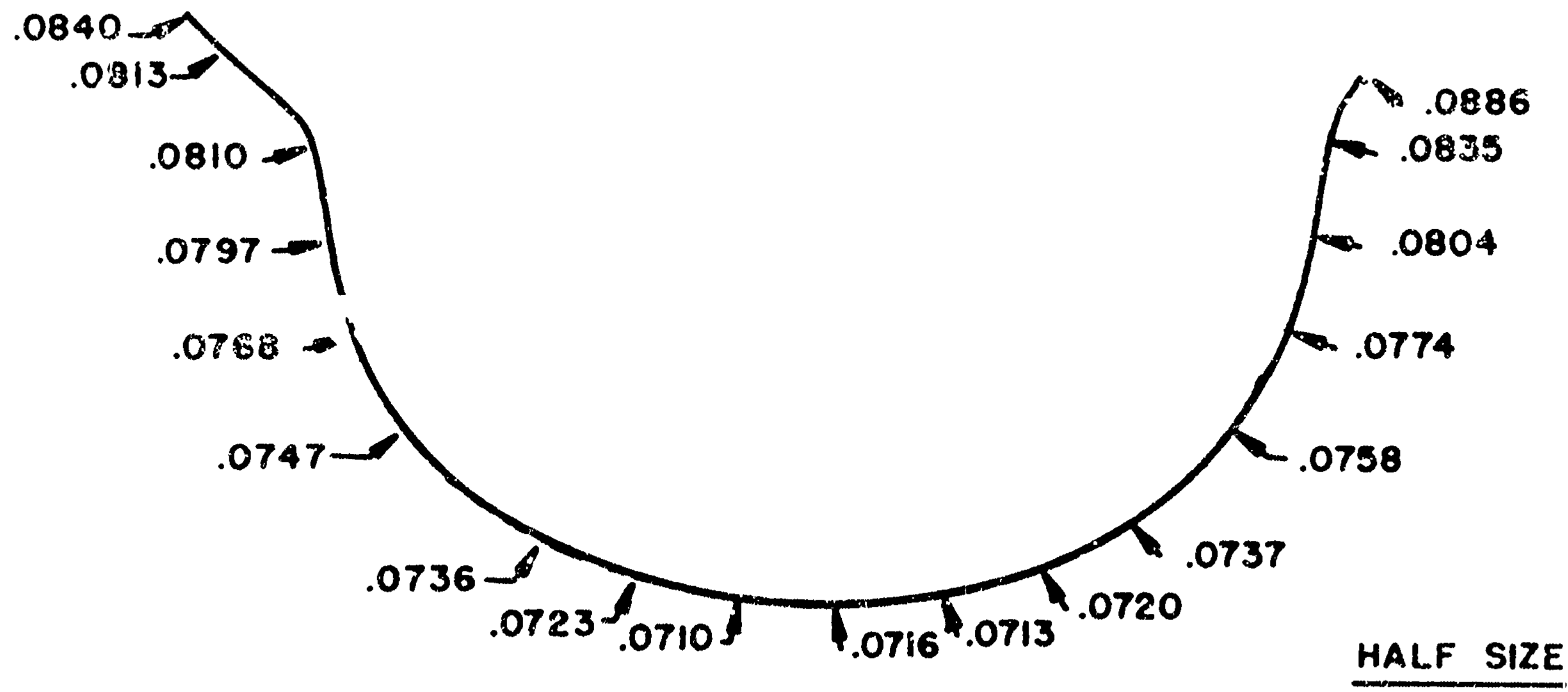


Figure 8. Thickness Measurements of 5Al-2.5 Sn Sheet along a Longitudinal Section of the Operation of the Forming Process.

increasing compressive stress to the edge of the helmet due to the circumferential reduction. In the vertical direction the female die friction and punch load result in a tensile stress additive to the tensile hoop component. The resultant of the circumferential compressive and vertical tensile stresses is a shear stress acting on the diagonal of the two principal stresses. As a large percentage of the material subjected to this operation has formed successfully, it is felt that while this stress condition is contributory to the failure behavior, it is not in itself so excessive as to be the primary cause of cracking in the initial forming stages.

Pole Figure Analysis.

Cracking in the initial stages of forming can be related to both the forming stress and material condition. An X-ray diffraction analysis on material taken adjacent to blanks which had been either formed successfully, or cracked, indicated that for the (0001) basal plane both sheet texture patterns were similar and normal for 5Al-2.5 Sn.

Chemical Analysis.

The chemical analyses of material from failed helmets is shown in Table I. These values are within the normal specification for this alloy. The chemical analyses of a helmet from Heat G-39, which was successfully formed in 36 out of 38 blanks, and the analysis of a sheet of Republic Steel 5Al-2.5 Sn, which was formed with no failures, are also shown. With the exception of the high iron content found in the Republic material, no composition variations of significant magnitude appear to relate to forming failure. Total elongation of Ti-Fe binary alloys decreases with additional iron up to one weight percent. In 5Al-2.5 Sn alloy, however, experience has shown that increased iron content to the range of 0.3 weight percent is generally beneficial in mechanical working.

Metallographic Examination.

The metallographic structure of undeformed sheet taken adjacent to failed helmet blanks is shown in Figures 9 and 10. The grain orientation in the direction of rolling is apparent. The structure of sheet from TMCA Heat G-39 and the Republic sheet are shown in Figures 11 and 12. Both of these specimens contain equiaxed structures.

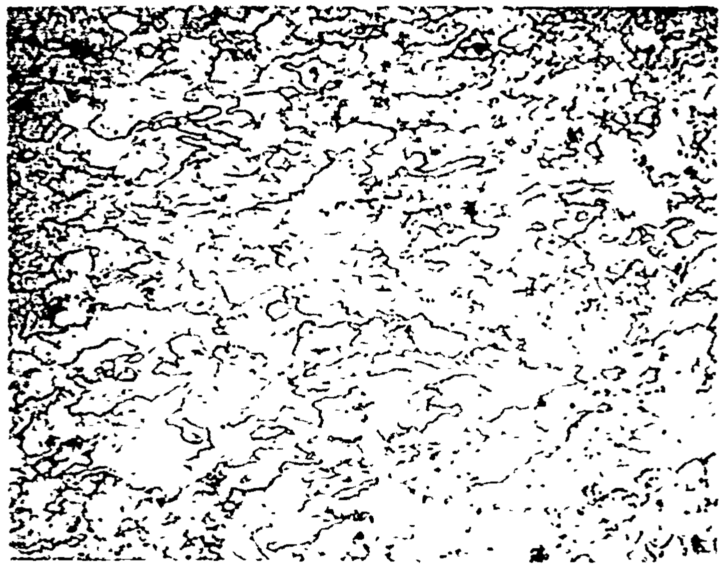
The ASTM grain size of the microstructure of the specimen from Heat G-39 is 7-8. The Republic specimen was slightly more refined and had a grain size of 8 (max.).

From markings and visible surface effects on the failed helmets it was noted that the cracks near the crown of the helmet were always

Table I

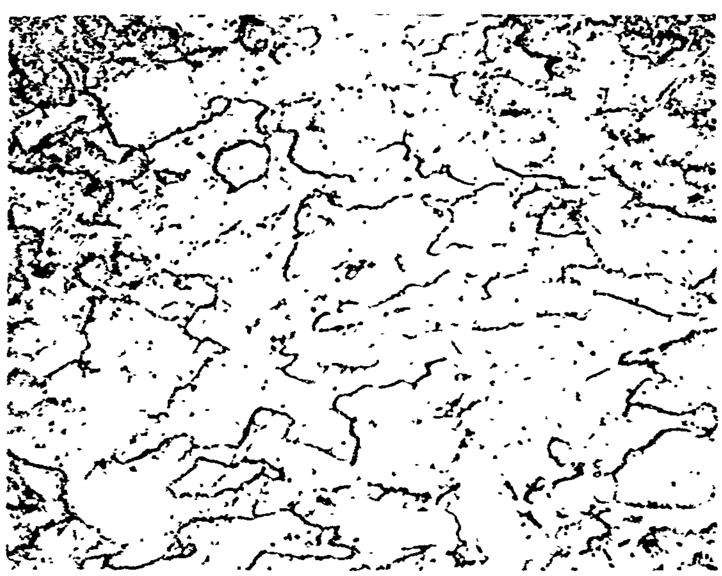
CHEMICAL ANALYSES OF VARIOUS 5Al-2.5 Sn
SHEET MATERIALS USED FOR HELMETS

	Material from Two Failed Helmets		Formable Material	
	TMCA Heat D-8773		TMCA Heat G-39	Republic Material Heat No. Unknown
Element	(Wt %)	(Wt %)	(Wt %)	(Wt %)
Al	5.31	5.33	5.16	5.13
Sn	2.55	2.55	2.71	2.62
H_2	.007	.007	.005	.003
O_2	.169	.186	.166	.133
C	.018	.028	.028	.016
N_2	.011	.012	.028	.027
Fe	.310	.311	.240	.428



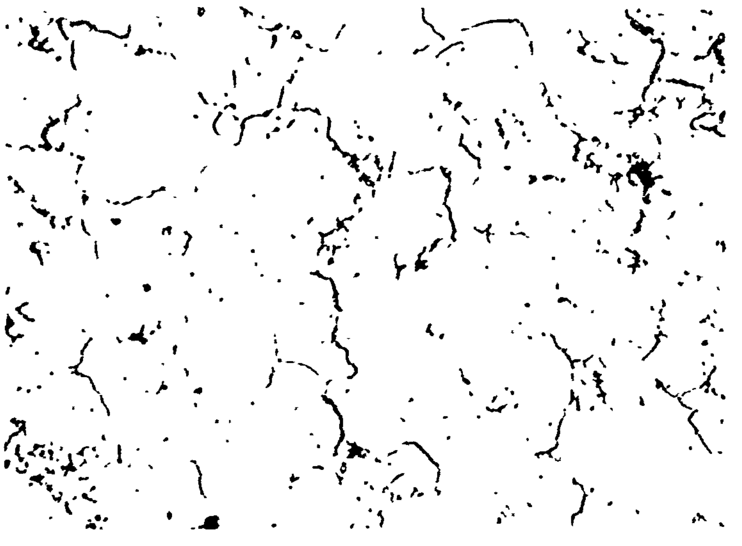
200X

Figure 9. Microstructure of 5Al-2.5 Sn Taken from an Undeformed Section of a Helmet which Failed during the First Operation.



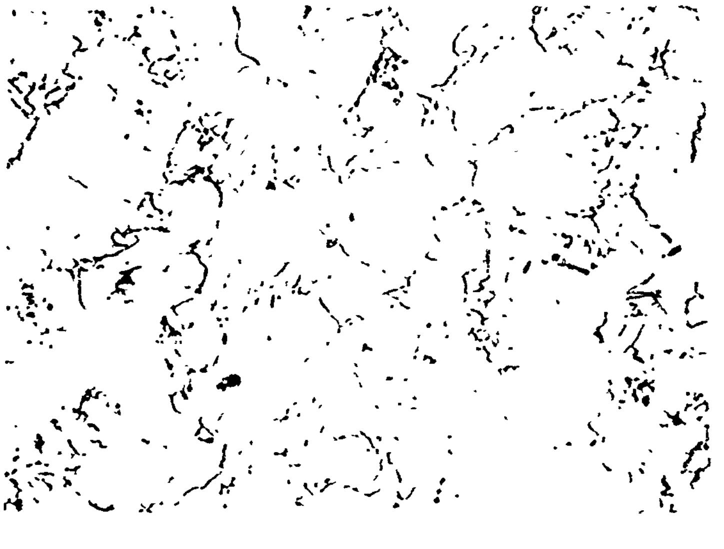
500X

Figure 10. Microstructure of 5Al-2.5 Sn of Specimen in Figure 9 shown at a higher Magnification.



66-141-H 500X

Figure 11. Microstructure of 5Al-2.5 Sn Sheet from Heat G-39.



66-141-G 500X

Figure 12. Microstructure of 5Al-2.5 Sn Sheet Produced by Republic Steel.

parallel, or at small angles, to the rolling direction but at 45° to the rolling direction at the helmet edge. Photomicrographs illustrating the grain orientation at the crown and brim along the crack edge are shown in Figures 13 and 14. Very local plastic deformation is observable; this implies that the failure mode was shear.

Tensile Properties.

Tensile results on both longitudinal and transverse specimens taken from the undeformed bottom of a failed "pan" preform are shown in Table II. Specimens were tested in the as-received, as-received plus pickled, and stress-relieved conditions. The as-received plus pickled specimens had .002 inch removed per surface to reduce any effect of contamination induced by lubrication or handling of the blanks. Stress relief treatments of 1350°F. (1/2 Hr) AC and 1350°F. (4 Hrs) AC were conducted in the laboratory at ADC.

It can be seen from the results that none of the laboratory treatments significantly affected the strengths, total elongation, or uniform elongation. The microstructure of the as-received material was similar to that shown in Figures 9 and 10. From the structure, it was deduced that the sheet had received the minimum time internal specification anneal at the mill.

The microstructures of the stress relieved specimens are shown in Figures 15 and 16. It may be noted that partial recrystallization has occurred after this treatment, although the degree of recrystallization did not significantly differ for the two time periods investigated. The tensile data of Table II indicates a slight decrease in strength levels with these treatments; however, the short time exposure period may have led to slightly deleterious elongation behavior.

All of the uniform elongation data are acceptable and thus do not suggest that the failures have occurred due to the lack of material ductility, or that further stress relief treatments on as-received material would improve its formability characteristics.

In order to get a qualitative value for the effect of the laboratory thermal treatments on texturing, $\overline{R}$ values were calculated from dimensional measurements of the tensile specimens. $\overline{R}$ is a parameter which relates the strength through the thickness to that in the plane of the sheet.

As shown in Table II, the $\overline{R}$ values did not show any significant change with the laboratory stress relief treatments used. This implies that the crystallographic texture was not changed.

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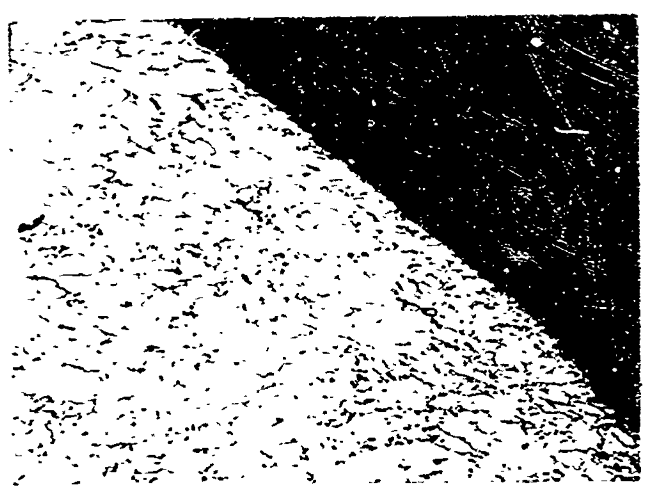
Figure 13. Microstructure of 5Al-2.5 Sn Taken along Failed Edge near the Crown of a Helmet. Note Low Angle between Grain Orientation and Crack Edge.



66-141-A 200X

Figure 14. Microstructure of 5Al-2.5 Sn Taken from Same Helmet as Above Showing Failed Edge near the Helmet Brim. Note 45° Angle between Grain Orientation and Crack Edge.

Table II

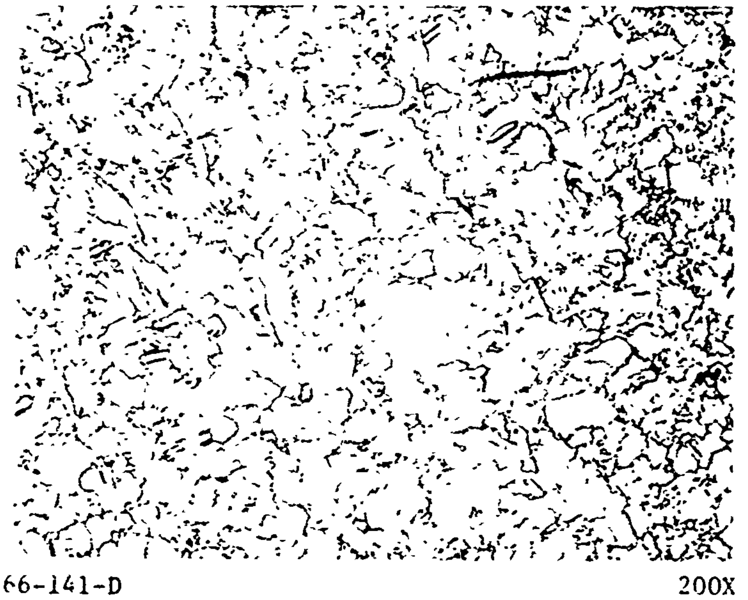
TENSILE PROPERTIES OF 5Al-2.5 Sn SHEET
FROM FAILED PARTIALLY FORMED HELMET

Specimen Direction	0.2% YS (Ksi)	UTS (Ksi)	% Elong	% Uniform Elong	$\bar{R}$ Value
		As-received in the Pan Stage			
L	123.2	138.5	1[illegible].0	10.2	0.503
L	122.5	138.1	15.0	11.7	0.640
T	131.7	146.5	16.0	9.3	1.097
T	132.5	147.3	14.5	9.0	1.280
		As-received + Pickled .002" per Surface			
L	122.5	139.0	16.0	11.5	-
L	124.0	138.8	16.0	10.3	-
T	132.8	146.7	14.5	9.0	-
T	131.5	145.9	15.5	9.0	-
		As-received + Laboratory Stress Relief 1350°F. (1/2 Hr) AC			
L	120.4	137.1	12.0(1)	8.8(1)	0.582
L	119.9	137.5	13.0	10.4	0.461
T	129.8	144.1	15.0	8.5	1.345
T	130.5	145.3	16.0	10.0	0.973
		As-received + Laboratory Stress Relief 1350°F. (4 Hrs) AC			
L	120.5	136.6	15.0	12.4	0.491
L	120.9	136.8	17.0	11.8	0.540
T	129.9	145.7	17.0	9.5	1.671
T	128.0	145.0	14.0	9.3	1.473

(1) Broke at Scribe Mark.

66-141-C 200X

Figure 15. Microstructure of 5Al-2.5 Sn Sheet as Shown in Figure 9 after 1350°F. (1/2 Hr) AC Laboratory Stress Relief.



66-141-D 200X

Figure 16. Microstructure of 5Al-2.5 Sn Sheet as Shown in Figure 9 after 1350°F. (4 Hrs) AC Laboratory Stress Relief.

$\overline{R}$ values of above 3.0 have been considered to indicate significant texture strengthening.[3] These data do not show that this condition was found in this sheet material from failed helmets.

Intermediate stress relief treatments on partially formed blanks have been used with some success by Greer; however, the time parameters used reportedly vary with the "feel" of the first forming stage. It is felt that this technique may be beneficial on marginal material for the process, but that its implementation under the present conditions is not recommended due to the attendant contamination problems which may result from the elevated temperature exposure in air with the presence of residual lubricants.

Tensile tests were run to compare formable and unformable material. Trim stock taken adjacent to formable and unformable blanks at Greer Products was sufficient to machine 45° direction specimens. Longitudinal and transverse specimens from the formable Republic sheet were tested. Unformable strip product was tested in the longitudinal, transverse, and 45° directions.

Table III shows the comparison of tensile properties from formable and unformable material. Although the strengths are slightly higher in the formable material, both the total elongation values and uniform elongation values are also higher. The higher ductility values confirm the forming response. The calculated $\overline{R}$ values show some variance but do not delineate a crystallographic difference.

The tensile data from the Republic sheet material exhibit no significantly informative properties as presented in Table IV. The strengths are somewhat lower, but no increase in ductility is shown. $\overline{R}$ is higher, but the increase is not substantial.

Tensile tests were performed on specimens from strip product material which had failed in forming. Data from these tests are shown in Table V.

This material exhibited preferred grain orientation. The test results show that it responded quite anisotropically to tensile stress. A photograph of the failed specimens, Figure 17, reveals that the fracture in each direction occurred by a different mode. The most significant finding was that the 45° specimens failed by total shear in the rolling direction. Due to the localized necking, a biaxial stress field was acting in the region of the fracture. This is the type of stress field which is imposed during the forming process, as explained earlier.

Table III

TENSILE PROPERTIES OF FORMABLE AND UNFORMABLE
5Al-2.5 Sn SHEET MATERIAL USED FOR FORMING HELMETS

Test Direction	0.2% YS (Ksi)	UTS (Ksi)	% Elong	% Uniform Elong	$\bar{R}$ Value
		Unformable			
45°	122.6	131.6	18.0	10.0	2.84
45°	125.1	133.8	17.5	10.7	1.18
		Formable			
45°	126.2	133.5	21.0	11.0	2.74
45°	126.6	133.8	20.0	15.7	1.41

Table IV

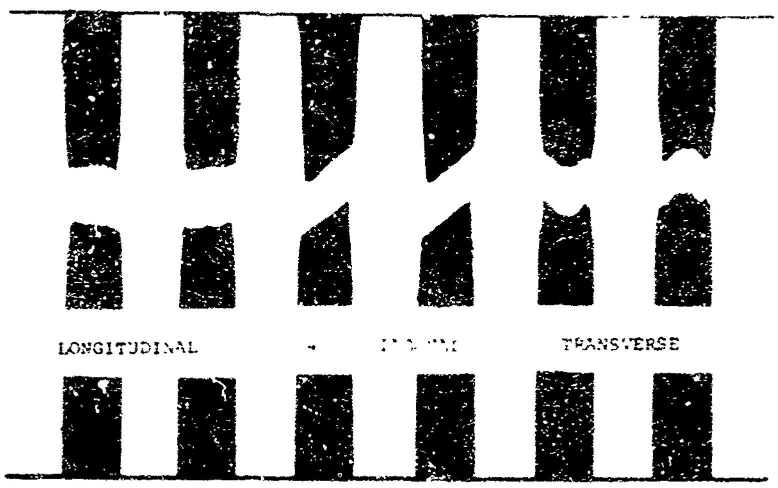
TENSILE PROPERTIES OF REPUBLIC STEEL
5Al-2.5 Sn SHEET USED IN FORMING HELMETS

Test Direction	0.2% YS (Ksi)	UTS (Ksi)	% Elong	% Uniform Elong	$\bar{R}$ Value
L	114.1	127.8	15.0	10.8	1.85
L	123.7	131.5	15.0	10.8	1.55
T	119.7	131.2	17.0	8.8	3.16
T	128.1	137.8	15.0	8.3	2.92

Table V

TENSILE PROPERTIES OF 5Al-2.5 Sn STRIP
PRODUCT WHICH FAILED TO FORM HELMETS

Test Direction	0.2% YS (Ksi)	UTS (Ksi)	% Elong	% Uniform Elong	$\bar{R}$ Value
L	119.6	142.5	15.0	10.2	1.22
L	120.1	142.4	15.0	10.4	1.12
45°	122.1	127.9	15.0	9.7	3.95
45°	121.4	127.7	15.5	8.8	3.47
T	130.5	142.5	13.5	8.9	1.95
T	130.6	142.2	14.0	9.9	1.61



5/8X

Figure 17. Tensile Specimen from 5Al-2.5 Sn Strip Product Exhibiting Variation in Fracture Mode with Test Direction.

Surface Condition Examination.

A surface condition analysis was run on the small pieces of trim stock previously mentioned as representative of good and bad material. The strip chart recordings of the surface roughness are shown in Figures 18 and 19. These charts were developed by traversing across the rolling direction in order to measure the obvious surface effect of the grind lines in these hand-mill sheets. This analysis was conducted with a Surfindicator manufactured by Standard Gage Company. The vertical scale is 16.6 microinches per division. Both samples contained a maximum surface variation on the order of 190 microinches. The horizontal magnification is 2250X. The surface RMS for the formable material was 36, and the unformable material measured 34 RMS. Again, the surface roughness and orientation can be related to the failure initiation, without being the exclusive cause.

The orientation of a surface effect relative to an initiation of a crack is shown in Figure 20. This picture illustrates residual die material trapped in the crack. The crack is parallel to adjacent surface effects in t e helmet which was formed from strip product. As strip does not in..tially contain these lines, similar to grind lines in hand-mill sheet, the helmet was forwarded to the Toronto Process Laboratory for examination. Their conclusion was that the lines were not residual grind lines from early stage processing. or marks due to transformed beta bands, but merely bands due to grain orientation effects. A photomicrograph of this material is shown in Figure 21. The microstructure of the strip is quite similar to that shown before as the as-received structure of failed hand-mill sheet helmets.

As shown in Figure 22, crack initiations in the crown area of helmets formed from hand-mill sheet have been seen. From these observations it is deduced that the forming failures in the initial stages are due to attendant shearing stresses acting parallel to surface effects and longitudinal boundaries of oriented grains. Longitudinal grain boundaries of oriented material provide a line of least resistance for crack initiation due to shear. These cracks initiate at the point of maximum shear, mid-longitudinally in the helmet, and propagate intragranularly to the helmet edge in the typical 45° configuration.

It has been shown that of the variables examined during this investigation an equiaxed microstructure was most often associated with resistance to shear cracking. Variations in chemistry, grain size, and surface condition were not sufficiently great to be cited as a primary cause of the forming failures. Processing schedules and treatments at the mill should therefore be specified on material

NOT

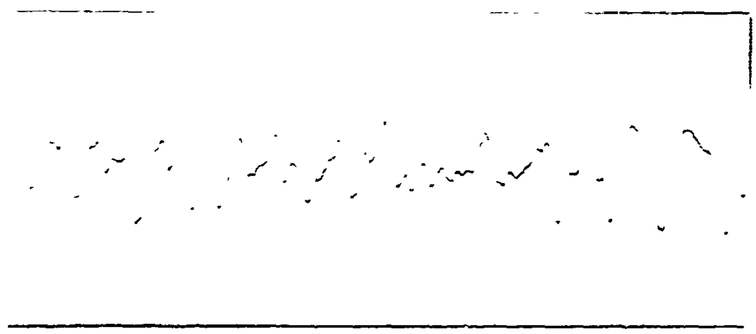


Figure 18. Surface Profile of Unformable
5Al-2.5 Sn Hand-Mill Sheet.

Vertical Scale 16.6 Microinches/Division.
Horizontal Magnification 2250X. 34 RMS.

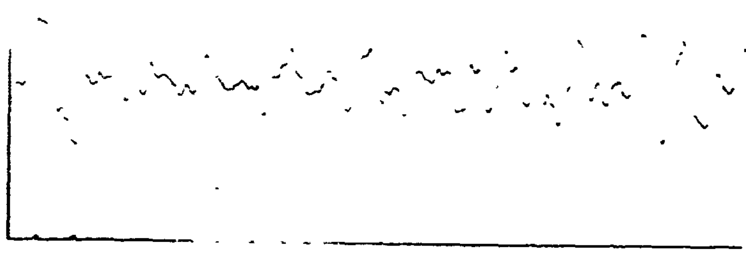
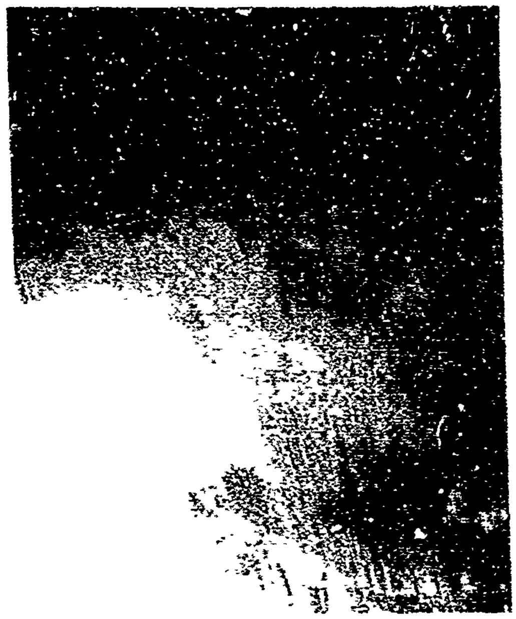


Figure 19 Surface Profile of Formable
5Al-2.5 Sn Hand-Mill Sheet.

Vertical Scale 16.6 Microinches/Division.
Horizontal Magnification 2250X. 36 RMS.



1X

Figure 20. Initiation of a Crack Parallel to the Rolling Direction in 5Al-2.5 Sn Strip Product.

100X

Figure 21. Microstructure of 5Al-2.5 Sn Strip Product from Helmet Shown in Figure 20.

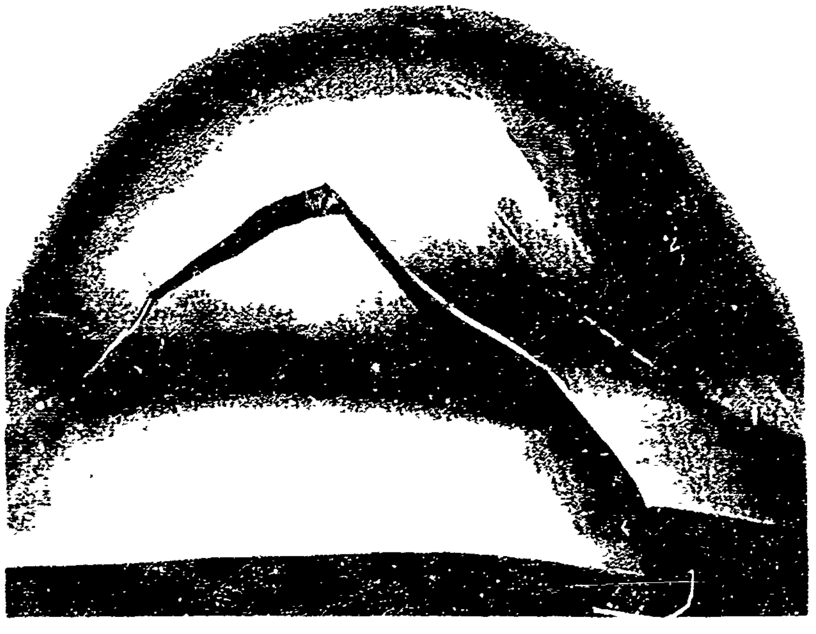


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Figure 22. Failed Helmet Showing Crack Initiations near the Helmet Crown in Hand-Mill Sheet Material.

supplied for this application which will provide a fully recrystallized, equiaxed microstructure. Additionally, however, material containing a minimum of 0.25 weight percent iron, 7-8 ASTM grain size, and high surface finish quality for drawing should be applied to obtain the optimum forming responses.

References:

1. Memorandum on Evaluation of the Deep Drawing Characteristics of A-110AT Alloy for Helmet Application. Titanium Metallurgical Laboratory, Battelle Memorial Institute. April 4, 1957.

2. Deep Drawing of Titanium Alloy Helmet Shell 6Al-4 V. Final Report, Contract DA-19-129-QM-1430, Project 7-80-05-001. Thompson-Ramo-Wooldridge, Incorporated. September 30, 1960.

3. Hatch, A. J., Texture Hardening of Titanium Alloys: Evaluation of Commercially Produced Sheet. Henderson Technical Laboratories, Progress Report No. 1, Project 48.5. March 5, 1963.

Acknowledgment is also made for the chemical and strip product analyses conducted under K. C. Fredley at the Toronto Process Laboratory, and the X-ray diffraction texture analysis conducted by the Henderson Technical Laboratory.

APPENDIX II

RESIDUAL STRESS ANALYSIS OF 5Al-2.5 Sn FORMED HELMET SHELLS

by

G. C. Kraft and M. L. Greenlee
Titanium Metals Corporation of America

Case Study M-110

October 1967

APPENDIX II

RESIDUAL STRESS ANALYSIS OF 5Al-2.5 Sn FORMED HELMET SHELLS

INTRODUCTION

The original report on the subject Case Study investigation, dated March 1967, mentioned an experimental stress analysis being performed on a formed 5Al-2.5 Sn helmet to determine qualitatively the residual stresses remaining after the cold forming operations. This addendum to the original report records results of the analysis and includes details of the experimental technique.

EXPERIMENTAL PROCEDURES

The qualitative residual stress analysis was performed on the finished 5Al-2.5 Sn helmet by the use of strain gage rectangluar rosettes. These were M&M Type EA-06-125RA-120 rosettes with each of the three gages having a resistance of 120 ohms and a gage factor of 2.70 or 2.95. Individual gage factors were used for all calculations.

Twelve strain gage rosettes were installed on the finished helmet around the brim, mid-radial, and crown areas on both the inside and outside surfaces. Representative locations are shown in Figure 1. Some were oriented parallel with, and others transverse to, the rolling direction. In some areas a rosette was placed on the inside surface directly below and in the same position as the rosette on the outside surface. The initial rosette readings were taken on a Baldwin Type 120 strain indicator; these were recorded as maximum residual stress readings.

In order to obtain partial elastic relief, the helmet was cut into several sections. Each area containing a rosette was then trimmed to a small coupon about 1-1/2 inches square. These were kept uniform in size and shape, as illustrated in Figure 2.

Readings for each coupon were then taken on the strain indicator and subtracted from the initial strain readings. This gave strain values for each gage, e_1, e_2, and e_3, which were substituted into the appropriate analytical equations to obtain a partial as well as a comparative interpretation of the residual stresses present after forming.

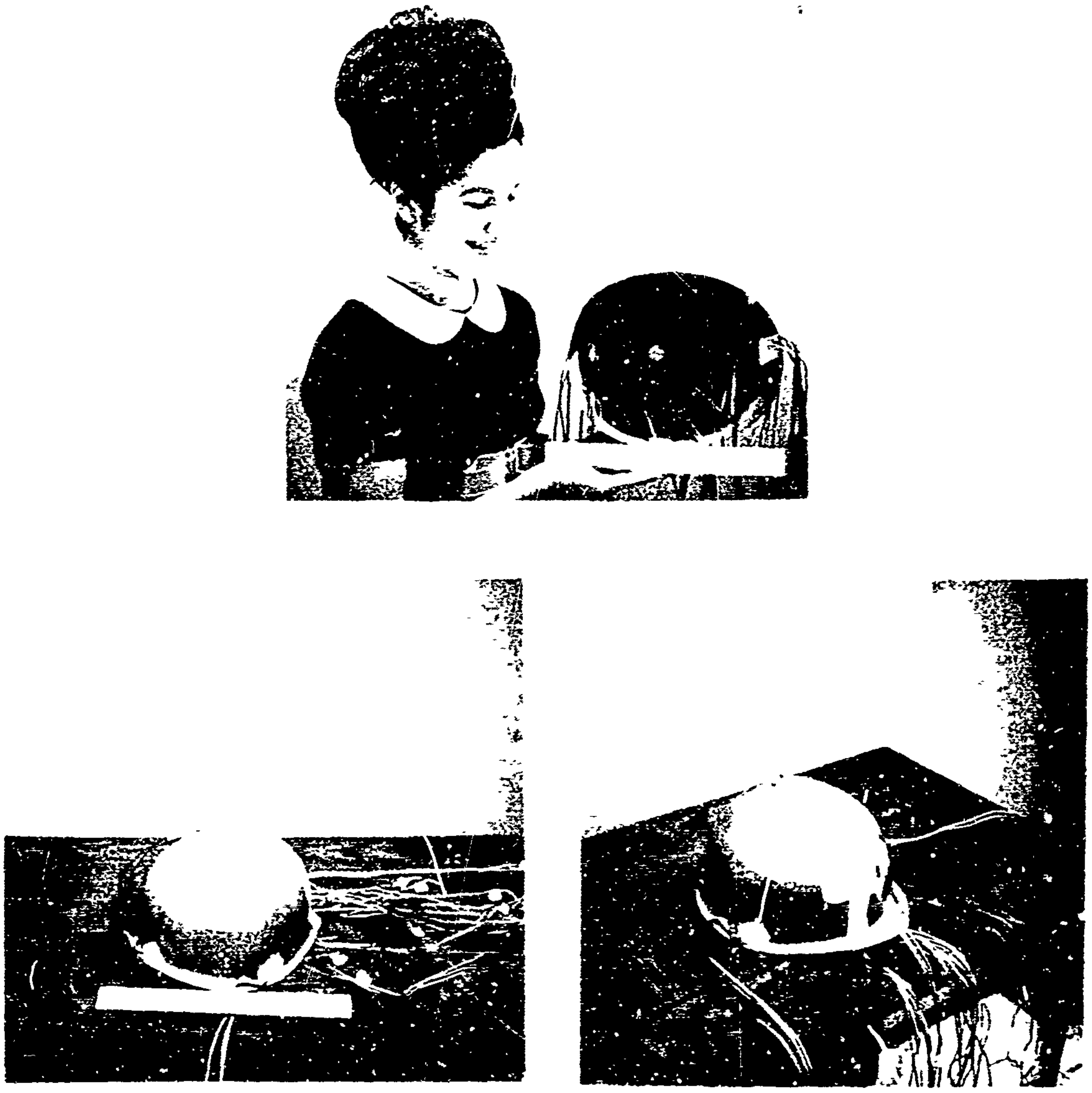

Figure 1. Views of Finished Helmet with Strain Gages Mounted on Inside and Outside Surfaces.

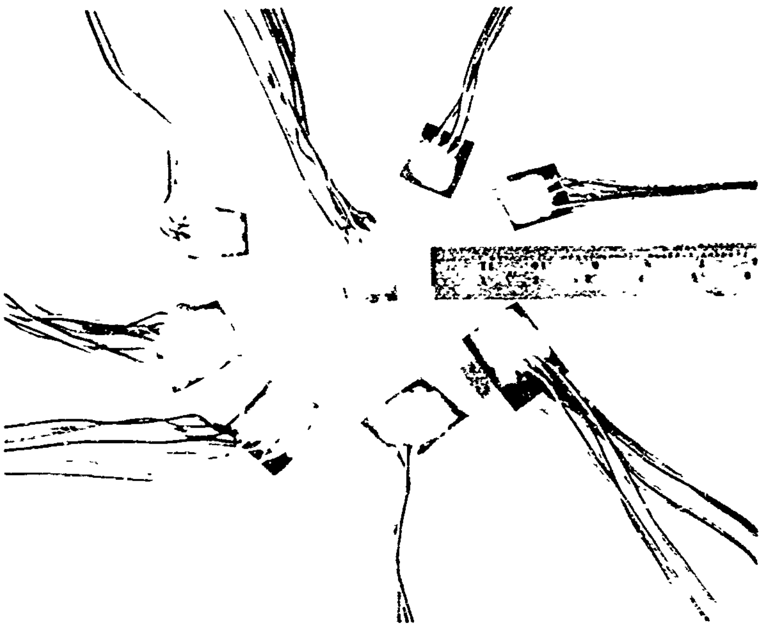

Figure 2. Coupons with Strain Gage Rosettes after Cutting from Helmet.

RESULTS AND DISCUSSION

Results of calculations to determine maximum and minimum principal stresses at the various locations indicated in Figures 3 and 4 are listed in Table I according to gage location. In order to determine the true maximum and minimum stress, a coupon would have to be infinitely small for total stress relief. Therefore, the values shown should be considered only as approximately the true values. In accordance with standard terminology, negative stress values indicate compression, and positive values indicate tension.

When considering the data, it should be kept in mind that the drawing operation requires overforming in order to achieve the proper contour in the finished helmet. Therefore, upon removal from the forming dies, some elastic recovery occurs. Thus, the values shown do not approach the yield strength for the material as might be expected.

The values shown in Table I and Figures 3 and 4 show a range of maximum stresses from 43,100 psi in compression at the inside back brim region (Gage F) to 55,000 psi in tension at the outside left brim location (Gage G).

Considering the location where the highest residual stresses were observed, location G, maximum and minimum principal stresses of 55,000 and 20,000 psi, respectively, were noted. These stresses, both being positive, correspond to a maximum residual shear stress of 17,500 psi as illustrated in Figure 5.

Assuming that the Von Mises, or distortion-energy, theory would predict the limiting stresses for failure of the helmet, the following equation can be used to judge the significance of the above-mentioned principal stresses.

$$T_{YS} = \frac{1}{\sqrt{2}} [(T_1-T_2)^2 + (T_2-T_3)^2 + (T_3-T_1)^2]^{1/2}$$

The theory states that if the right side of the equation is less than the uniaxial yield strength in tension, yielding will not occur. In the present case a state of biaxial stress exists; that is, stresses in the thickness direction may be assumed to be zero. Therefore, T_3 in the above equation is zero, and substitution of 55,000 and 20,000 psi for T_1 and T_2 results in a value of 48,100 psi. This stress is considerably below the yield strength for 5Al-2.5 Sn.

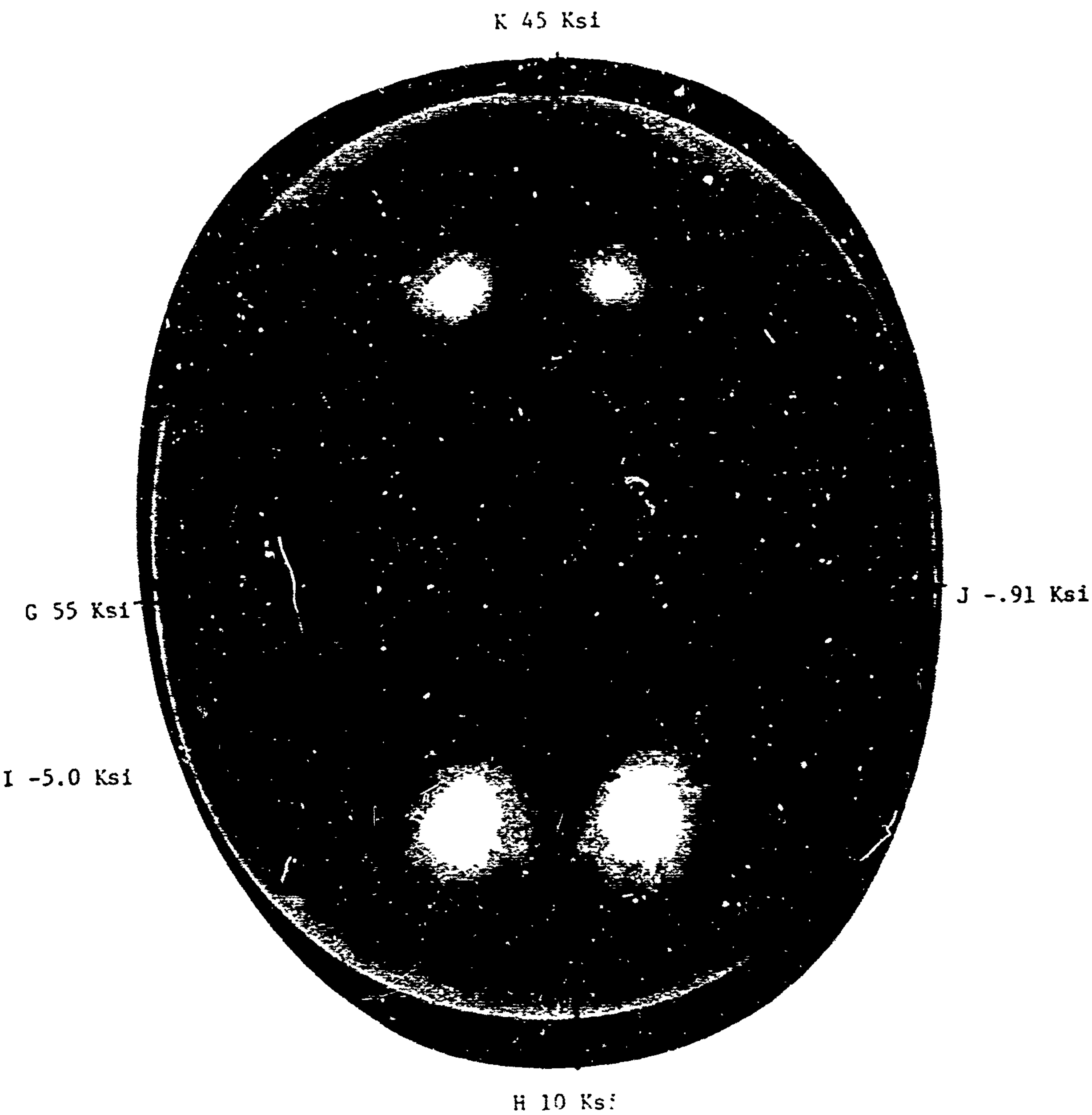

Figure 3. Outside View of Helmet illustrating Position of Strain Gage Rosette.

(Values Represent Maximum Normal Stress in Ksi.)
Arrow Indicates Rolling Direction.

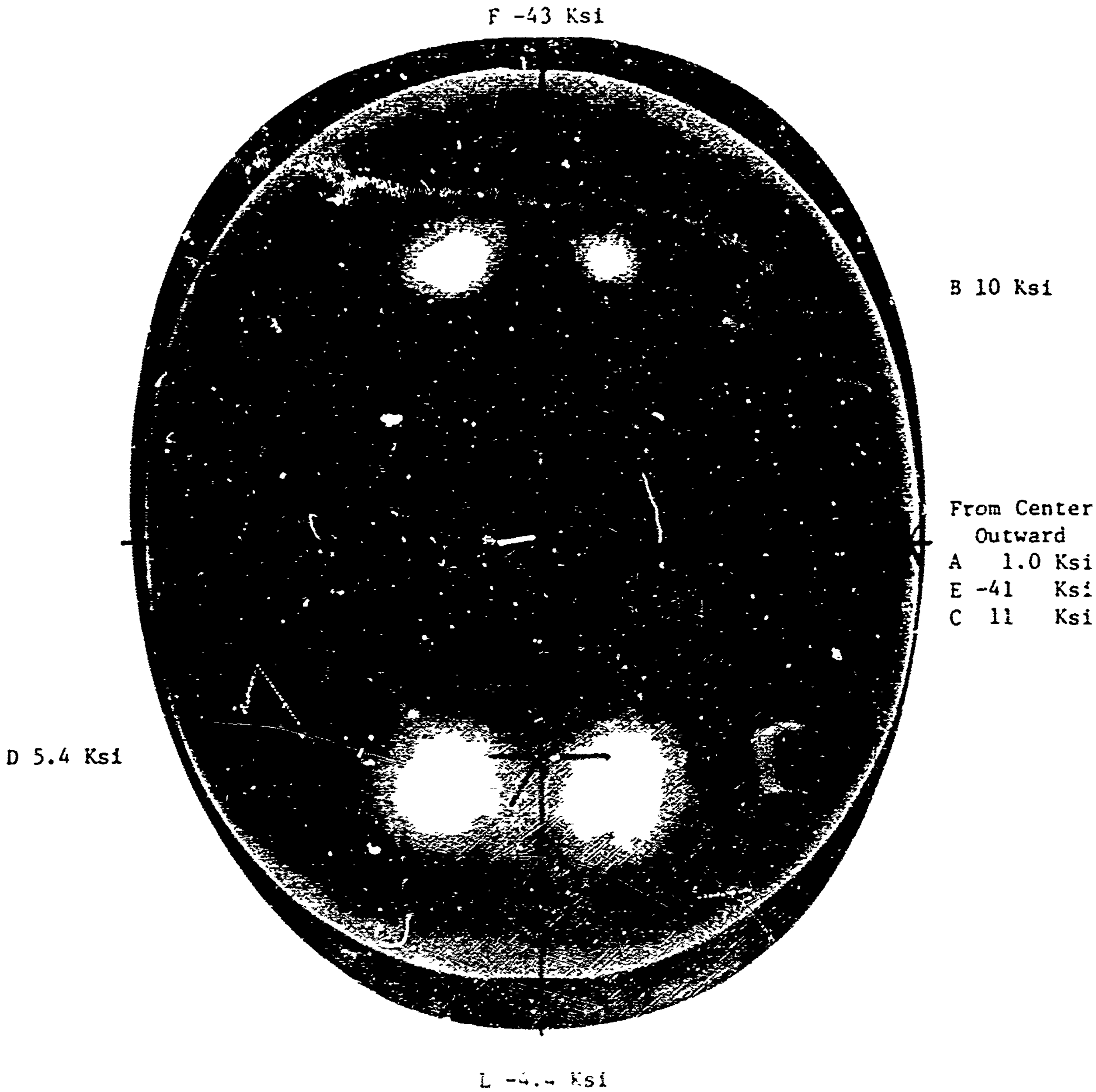

Figure 4. Location of Strain Gage Rosettes on Inside Surface of Helmet as Viewed from Above Crown.

(Values Represent Maximum Normal Stress in Ksi.)
Arrow Indicates Rolling Direction.

Table I

RESIDUAL STRESSES REMAINING AFTER FORMING OF 5Al-2.5 Sn HELMET

Gage	Position	Principal Stresses T_1 (Max) Ksi	T_2 (Min) Ksi
A}	Inside Crown	1.0 }	.10
J	Outside Crown	- .91	-11.0
I}	Outside Mid-Radial Front	- 5.0 }	- 8.1
D	Inside Mid-Radial Front	5.4	- 3.2
B	Inside Mid-Radial Back	10.0	1.9
E	Inside Mid-Radial Right	-41.0	-49.0
L}	Inside Front Brim	- 4.4 }	-16.0
H	Outside Front Brim	10.0	- 1.0
C	Inside Right Brim	11.0	10.0
G	Outside Right Brim	55.0	20.0
F}	Inside Back Brim	-43.0 }	-65.0
K	Outside Back Brim	45.0	27.0

Brackets Indicate Gages Located on the Same Area, Positioned Identically Inside and Outside.

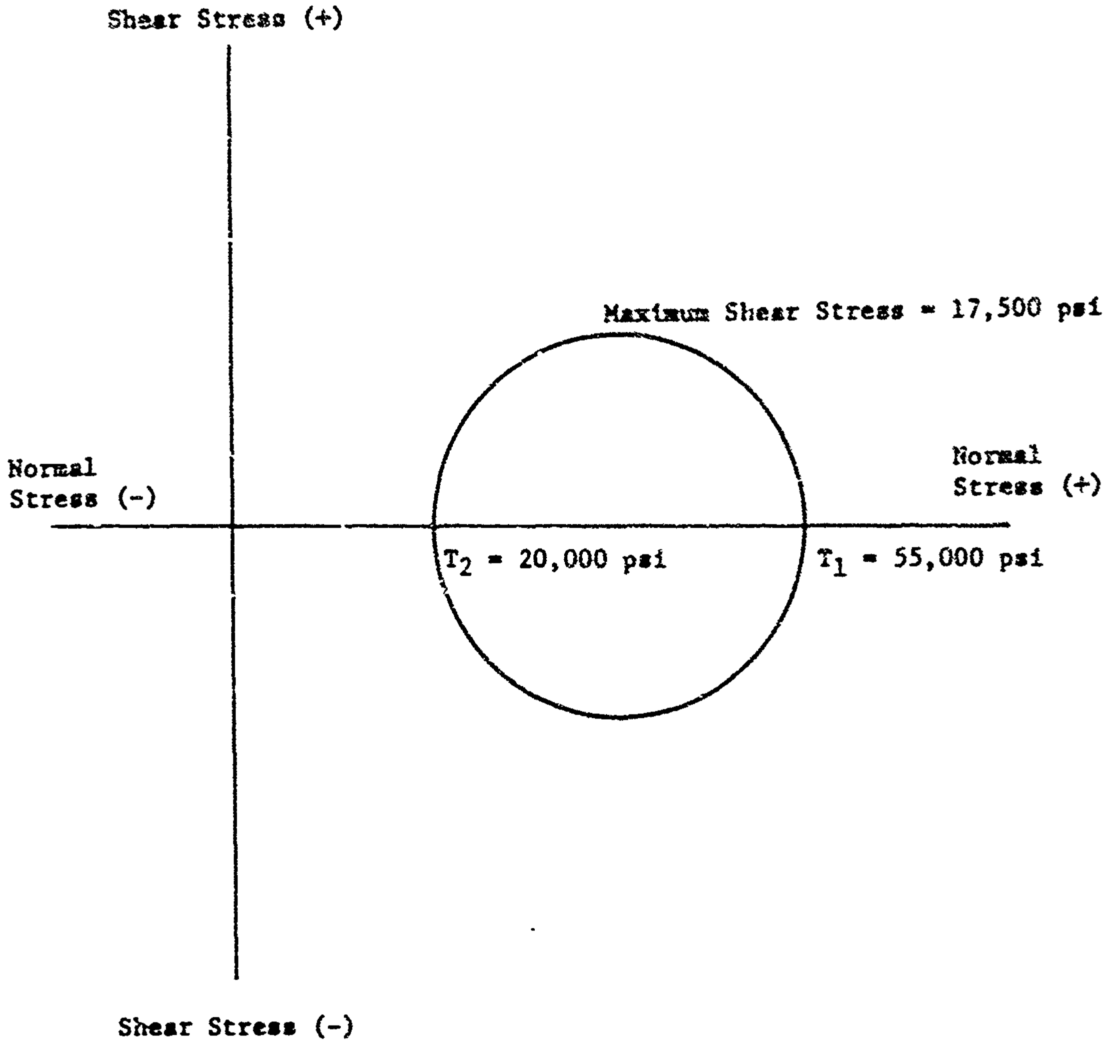

Figure 5. Mohr's Circle Describing Approximate State of Stress at Gage Location G.

Should the residual shear stress be considered to be limiting, it may be compared against the theoretical shear strength of the material. In the theoretical case, the shear strength equals approximately 60 percent of the uniaxial yield strength. Using a conservative estimate of the yield strength for the material of 110,000 psi, the theoretical shear strength would be 66,000 psi: 17,500 represents less than 30 percent of this level.

CONCLUSIONS

Results of this experimental study indicated that residual stresses were not exceedingly high after the final forming operation. From the standpoint of metallurgical or mechanical stability, final stress relieving would not then appear necessary. Possible effects of these stresses on ballistic properties are not known, however. Thus, the necessity for stress relieving cannot be judged solely on the basis of these experimental results.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Titanium Metals Corporation of America West Caldwell, New Jersey	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE A Forming Technique for Soldiers Titanium Helmets.	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report dated July 1968, initiated October 1965 and expanded July 1966.	
5. AUTHOR(S) (First name, middle initial, last name) Robert L. Kane (Titanium Metals Corporation of America), and Robert S. Smith (U. S. Army Natick Laboratories).	

6. REPORT DATE July 1968	7a. TOTAL NO. OF PAGES 56	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. DA19-129-AMC-940(N) b. PROJECT NO. Task 5-09 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) 69-32-GP	
10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Natick Laboratories Natick, Massachusetts 01760	

13. ABSTRACT

The 5Al-2.5 Sn, 6Al-4 V, 4Al-3 Mn, and commercially pure grades of titanium were investigated for use in infantry helmets.

The 5Al-2.5 Sn grade of titanium alloy was found to be the best commercially available grade for this application. This selection was based upon a combination of ballistic performance and formability using the "Greer" process.

The forming and intermediate stress-relieving operations were found to improve the ballistic properties of the titanium.

A total of 500 helmets were fabricated, and the feasibility of mass-producing titanium alloy helmets at room temperature, using the "Greer" forming process, was demonstrated.

It was determined that up to a one-pound weight reduction could be achieved in a titanium helmet without significantly reducing the ballistic protection as compared to the standard M-1 Hadfield manganese steel helmet. A significant increase in ballistic protection could also be achieved with a titanium helmet of equivalent weight to the M-1 steel Helmet.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fabrication	8					
Helmets	2					
Titanium	1					
Titanium alloys	1					
Cost	8					