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HEAT TREATMENT INVESTIGATION OF 4330 VANADIUM-MODIFIED STEEL

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MATERIALS PRODUCIBILITY BRANCH

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Block No. 20

ABSTRACT

The shear pin material for the T5106 155-mm torsional impact round was originally specified to have been 4340 steel. It was determined by the authors that the required properties of an ultimate shear strength of 150 ksi and Charpy impact value of 20 ft-lb at -40^{0}F were not obtainable in 4340. The decision to employ 4330 vanadium-modified steel as a substitute shear pin material initiated this heat treatment and mechanical property investigation.

The 4340 steel is a low alloy, martensitic, ultrahigh strength steel developed from the modification in composition of 4340 steel. The reduction of the carbon level in this alloy increases its performance, relative to its predecessor; in the areas of fracture toughness, weldability, and general fabrication.

Mechanical properties were determined from 1/2-inch- and 5/8-inch-diameter bar stock for austenitizing temperatures of 1500 and 1600^{0}F and tempering temperatures ranging form 375 and 675^{0}F. The material was evaluated for the specification requirements mentioned above in addition to being tested for hardness, fracture toughness, and tensile properties.

The shear strength and Charpy impact requirements were reached by austenitizing 5/8-inch-diameter rod at 1500^{0}F for 1 hour followed by an oil quench and double tempering (2 + 2 hr) at 400^{0}F. This heat treatment resulted in an ultimate shear strength of approximately 158 ksi and a Charpy V-notch impact value of 27 ft-lb.

A-1

BACKGROUND AND INTRODUCTION

The shear pin material used in the 155-mm T5106 torsional impact round was specified, per Picatinny Arsenal drawing number 9203276, to have been 4340 steel. Through an analysis outlined in Appendix A it was determined that the mechanical properties required of the pin could not have been met using 4340 steel. A substitution of 4330 vanadium-modified steel was requested by MTL and authorized by PM-NUC at the U.S. Army Armament Research, Development and Engineering Center (ARDEC).

The mechanical properties desired were an ultimate shear strength of 150 ksi, which corresponds to an ultimate tensile strength of approximately 240 ksi (see Appendix B), and a Charpy V-notch impact value of 20 ft-lb tested at -40°F. The purpose of this program was to determine a heat treatment which would provide this combination of properties.

Table 1. CHEMICAL ANALYSIS OF FRY HEAT NO. 3956360 (WEIGHT PERCENT)

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Fe
0.32	0.95	0.007	0.001	0.22	0.15	1.81	0.86	0.39	0.07	Bal.

MATERIALS AND EXPERIMENTAL PROCEDURE

The 4330 steel is a low alloy, martensitic, ultrahigh strength steel developed from the modification in composition of 4340 steel. The reduction of the carbon level in this alloy increases its performance, relative to its predecessor, in the areas of fracture toughness, weldability, and general fabrication. The specific composition of the material used in this study is shown in Table 1.

The material was purchased in the form of 1/2-inch- and 5/8-inch-diameter rods. In order to obtain a standard 0.394-inch-square cross section Charpy V-notch specimen (type CV-2) a diameter of 5/8 inch was required. The Charpy V-notch impact specimens were machined from both the 1/2-inch- and 5/8-inch-diameter stock, with undersized Charpy V-notch specimens resulting from the 1/2-inch stock. The bars were austenitized at either 1500 or 1600°F for 1 hour then oil quenched. They were then double tempered (2 + 2 hr) at a temperature ranging from 375 to 675°F and air cooled.

The specific number of specimens that were used in each test is shown in Table 2. Due to the attainment of the desired properties, using the results from the tensile and subsized Charpy impact tests on the 1/2-inch-diameter stock our further investigations using the 5/8-inch-diameter stock were concentrated at the lower tempering temperatures. The results from the subsized impact specimens are presented in Appendix C.

The tensile and shear tests were conducted at room temperature while the Charpy specimens were tested at -40°F. The buttonhead tensile specimens were all tested with a crosshead speed of 0.05-inch per minute on an Instron machine with the strain measured using a 1/2-inch, 10% extensometer with a remote power supply and x-y recorder. The double shear specimens were tested on an Instron Series IX Automated Materials Testing System with a crosshead speed on 0.10-inch per minute. Precracked Charpy V-notch impact specimens (0.394-inch square) were used to obtain fracture toughness data with each specimen fatigue precracked such that the ratio of the notch plus precrack to the total specimen depth is between 0.45 and 0.55. The data obtained is expressed as K_{IQ}, which is a conditional plane-strain (K_{IC}) value.

Table 2. NUMBER OF SPECIMENS PER HEAT TREATMENT CONDITION
(1/2-INCH BAR STOCK UNLESS OTHERWISE INDICATED)

Austenitizing Temperature (°F)	Tempering Temperature (°F)	Charpy V-notch	Buttonhead Tensile	3/8-Inch Ultimate Shear	Fracture Toughness
1500	375	3,3*	3,3*	3,3*	3*
	400	3,3*	3,3*	3,3*	3*
	625	3	3	3	
	650	3	3	3	
	675	3	3	3	
1600	400	3	3	3	
	500	3		2	
	575	3		2	
	600	3		2	
	625	3		2	

*Indicates specimens from the 5/8-inch bar stock, from which full-sized Charpy V-notch specimens were obtained.

RESULTS

Rockwell C hardness data (HRC) as a function of austenitizing and tempering temperature are tabulated in Table 3 and plotted in Figure 1. Each value in the table and figure represents the average of four readings which were obtained from either two or three Charpy specimens. The standard deviation is also shown in Table 3 and the equation Y = 56.1 - 0.0017X, with correlation coefficient* R = 0.97, represents the best fit for the data plotted in Figure 1.

Table 3. EFFECT OF TEMPERING TEMPERATURES ON HARDNESS VALUES

Austenitizing Temperature (°F)	Tempering Temperature (°F)	Average Hardness (HRC)	Standard Deviation
1600	400	48.8	0.14
	500	46.7	0.39
	575	46.4	1.05
	600	45.5	0.59
	625	45.7	0.50
1500	375	50.3	0.12
	400	49.9	0.21
	625	45.9	0.24
	650	45.2	0.27
	675	44.8	0.23

*The correlation coefficient, often referred to as R, is the standard error divided by the standard deviation.

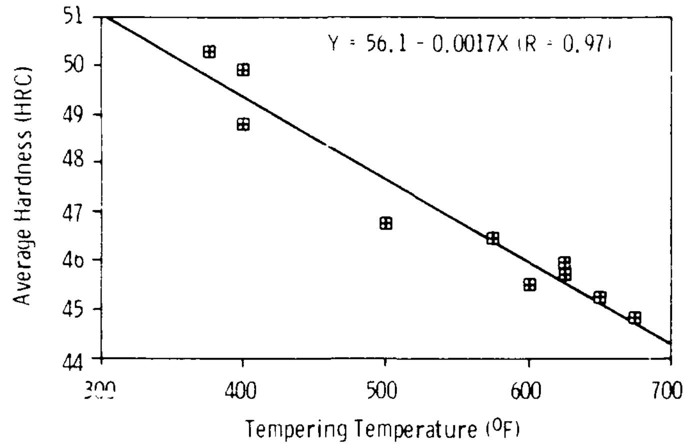

Figure 1. Hardness as a function of tempering temperature.

Tensile strength is shown in both tabular and graphical form versus tempering temperature, Table 4 and Figure 2, respectively. The equation in Figure 2 describing the relationship between the UTS and tempering temperature has a correlation coefficient of R = 0.99 while the similar relationship for the 0.2% yield strength has a correlation coefficient of R = 0.80

The shear strength data is shown graphically versus tempering temperature in Figure 3. As shown, both the 375 and 400°F tempering temperatures meet the specification requirement of 150 ksi minimum.

The standard sized Charpy impact specimens from the 5/8-inch bar stock were austenitized at 1500°F, oil quenched to room temperature, and double tempered at 375 and 400°F for 2 hours. The results are shown in Table 5 with average values of 27.1 and 26.8 ft-lb for the 375 and 400°F tempers, respectively. These values are well above the 20 ft-lb required by the specification. The data for the subsized Charpy specimens is shown graphically in Appendix C as a function of tempering temperature. This data gave a good indication that the Charpy energy for full-sized specimens (0.394-inch-square cross section) would be near our expected values. Due to the dimensions of the subsized Charpy specimens, the data cannot be scaled accurately to represent the full-sized specimen.

Table 4. TENSILE PROPERTIES AS FUNCTIONS OF AUSTENITIZING AND TEMPERING TEMPERATURES

Austenitizing Temperature (°F)	Tempering Temperature (°F)	0.2% YS (ksi)	UTS (ksi)	Elon. (%)	RA (%)
1600	400	192	249	14.8	58.4
1500	375	206	259	12.5	60.1
	400	210	258	14.6	60.3
	625	191	223	14.6	59.8
	650	191	221	14.1	59.9
	675	187	218	14.3	62.0

Fracture toughness tests, using precracked Charpy V-notch specimens, were performed on specimens machined from the 5/8-inch-diameter stock only. These tests yielded results shown in Table 6 with average K_{IQ} values of 45.3 and 47.6 ksi$\sqrt{in.}$ for the 375 and 400°F tempering temperatures, respectively.

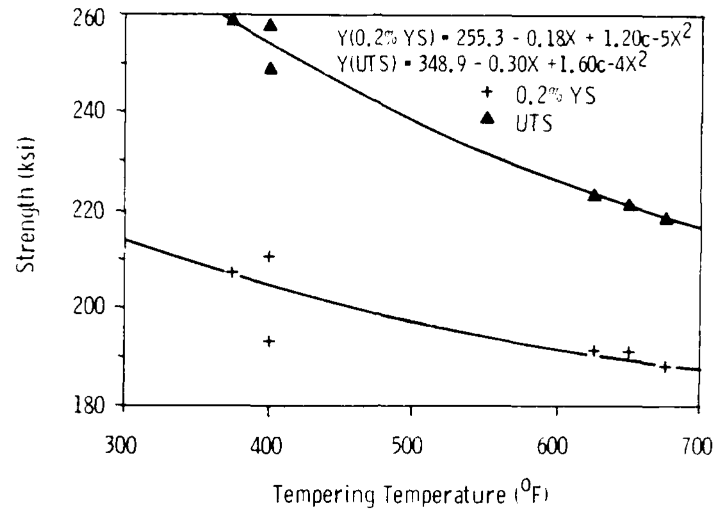

Figure 2. Tensile properties as functions of tempering temperature.

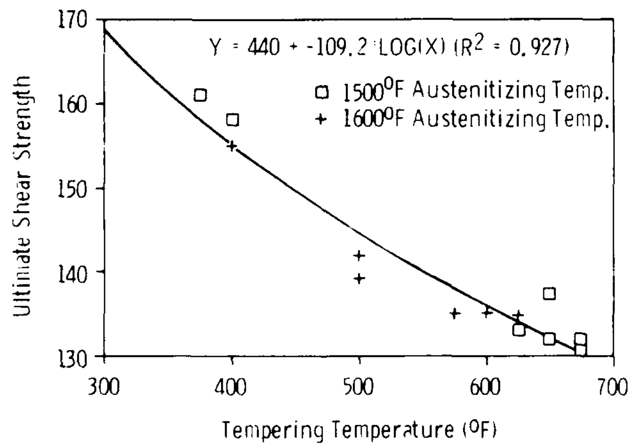

Figure 3. Ultimate shear strength as a function of austenitizing and tempering temperatures.

Table 5. EFFECT OF TEMPERING TEMPERATURE ON CHARPY V-NOTCH IMPACT ENERGY (TESTED AT -40°F)

Tempering Temperature (°F)	Charpy Impact Energy (ft-lb)
375	27.2 28.8 (Avg.) 27.[illegible] 25.4
400	27.9 26.0 (Avg.) 26.8 26.6

NOTE: 1500°F Austenitizing Temperature

Table 6. EFFECT OF TEMPERING TEMPERATURE ON FRACTURE TOUGHNESS

Tempering Temperature (°F)	Fracture Toughness (ksi$\sqrt{\text{in.}}$)
375	48.4 43.1 (Avg.) 45.3 44.4
400	47.9 46.2 (Avg.) 47.6 48.7

NOTE: 1500°F Austenitizing Temperature

CONCLUSIONS

The ultimate goal of this study was to determine a heat treatment for 4330 vanadium-modified steel to attain a room temperature ultimate shear strength of 150 ksi and a Charpy V-notch impact energy of 20 ft-lb at -40°F. The recommended heat treatment is as follows:

Austenitize at 1500°F, 1 hour, oil quench, and double tempering at 400°F (2 hr, AC + 2 hr, AC).

With the above process, an ultimate shear strength of approximately 158 ksi and a Charpy impact energy of 27 ft-lb were obtained.

Due to the attainment of the required properties with 4330 vanadium-modified steel, the shear pin specification for the T5106 155-mm torsional impact round will be updated to reflect this material change. This information is not only of value to the T5106 and future shell programs, but will be a contribution to the technical literature.

APPENDIX A

As shown in Appendix B, the ratio of ultimate shear strength to ultimate tensile strength for 4340 is 0.58. Thus, to obtain the minimum requirement of an ultimate shear strength of 150 ksi for the shear pin material, an ultimate tensile strength of 258 ksi is needed. Using Figure 3.02122 in the Aerospace Structural Metals Handbook,[1] a temper of 575°F yields an ultimate tensile strength of 258 ksi for 4340. From Figures 1.063 and 3.0332 in the handbook, this tempering temperature corresponds to an approximate hardness of 50 HRC which in turn yields a Charpy impact energy of approximately 10 to 15 ft-lb at -40°F.

In support of this initial conclusion that 4340 would not be a suitable shear pin material, a study by Hickey and Anctil[2] investigated the tensile, hardness, and Charpy impact properties of ESR 4340. In this study, a tempering temperature of 575°F resulted in an approximate hardness of 51 HRC and from Figure A1, constructed from their data, a room temperature Charpy impact energy of 14 ft-lb can be estimated.

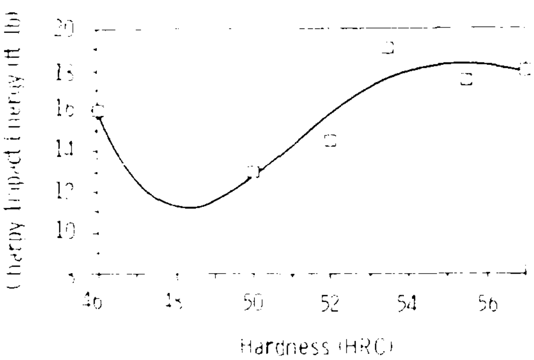

Figure A1. Charpy impact energy as a function of hardness for ESR 4340 (data from Ref. 2).

1 Aerospace Structural Metals Handbook, v. 1, Code 1206, 1963, p. 2-15.
2 HICKEY, C. F., Jr., and ANCTIL, A. A. *Split Heat Mechanical Property Comparison of ESR and VAR 4340 Steel.* U.S. Army Materials Technology Laboratory, AMMRC TR 83-27, May 1983.

APPENDIX B

Using the Table 3.011 in the Aerospace Structural Metals Handbook,[3] the relationship between the ultimate tensile strength and the ultimate shear strength for 4340 steel can be determined. From this calculation an estimation for the same relationship in 4330 vanadium-modified steel can be made.

For an estimated UTS of 235 ksi in 4340, interpolation gives the following ratio:

$$\frac{260-200}{260-235} = \frac{149-119}{149-x}$$

x = 136.5 ksi equivalent shear for a UTS of 235 ksi (4340).

Using the above value and the desired result the ratio can be determined.

$$\frac{137}{235} = 0.58.$$

This ratio implies that the ultimate shear strength of 4340 is 58% of the ultimate tensile strnegth. Comparing this with out data for 4330. . .

As shown in Table B1, the ratio 0.58 in 4340 was a good approximation for the same ratio in 4330. In order to obtain an ultimate shear strength of 150 ksi for 4330, it is evident that we need an ultimate tensile strength of 250 ksi.

Table B1 ULTIMATE SHEAR/ULTIMATE TENSILE RATIO DATA (4330 V-MODIFIED)

Temperature (°F)	Mean UTS (ksi)	Mean Max Shear (ksi)	Ratio
625	223.4	133.5	0.59
650	221.2	133.3	0.60
675	218.0	130.1	0.60

3 Aerospace Structural Metals Handbook, v. 1, Code 1206, 1963, p. 2.

APPENDIX C

For standard Charpy V-notch specimens type CV-2 (0.394-inch-square cross section), a minimum bar stock diameter of 0.556 inch is needed. Initial availability of 1/2-inch-diameter stock led to the testing of subsized Charpy specimens. These subsized specimens, outlined in Figure C1, were used to estimate the range of heat treatments that would yield the desired properties from the full-sized Charpy specimens upon receiving the 5/8-inch-diameter stock.

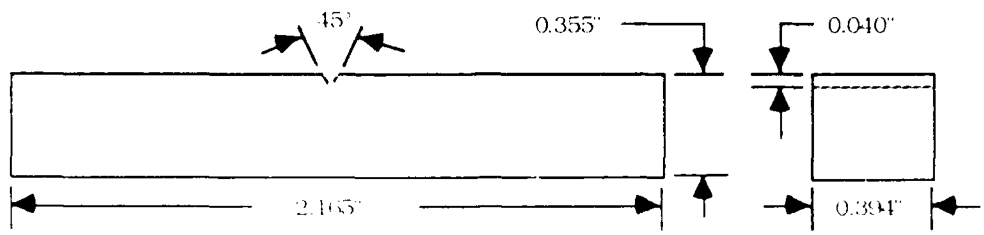

Figure C1. Nominal dimensions of the subsized Charpy V-notch impact specimens.

The impact test results at -40°F are shown in Figure C2. These data cannot be manipulated in order to reflect data from full-sized specimens although it does give a good indication of the range of expected values.

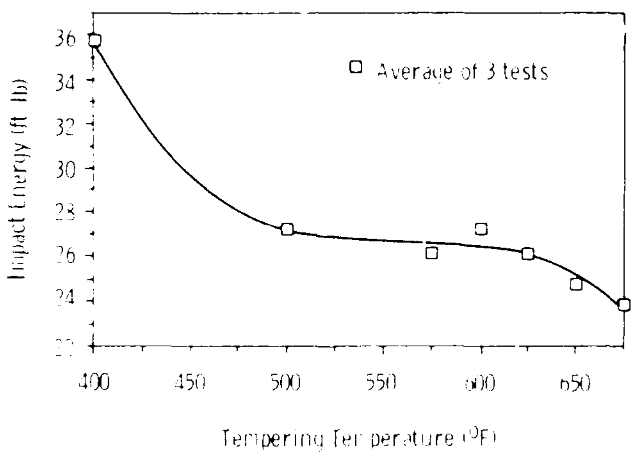

Figure C2. Effect of tempering temperature on subsized Charpy V-notch impact energy.

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The shear pin material for the T5106 155-mm torsional impact round was originally specified to have been 4340 steel. It was determined by the authors that the required properties of an ultimate shear strength of 150 ksi and Charpy impact value of 20 ft-lb at -40°F were not obtainable in 4340. The decision to employ 4330 vanadium-modified steel as a substitute shear pin material initiated this heat treatment and mechanical property investigation. The 4330 steel is a low alloy, martensitic, ultrahigh strength steel developed from the modification in composition of 4340 steel. The reduction of the carbon level in this alloy increases its performance, relative to its predecessor, in the areas of fracture toughness, weldability, and general fabrication. Mechanical properties were determined from 1/2-inch- and 5/8-inch-diameter bar stock for austenitizing temperatures of 1500°F and 1600°F and tempering temperatures ranging from 375 to 675°F. The material was evaluated for the specification requirements mentioned above in addition to being tested for hardness, fracture toughness, and tensile properties. The shear strength and Charpy impact requirements were reached by austenitizing 5/8-inch-diameter rod at 1500°F for one hour followed by an oil quench and double tempering (2 + 2 hr) at 400°F. This heat treatment resulted in an ultimate shear strength of approximately 158 ksi and a Charpy V-notch impact value of 27 ft-lb.

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Technical Report MTL TR 89-84, August 1989, 10 pp - illus-tables, AMCMS Code 612105-H84001l

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