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EFFECT OF MICROSTRUCTURE ON BALLISTIC PERFORMANCE OF ESR 4340 STEEL

August 1989

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ABSTRACT

The objective of this investigation was to develop heat treating procedures which will consistently produce microstructures essentially free from large spheroidal carbides and, thus, provide reproducible and predictable ballistic behavior. Increasing normalizing temperature of ESR 4340 from 1600°F to 2000°F has little effect in reducing the size or number of carbide spheroids which are 1 micrometer in diameter or larger. In the range of 1500°F to 2000°F, increasing austenitizing temperature drastically reduces spheroid size and population. Grain coarsening produced by high austenitizing temperatures is reduced by a second austenitizing treatment at 1600°F. As spheroid population decreases, hardness, ultimate strength, and fracture toughness increase slightly while elongation, reduction of area, and Charpy impact values decrease. Ballistic test plates which were heat treated to produce microstructures with very few carbide spheroids had V_{50} values which were more than 50 percent higher than those of plates which were normalized at 1600°F and austenitized at 1500°F. None of the standard static mechanical tests can be used to predict the ballistic performance of ESR 4340.

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INTRODUCTION AND BACKGROUND

The outstanding ballistic performance of electroslag remelted (ESR) 4340 steel, vacuum heat treated to HRC 54 to 57, resulted in its wide usage in Army helicopters.^{1,2} During the development phase of the attack helicopter Apache AH-64 Program, certain anomalies were observed.

Qualification test plates from six steel producers, domestic and foreign, were prepared. Duplicate plates from each ESR heat are rolled from a small (approximately 100 lb) portion of a forged billet and heat treated simultaneously to minimize possible composition and thermal response variations. These test plates were all vacuum heat treated to HRC 54.5 ± 0.5 . However, the ballistic limit values defined as the average of an equal number of highest partial penetration velocities and the lowest complete penetration velocities which occur within a specified velocity spread (V_{50}) varied from 1309 to 1670 feet per second (fps). Moreover, V_{50} values for duplicate plates from a given ESR heat often differed by as much as 200 fps. Visual and macroscopic examination of the target plates showed no correlation between ballistic performance and appearance of the impact areas.

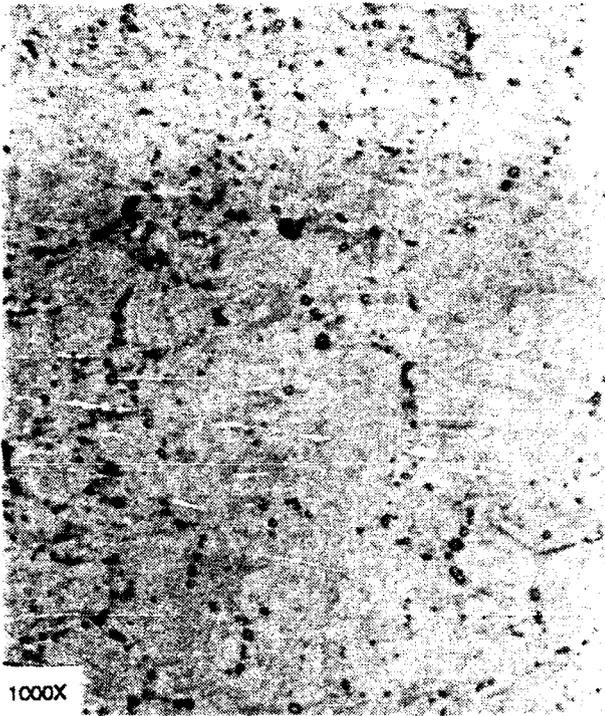
Metallographic samples were prepared from 15 test plates with the entire range of V_{50} values. Mechanically polished specimens etched with nital showed no discernible differences among the specimens. The rapid action of the nital obscured many of the fine details of a primarily martensitic structure.

When 4% picral with 0.1% HCl added was used as the etchant, the results were excellent. The slower acting picral revealed the fine structure, especially spheroidal carbides, very clearly. Figure 1 shows typical microstructures of plates with V_{50} values between 1309 fps and 1660 fps. When viewed at 1000X, coarse carbides which are 1 micrometer or greater in diameter, have a spherical shape while fine carbides (<0.5 micrometer) appear as dark dots. Plates with high V_{50} values contained few coarse carbides and those present had typical interparticle separation distances of 25 micrometers or greater. As a second constituent, the bond between a carbide sphere and the martensitic matrix is very weak and behaves like an internal defect in the propagation of cracks. Fracture toughness studies have established that the critical defect diameter of dispersoids in the 7000 series of aluminum alloys is approximately 1 micrometer.³ These large particles have an adverse effect on fracture toughness of aluminum and a similar effect is obtained by coarse carbide spheroids on the ballistic performance of ESR 4340.

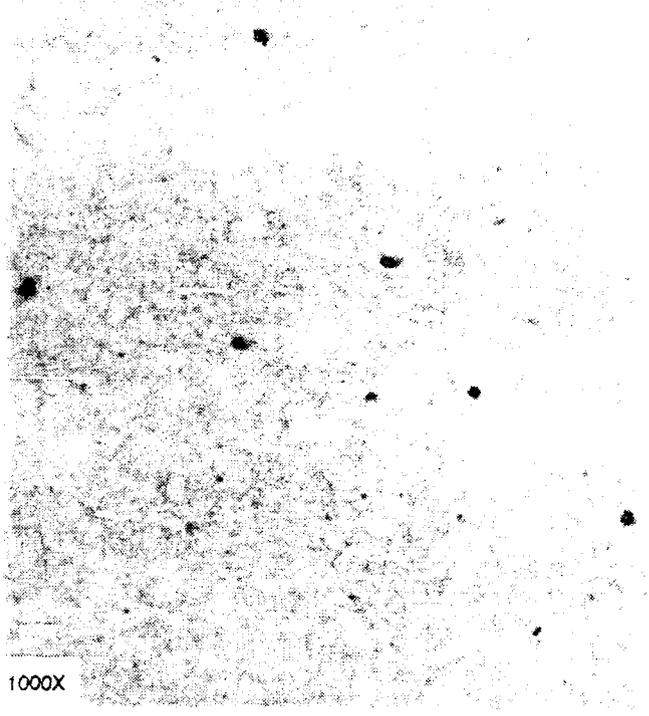
In low alloy steels such as 4340, carbide morphology is determined by the alloying elements and thermal processing. Chromium and molybdenum form stable carbides which resist re-resolution in the matrix during normalizing and austenitizing. Time and temperature variations in heat treating cycles affect spheroid size and population.

While major differences in carbide morphology had no significant effect on the hardness and tensile properties of the ballistic plates, no data existed on fracture toughness and impact strength of the tested plates. Therefore, any correlation between carbide morphology, toughness, and impact test properties would be useful in selecting thermal treatment procedures. Ballistic test plates processed to produce the resulting undesirable, normal, and optimal carbide morphologies needed to be test fired to evaluate the effect of microstructure on the ballistic performance of ESR 4340 steel.

1. HICKEY Jr., C. F., ANCTIL, A. A., and CHAIT, R. *The Ballistic Performance of High Strength 4340 Steel Processed by Electroslag Remelting*. Proceedings on Fracture of Wrought and Cast Steels, E. Fortner, ed., ASME MPC-13, 1980.
2. HICKEY Jr., C. F., THOMAS, T. S., and ANCTIL, A. A. *Comparison of Ballistic Performance of a Split Heat of ESR and VAR 4340 Steel*. American Society for Metals International, Proceedings of the Mechanism of Fracture, International Conference on Fatigue, Corrosion Cracking, Fracture Mechanics, and Failure Analysis, 1985, p. 421-432.
3. STALEY, J. T. *Microstructures and Toughness of High Strength Aluminum Alloys*. Properties Related to Fracture Toughness, ASTM STP 605, 1976.



1309 fps



1483 fps



1603 fps



1660 fps

Figure 1. Effect of carbide spheroids on ballistic performance as measured by V_{50} ESR steel plates 0.255-inch thick.

PROGRAM OBJECTIVES AND TASKS

On the basis of metallographic evaluation of ballistic test plates, a study program was proposed. The objective of this effort was to develop heat treating procedures for ESR 4340 steel which will consistently produce microstructures essentially free from large spheroidal carbides and, thus, provide reproducible and predictable ballistic behavior. Three specific tasks constituted the scope of the investigation.

Task I

This part of the investigation studied the effects of normalizing temperatures between 1600°F and 2000°F, austenitizing temperatures between 1500°F and 2000°F, and postnormalizing stress relief treatments on the formation of carbide spheroids in ESR 4340.

Task II

ESR 4340 specimens with specific carbide morphologies were tested to determine whether a relationship exists between microstructures and tensile, impact, and fracture toughness properties. Duplicate test results were obtained.

Task III

Six ballistic test plates measuring 14 in. x 14 in. x 0.435 in. thick, supplied by the U.S. Army Materials Technology Laboratory (MTL), were heat treated to produce three duplicate plate sets with (1) undesirable, (2) acceptable, and (3) preferred microstructures as determined in Tasks I and II. The plates were ballistically tested using 0.5 caliber AP M2 projectiles at MTL as part of this program.

EVALUATION OF TEST RESULTS

Task I

One of the plates supplied by MTL was cut to provide eight samples which were 7-inches long and 1.5 inches wide. Each strip was identified by a letter (A, B, C . . . H) which identified the normalizing and tempering temperatures used as shown in Table 1. Normalizing temperatures were varied between 1600°F and 2000°F. These temperature ranges were selected because conventional practice for normalizing 4340 calls for 1600°F to minimize grain growth. Post normalizing tempering temperatures of 1000°F and 1200°F were representative of Apache practice to provide hardness preferred by machining vendors.

Each of the lettered strips were cut to provide 1-inch-long specimens which were identified by a number representing the austenitizing temperature. To minimize variations, each numbered group (e.g., A-2, B-2, C-2 . . . H-2) was simultaneously austenitized for 3 hours at the selected temperatures, and tempered for 4 hours at 325°F. In Table 1, the sample letters describe the normalizing temperatures while the numbers define the austenitizing cycles.

HRC readings were made on freshly cut surfaces of the heat-treated specimens. Metallographic mounts were made for studies of carbide morphologies. Mechanically polished specimens were etched with HCl-acidified picral. Conventional bright field photomicrographs at 1000X were made to determine carbide spheroid size and particle distribution. Limited

evaluation by electropolishing and dark field illumination gave promising results which should be investigated.

Table 1. HEAT TREATMENT SCHEDULE. ALL STRIPS WERE TEMPERED AT 325°F FOR 4 HOURS

Strip	A	B	C	D	E	F	G	H
T _N [†] - °F (1 hr)	1600	1600	1700	1700	1800	1800	2000	2000
T _T [‡] - °F (3 hr)	32* 1000	24* 1200	32* 1000	24* 1200	38* 1000	28* 1200	37* 1000	28* 1200
T _A ^{**} - 1500°F (3 hr)	54* A-1	B-1	C-1	D-1	E-1	F-1	54* G-1	H-1
T _A ^{**} - 1600°F (3 hr)	A-2	B-2	C-2	D-2	E-2	F-2	54* G-2	H-2
T _A ^{**} - 1700°F (3 hr)	A-3	B-3	C-3	D-3	E-3	F-3	G-3	H-3
T _A ^{**} - 2000°F (1 hr)	54* A-4	54* B-4	54* C-4	54* D-4	54* E-4	54* F-4	54* G-4	54* H-4
2000°F (1 hr) T _A ^{**} - 1600°F (3 hr)	A-5	56* B-5	56* C-5	D-5	E-5	F-5	56* G-5	H-5

*Hardness (HRC) values for selected specimens

†Normalizing temperature

‡Tempering temperature after normalizing

**Austenitizing temperature

Examples: B-1 Normalized 1 hour at 1600°F; tempered 3 hours at 1200°F; austenitized 3 hours at 1500°F; oil quenched and tempered 4 hours at 325°F.

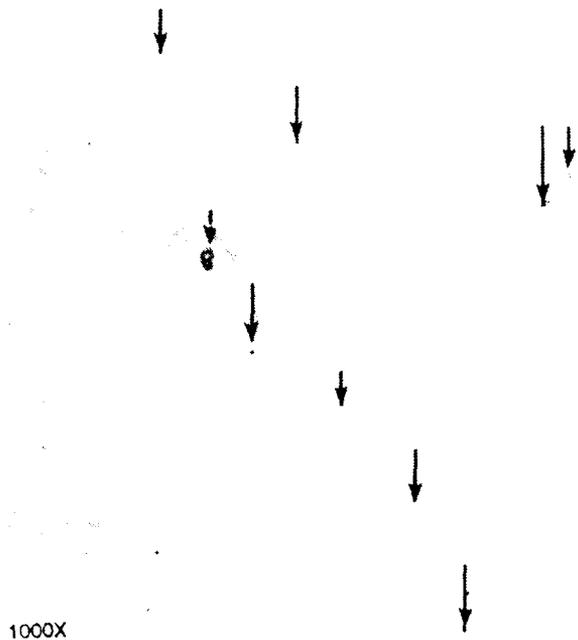
G-5 Normalized 1 hour at 2000°F; tempered 3 hours at 1000°F; austenitized 1 hour at 2000°F; oil quenched and tempered at 325°F 4 hours; re-austenitized 3 hours at 1600°F; oil quenched and tempered 4 hours at 325°F.

Metallographic studies showed that carbide morphology is drastically modified by variations in heat treating temperatures. Figure 2 compares the microstructures produced by two heat-treat schedules. B-1 was normalized at 1600°F, tempered at 1200°F, austenitized at 1500°F, oil quenched, and tempered at 325°F. This was the heat-treat schedule used in the development stage of the Apache helicopter and produced a large scatter in V_{50} values. Carbide spheroids, indicated by arrows, with diameters at least 1 micrometer are readily seen.

Specimen C-2 was normalized at 1700°F, tempered at 1000°F, austenitized at 1600°F, oil quenched, and tempered at 325°F. The number of large carbide spheroids is greatly reduced and the interparticle distances are greater. Apache parts made since 1983 are processed per this heat-treat schedule and V_{50} values are more consistent.

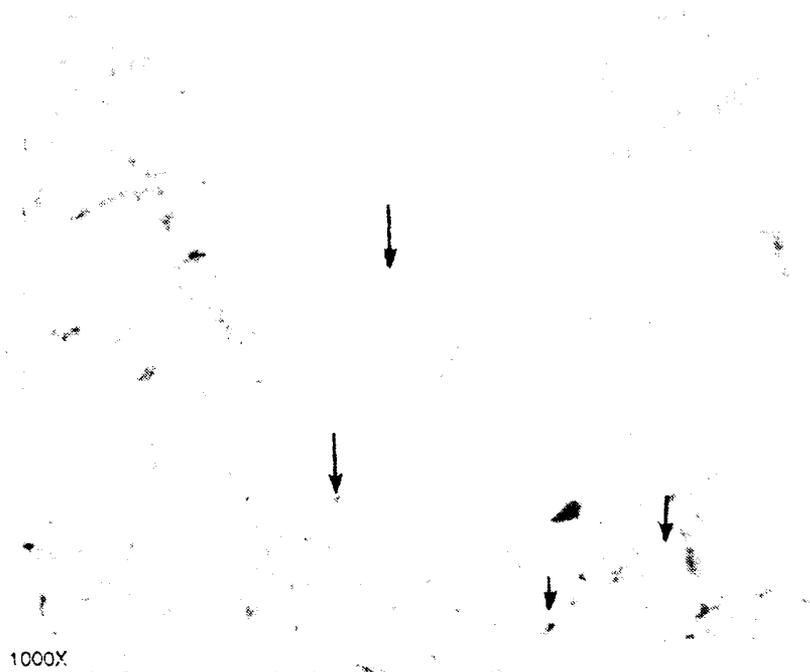
Figure 3 shows the relative effects of normalizing temperature and austenitizing procedures on carbide morphology. High (2000°F) normalizing and low (1500°F) austenitizing temperatures produce an undesirable carbide pattern while a low (1600°F) normalizing temperature followed by double (2000°F and 1600°F) austenitizing produces a desirable structure. The second austenitizing procedure was used to refine the coarse grain produced by the 2000°F treatment. Very few spheroids were observed in specimen B-5.

Figure 4 shows that a desirable carbide morphology is produced by a double (high-low) austenitizing temperature. Austenitizing has a much greater influence on carbide morphology than variations of the normalizing temperatures.



1000X

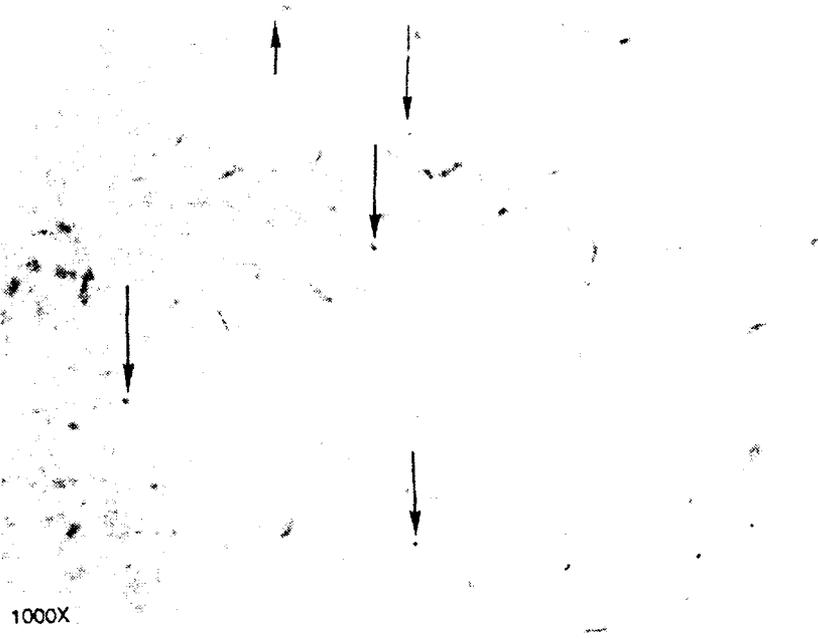
(a) Heat Treatment B-1: Normalize 1600°F, Temper 1200°F, Austenitize 1500°F, Oil Quench, and Temper 325°F



1000X

(b) Heat Treatment C-2: Normalize 1700°F, Temper 1000°F, Austenitize 1600°F, Oil Quench, and Temper 325°F

Figure 2. Comparison microstructures for heat treatments B-1 and C-2. Arrows indicate carbide spheroids.

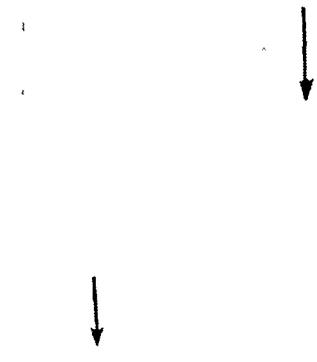


(a) Undesirable Carbide Pattern, G-1: Normalize 2000°F, Austenitize 1500°F



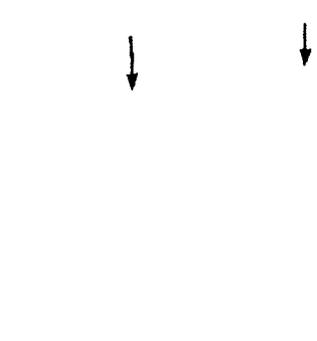
(b) Minimum Carbide Dispersion, B-5: Normalize 1600°F, Double Austenitize 2000°F, then 1600°F

Figure 3. Comparison of the effects of normalizing and austenitizing temperatures on carbide dispersion. Arrows indicate carbide spheroids.



1000X

(a) Heat Treatment C-5: Normalize 1700°F, Double Austenitize 2000°F, then 1600°F



1000X

(b) Heat Treatment G-5: Normalize 2000°F, Double Austenitize 2000°F, then 1600°F

Figure 4. Dominant effect of austenitizing temperature in control of spheroids.
Arrows indicate carbide spheroids.

A relationship was observed between HRC values of specimens and significant higher and larger carbide spheroid content produced by lower austenitizing temperatures. Conventionally treated, double austenitized specimens with very few spheroids had hardnesses of HRC 53.5 to 54. Re-solution of the carbide spheroids in the matrix raised the carbon content of the martensite with a corresponding increase in hardness to HRC 56.

Task II

On the basis of the results obtained in Task I, three heat-treat schedules were selected to produce (1) undesirable, (2) normal, and (3) preferred carbide spheroid morphologies in tensile, Charpy V-notch, and compact tension specimens. Schedule B-1 (1600°F normalize, 1200°F temper, 1500°F austenitize, oil quench, 325°F temper) is generally used in heat treating 4340 steel but produces variable and unpredictable ballistic performance. Schedule C-2 (1700°F normalize, 1000°F temper, 1600°F austenitize, oil quench, 325°F temper) developed at McDonnell Douglas Helicopter Company (MDHC) produces excellent mechanical properties and more reproducible ballistic performance. Schedule C-5 (1700°F normalize, 1000°F temper, 2000°F austenitize, oil quench, 325°F temper, 1500°F austenitize, oil quench, 325°F temper) produces a structure with very few carbide spheroids.

Each lot of specimens consisted of four tensile specimens, six Charpy V-notch, and two compact tension specimens which were vacuum heat treated per schedules B-1, C-2, and C-5.

The mechanical testing was performed at MTL. This provided a good basis of comparison with other data obtained at MTL.² One tensile test specimen of each heat-treat schedule (B-1, C-2, and C-5) was also tested for MDHC by an approved independent testing laboratory for comparison with the MTL data. The results are shown in Table 2.

As the carbide spheroids were reduced in number and size, the tensile ultimate values increased slightly from 291 ksi to 306 ksi. The elongation values were 15.5% for B-1, 13.5% for C-2, and 6% for C-5. Reduction of area was 50% for B-1, 38% for C-2, and 0% for C-5. The B-1 and C-2 values are typical of those previously found at MDHC. No prior tensile data exists on schedule C-5. Charpy impact values were 21 ft-lb for B-1, 17 ft-lb for C-2, and 15 ft-lb for C-5. Fracture toughness values (K_{Ic} and K_{IQ}) increased slightly for C-2 over B-1. C-5 values were slightly lower than those of C-2.

Hardness measurements made on Charpy V-notch specimens confirmed the results obtained in Task I. Using a digital HRC tester calibrated against a Yamamoto precision standard block (HRC 55 + 0.1), B-1 averaged 53.6, C-2 was 54.5, and C-5 was 56.8.

Figure 5 shows the fracture surfaces of tensile bars heat treated per schedules B-1, C-2, and C-5. The cup and cone fracture in B-1 is usually considered the most desirable, resulting from microvoid coalescence originating at the center and progressing radially to a large shear area at the perimeter. This type of failure produces high elongation and reduction of area values.

Table 2. EFFECT OF HEAT TREATMENT VARIABLES ON MECHANICAL PROPERTIES OF ESR 4340 STEEL. CHEMICAL COMPOSITION: 0.41C, 0.70 Mn, 0.26 Si, 1.73 Ni, 0.90 Cr, 0.22 Mo, 0.008 P, 0.001 S, 0.21 Cu, 0.035 Al, BAL. Fe

Spec. ID	Heat Treatment °F				0.2% YS (ksi)	UTS (ksi)	Elong. (%)	RA (%)	K _Q [†] (ksi√in.)	K _{Ic} [‡] (ksi√in.)	Energy (ft-lb)	HRC**
	T _N	T _T	T _A	T								
B-1	1600 1 hr	1000 3 hr	1500 3 hr	325 4 hr	222	291	15.5	50	50	53	21	53.8
C-2	1700 1 hr	1000 3 hr	1600 3 hr	325 4 hr	215	302	13.5	38	53	54	17	54.5
C-5	1700 1 hr	1000 3 hr	2000/1 hr 1600/3 hr	325 4 hr	217	306	6.0	*	52	48	15	56.8

*Negligible

†CVN spec

‡Compact tension spec

**Hardness from Charpy specimens

Fracture surfaces of specimens C-2 and C-5 indicated that the failures (as indicated by arrows) initiated at the surface of tensile bars and progressed inward to produce a streamlined area of microvoid coalescence failure. Final fracture occurred near the perimeter with substantial areas of shear failure. Secondary cracks, which were parallel to the fracture plane, formed on specimen C-5 tested at MDHC, as shown in Figure 6. The unusual fracture surface patterns on specimens C-2 and C-5 were disturbing, and raised the possibility of defective specimens or off-axis loading during the tensile test. However, tensile specimens tested at MTL showed very similar fracture surface patterns and it was concluded that they were not caused by testing anomalies.⁴

Scanning electron micrographs of specimens B-1, C-2, and C-5 made at 2000X showed distinct patterns on the fracture surfaces (Figure 7). The B-1 specimen showed the typical dimpled surface present in an overload failure. The dimpled areas were subdivided by shear planes along which the metal deformed. This produced the high elongation and reduction of area measured in the specimen. The dimpling was produced by microvoid coalescence which originated at the carbide/matrix interface.⁵

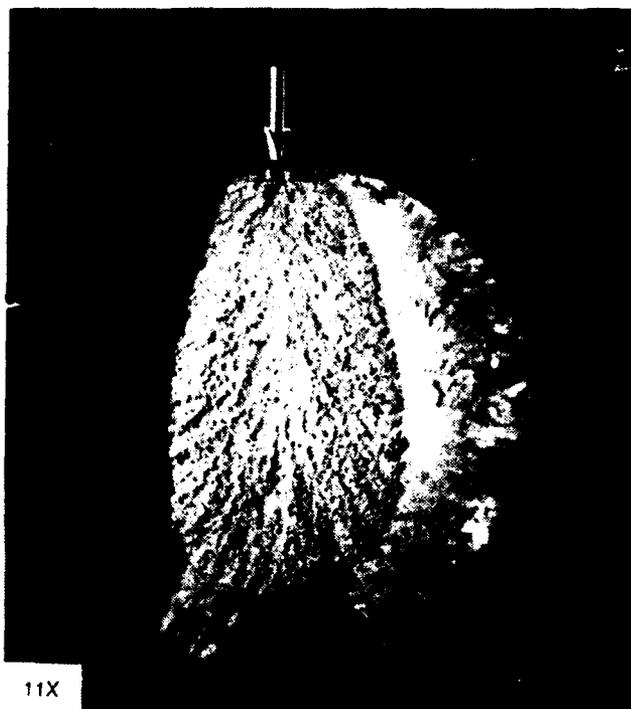
Specimen C-2 exhibited a typical dimpled fracture produced in a ductile steel which failed in overload. The major shear planes, which were quite prominent in the B-1 fracture, were not as prominent in the fracture surface. The reduced influence of shear in the failure mechanism would be expected to reduce the ductility and reduction of area values in the tensile bars. The dimples were more uniform and smaller than those in B-1.

The fracture surface in tensile specimen C-5 shows a predominantly flat break which was normal to the loading direction. The difference in the number and prominence of the shear planes compared to B-1 is quite pronounced. With less shear occurring during fracture, the ductility values are reduced. The higher carbon content of the matrix produces higher ultimate strength and lower ductility.

- OLSON, G. B., ANCTIL, A. A., WYSTO, T. S., and KULA, E. B. *Anisotropic Embrittlement in High-Hardness ESR 4340 Steel Forgings*. Met. Trans., v. 14A, 1983, p. 1621-1629.
- LIU, C. T., and GARLAND, J. *Fracture Behavior of Spheroidized Carbon Steels*. Transactions of the ASM, v. 7A, June 1976.

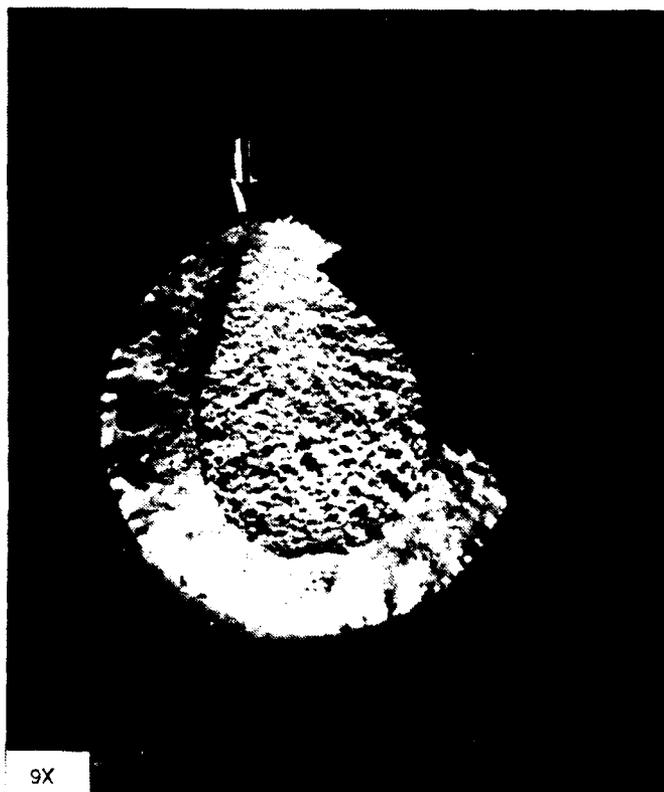


B-1



11X

C-2



9X

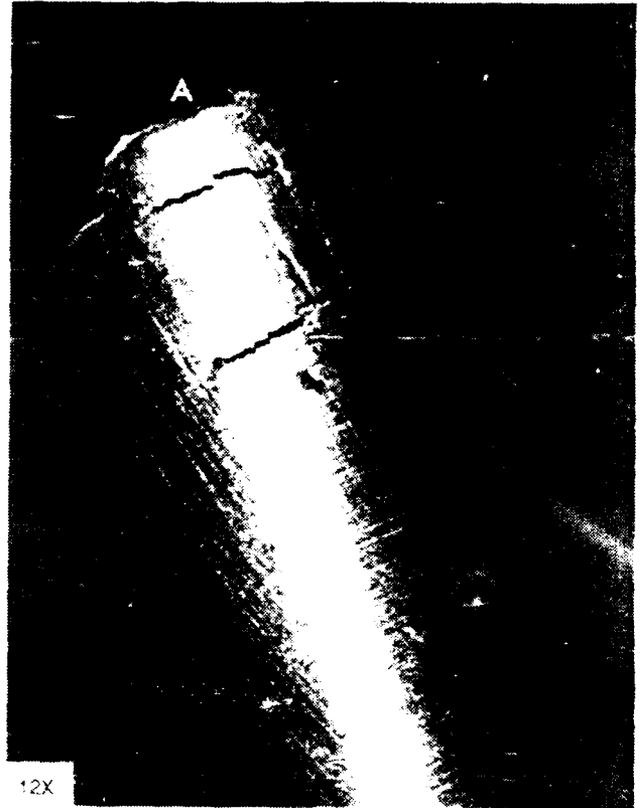
C-5

Figure 5. Fracture surfaces of tensile specimens heat treated per schedules B-1, C-2, and C-5. Tested at MTL. Arrows indicate fracture origin.



12X

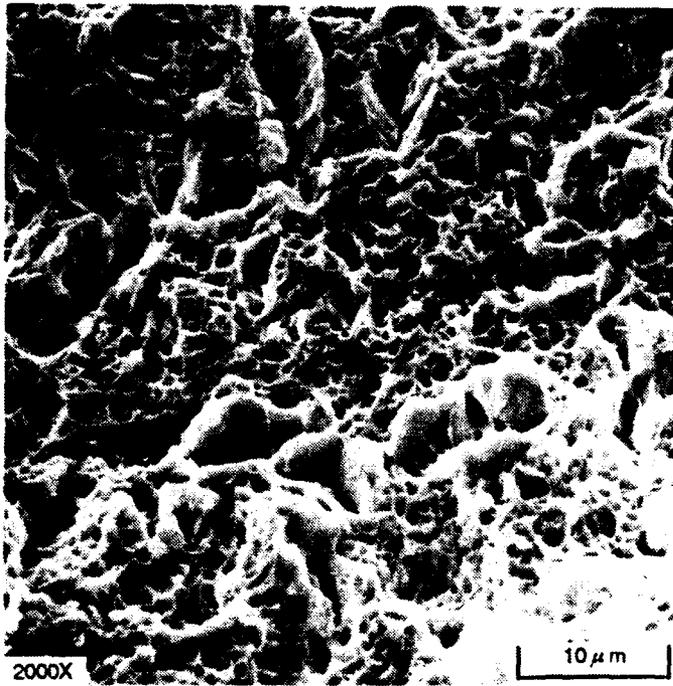
Radial View



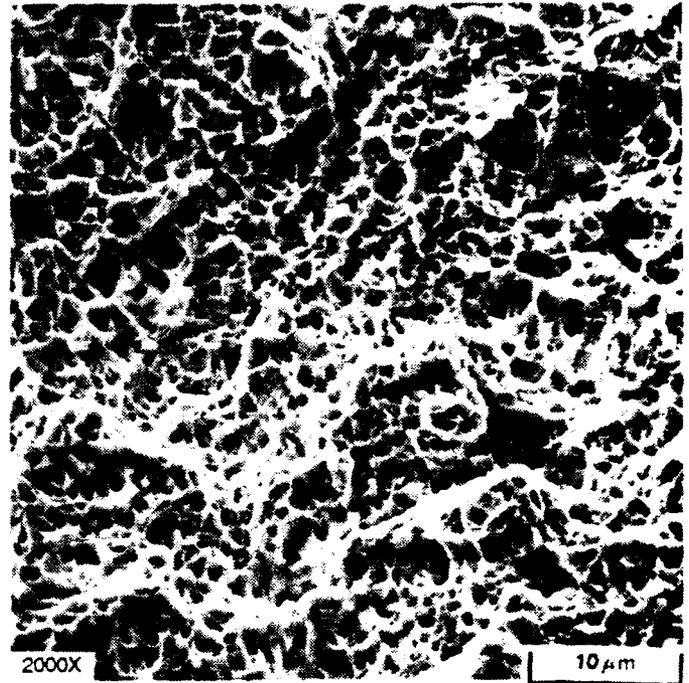
12X

Axial View

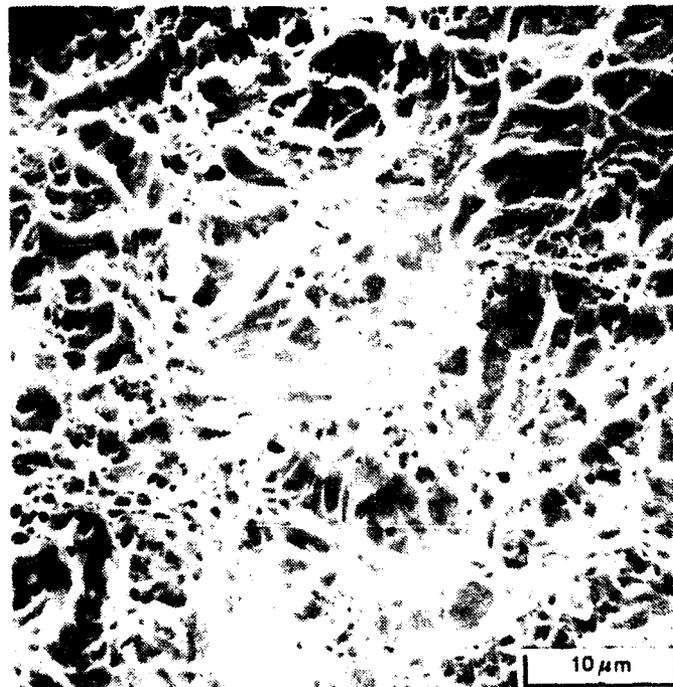
Figure 6. Fracture surface and axial view of tensile specimen C-5, tested at MDHC. Final break at "A."



B-1



C-2



C-5

Figure 7. Scanning electron photomicrographs of tensile bar fracture surfaces of specimens B-1, C-2, and C-5.

Previous investigators⁶ have reported that high austenitizing temperatures (approximately 2200°F) followed by oil quenching after step quenching to 1560°F increased fracture toughness and decreased impact strength in 4340 steel. The present work confirms the effect of high austenitizing temperature on fracture toughness and impact strength but the effects are less pronounced since the second austenitizing treatment refines the coarse grain produced at high temperatures. The large changes in fracture toughness and impact strength have been attributed to grain size effects.

In summary, increased ultimate strength and fracture toughness, but lower ductility and Charpy impact strength, were observed with a decreased presence of coarse carbide spheroids in the heat-treated ESR 4340.

Task III

Duplicate sets of ballistic test plates, 14 in. x 14 in. x 0.375 in., were heat treated per schedules B-1, C-2, and C-5 to determine the effect of carbide morphology on the ballistic performance of ESR 4340 steel. Table 3 summarizes the ballistic test results.

Table 3. VARIATIONS IN BALLISTIC PERFORMANCE AS A FUNCTION OF HEAT TREATMENT

Heat Treatment	HRC	Test No. 1 V ₅₀ fps	Test No. 2 V ₅₀ fps
B-1	53.8	<1282	<1278
C-2	54.5	2055	2002
C-5	56.8	2004	2011

Note: Hardness from Charpy specimens, ballistic penetration by plugging, and areal density 15 pounds per square foot.

The V₅₀ values showed a marked improvement as the coarse carbide spheroid population decreased, increasing from average values of 1280 fps for B-1, to 2029 fps for C-2, and 2008 fps for C-5. The HRC for C-5 was 56.8 which was higher than the 53.8 for B-1 and 54.5 for C-2. The slight reduction in V₅₀ for C-5 compared to C-2 may have been due to the higher hardness.

SUMMARY

Increasing normalizing temperature of ESR 4340 from 1600°F to 2000°F has little effect in reducing the size or number of carbide spheroids which are 1 micrometer in diameter or larger. In the range of 1500°F to 2000°F, increasing austenitizing temperature drastically reduces spheroid size and population. Grain coarsening produced by high austenitizing temperatures is reduced by a second austenitizing treatment at 1600°F. As spheroid population decreases, hardness, ultimate strength, and fracture toughness increase slightly while elongation, reduction of area, and Charpy impact values decrease. Ballistic test plates which were heat treated to produce microstructures with very few carbide spheroids had V₅₀ values which were more than 50 percent higher than those of plates which were normalized at 1600°F and austenitized at 1500°F. None of the standard static mechanical tests can be used to predict the ballistic performance of ESR 4340.

6. RITCHIE, O., BENJAMIN, F., and SERVER, W. L. *Evaluation of Toughness in AISI 4340 Alloy Steel Austenitized at Low and High Temperatures*. Metallurgical Transactions A., v. 7A, June 1976.

CONCLUSIONS AND RECOMMENDATIONS

This investigation has shown that carbide spheroids in heat-treated ESR 4340 have a deleterious effect on ballistic performance when the spheroid diameter is 1 micrometer or greater and typical separation between spheroids is 25 micrometers or less. Static mechanical properties of heat-treated ESR 4340 do not correlate with ballistic performance.

The limited scope of this investigation could not determine all of the factors which affect ballistic performance. Future investigations which would provide a better understanding of the factors which determine ballistic performance are: (1) the effect of grain size, (2) the effect of retained austenite, and (3) the effect of increasing time at the 1600°F austenitizing temperature on carbide morphology and ballistic performance.

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EFFECT OF MICROSTRUCTURE ON BALLISTIC
PERFORMANCE OF ESR 4340 STEEL -
Edward T. Myskowski - McDonnell Douglas Aircraft Co.
and Albert A. Ancill - U.S. Army Materials
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The objective of this investigation was to develop heat treating procedures which will consistently produce microstructures essentially free from large spheroidal carbides and, thus, provide reproducible and predictable ballistic behavior. Increasing normalizing temperature of ESR 4340 from 1600°F to 2000°F has little effect in reducing the size or number of carbide spheroids which are 1 micrometer in diameter or larger. In the range of 1500°F to 2000°F, increasing austenitizing temperature drastically reduces spheroid size and population. Grain coarsening produced by high austenitizing temperatures is reduced by a second austenitizing treatment at 1600°F. As spheroid population decreases, hardness, ultimate strength, and fracture toughness increase slightly while elongation, reduction of area, and Charpy impact values decrease. Ballistic test plates which were heat treated to produce microstructures with very few carbide spheroids had V_{50} values which were more than 50 percent higher than those of plates which were normalized at 1600°F and austenitized at 1500°F. None of the standard static mechanical tests can be used to predict the ballistic performance of ESR 4340.

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