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TEXTURE AND ITS INFLUENCE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES

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Abstract: By appropriate thermomechanical processing treatment in the austenite region of a medium carbon 5Ni steel, three different types of textures, each with various degrees of intensity, have been produced in the quenched-and-tempered high-hardness steel armor plates. The various mechanical properties, including tension, through-thickness tension and compression, impact, fatigue, and fracture toughness, together with the ballistic performance of the plates as a function of the intensity of the texture, in particular the (112)+(111) type, are presented and discussed.

INTRODUCTION

It has long been known that the crystallographic texture in cold-rolled and annealed metal sheets can very significantly affect the physical or mechanical properties of the sheet. As a matter of fact, specific textures have been deliberately produced in steel sheets and utilized advantageously in commercial applications, such as grain-oriented silicon steel or nickel-iron and the deep-drawing low-carbon steels. On the other hand, the effects of texture on the properties of hot-rolled steel sheets or hot-rolled and quenched-and-tempered plates have been widely questioned. This was largely because the textures normally produced in these materials were weak, and when a significantly strong texture was produced, the observed influence on properties could be attributed to other metallurgical factors coexisting with texture.

Recently, a carefully planned study of the effects of texture on the mechanical and ballistic properties of the quenched-and-tempered plates of a medium carbon 5Ni steel was conducted. By appropriate thermomechanical processing treatments, several types of textures each with a range of texture intensities were produced in the quenched-and-tempered plates, while other metallurgical factors were kept practically constant. The various mechanical properties, including tension, through-thickness tension and compression, impact, fatigue, and fracture toughness, together with the ballistic performance of the plates as a function of the intensity of the texture, in particular the (112)+(111) type which could be produced with very high intensities, will be presented and discussed.

MATERIALS AND PROCESSING

The material used in these studies was a medium carbon 5Ni-Si-Cu-Mo-V steel,vacuum-melted and cast into a 7-inch- ($\sim$180 mm) thick rectangular cross-sectioned ingot. The nominal composition of the steel is given in Table I. The ingot

TABLE I

Chemical Composition of Armor Steel in Weight Percent

C	Mn	P	S	Si	Cu
0.40	0.59	0.003	0.004	1.06	0.70
Ni	**Mo**	**V**	**Al**	**N**	**O, ppm**
5.50	0.44	0.073	0.083	0.004	26

was hot-charged into a preheating furnace at 2250°F (1232°C) and soaked at temperature for 2 hours. It was first reduced by preliminary hot rolling to slabs of 4 intermediate thicknesses, namely, 5.50, 2.75, 1.85, and 1.40 inches (140, 70, 47, and 36 mm, respectively). These slabs were then reheated to 1700°F (927°C), soaked at temperature for 2 hours, and isothermally rolled at 1500°F (816°C) to a common final thickness of 0.55 inch (14 mm). A thermocouple, which was inserted into the geometric center of each slab, was used for monitoring the temperature during rolling. The amount of final rolling reduction was, therefore, 60, 70, 80, and 90 percent for the slabs 1.40, 1.85, 2.75, and 5.50 inches thick, respectively. As will be described later, several different kinds of textures could be produced in the final finished plates, depending on the mode or variation of the thermomechanical processing treatment employed before quenching. The water-spray-quenched plates were all tempered at 350°F (177°C) for 1 hour before specimens were prepared for structural and textural examinations and for various mechanical and ballistic tests.

TEXTURAL BEHAVIOR OF THE 5Ni STEEL

The textural behavior of the 5Ni armor steel was investigated extensively with small specimens before the 1/2-inch-thick textured armor plates were processed. The temperature limits in the austenite region for isothermal rolling up to 90 percent reduction without dynamic or static recrystallization and ferrite formation were found to be around 1600 and 1300°F (871 and 704°C), respectively. Within this range of temperatures for isothermal rolling, the effect of initial heating temperature (in the range 1350 to 2100°F or 732 to 1149°C), and the effect of the temperature of post-rolling annealing for recrystallization of the deformed austenite (in the range 1650 to 2000°F or 899 to 1093°C), on the nature and degree of texture of the martensite were also thoroughly investigated.

Results of these experiments indicated that isothermal rolling within the temperature range 1300 to 1600°F (704 to 871°C) develops the *copper-type* rolling texture in the deformed austenite. Annealing at a higher temperature immediately after rolling recrystallizes the austenite and changes the copper-type rolling texture to the cube texture. The sharpness of the cube texture of recrystallized austenite (as deduced from the sharpness of the texture of quenched martensite) will be affected by the reheating temperature, the amount of rolling reduction, and the temperature of the recrystallization anneal in a way that is completely consistent with the principles of rolling and annealing texture formation in fcc metals of high stacking-fault energies.[1-3]

Because the nature and the intensity of the texture of martensite depend entirely on the texture of the parent-phase austenite, the texture of the quenched-and-tempered plates can only be controlled by appropriate thermomechanical processing treatments of the austenite. Results from these experiments indicated that, for straightaway rolling, at least two different kinds of textures, each having variable intensities, could be produced by controlled thermomechanical processing treatments, such as quenching immediately after finish rolling and quenching after the rolled plate was annealed for complete recrystallization.

As is also known, the texture of heavily cross-rolled copper[1,4] or an fcc alloy of low stacking-fault energy, such as 70-30 brass,[1] is substantially different from the texture of the same material when straightaway-rolled. Quenching heavily cross-rolled austenite will, therefore, produce another different kind of texture in the martensite. Recrystallization of the cross-rolled copper produces a texture which is considerably more complex than the cube texture.[4] Hence, a similar processing treatment for the armor steel would not be particularly useful in the present studies because the texture of the martensite would be even more complex than the parent texture of the recrystallized austenite.

Textures of the Thermomechanically Processed Armor Plates

The textures of the 1/2-inch-thick plates, isothermally rolled at 1500°F (816°C) to various reductions, immediately quenched, and subsequently tempered, are shown in Figures 1

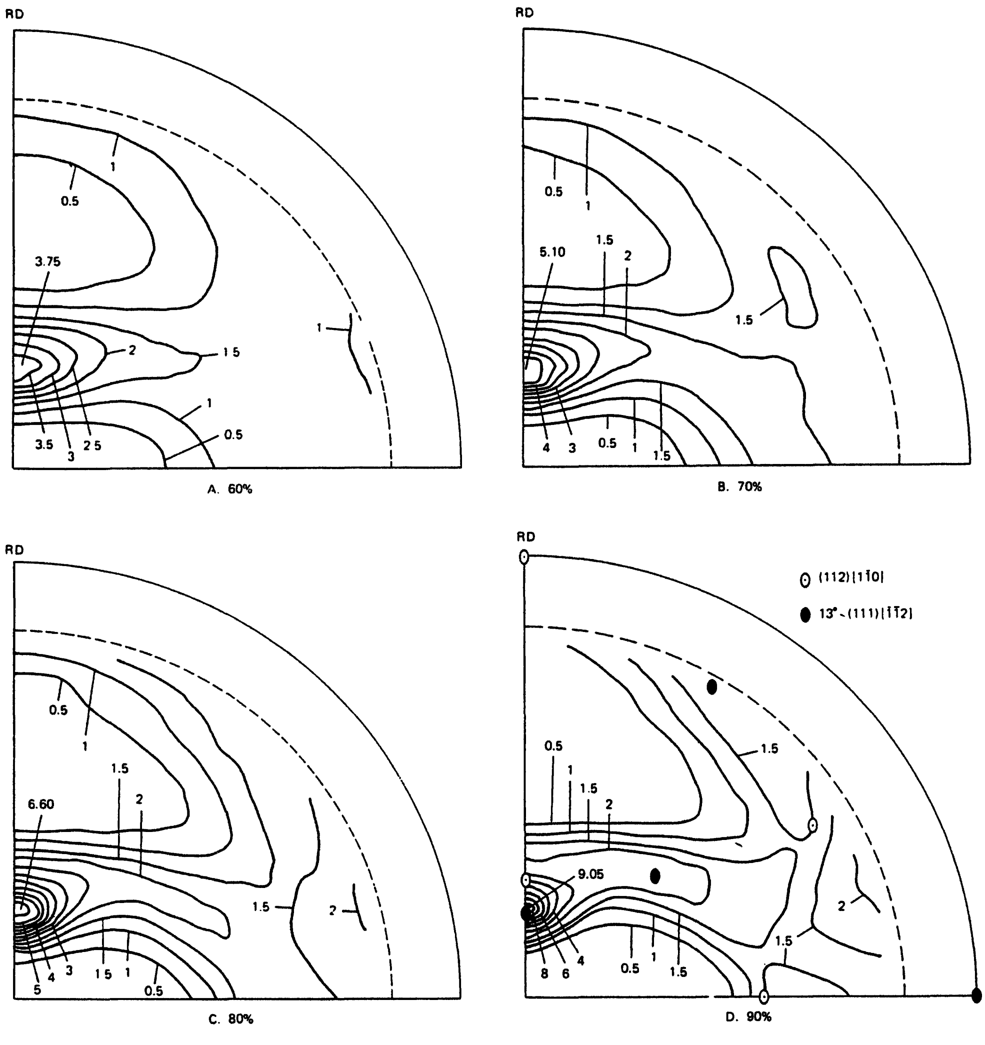


Figure 1. (110) pole figures of plates rolled to various reductions at 1500°F (816°C) then quenched and tempered.

and 2. These are the (110) and (200) pole figures of the plates rolled 60, 70, 80, and 90 percent, and show the same kind of texture for all these plates, although the degree of texture intensity increases with rolling reduction. We call this texture the (112)+(111) type because it consists mainly of {112}<110> and {111}<112> orientations. The highest

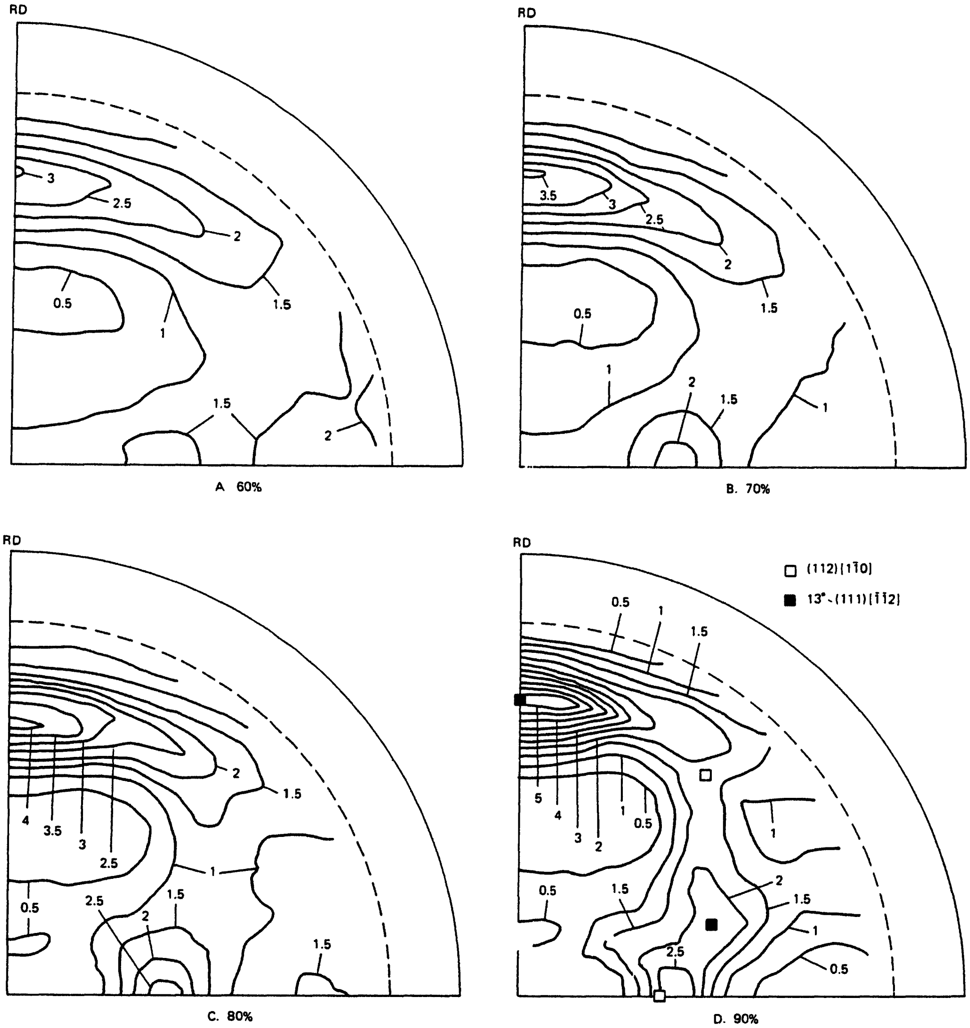


Figure 2. (200) pole figures of plates rolled to various reductions at 1500°F (816°C) then quenched and tempered.

intensity maxima of this type of texture, as shown by the (110) pole figure of the plate rolled 90 percent (D in Figure 1), were approximately 9.1 times random.

A completely different texture was produced by quenching the recrystallized austenite, which had developed a cube texture. The textures of the plates that were isothermally rolled 60 to 90 percent, immediately annealed at 1800°F (982°C) for one hour to recrystallize the deformed austenite, then quenched are shown by the (110) pole figures in Figure 3, and the (200) pole figures in Figure 4. We call this texture the *∿ (110) type*. The intensity of the texture, as in the previous case, increased with rolling reduction. However, the intensity maxima of the texture were much lower than those in the plates quenched from the deformed austenite. The highest intensity maxima in the (110) pole figure were less than three times random (D in Figure 3). Judging from the spread

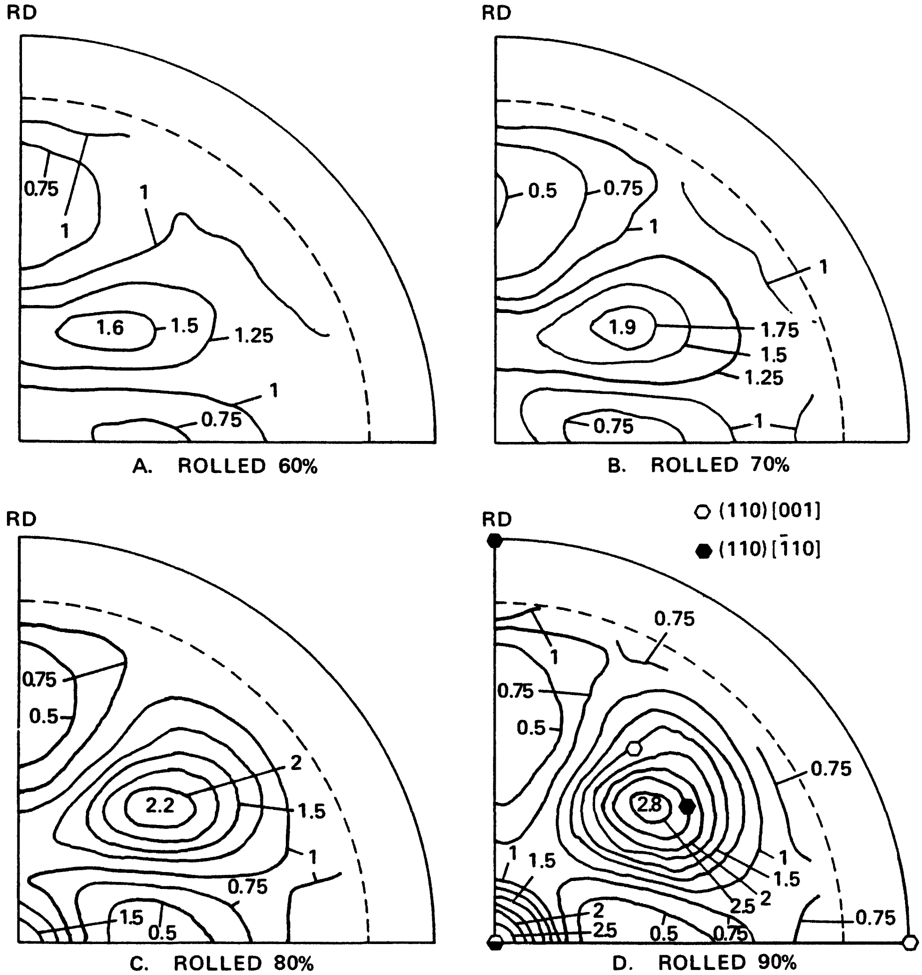


Figure 3. (110) pole figures of plates rolled at 1500°F (816°C) to various reductions, recrystallized, then quenched and tempered.

of this texture, the cube texture was probably not very sharply developed, accounting for the low intensity maxima of the martensite texture.

A third kind of texture of the martensite was produced by quenching cross-rolled austenite. Because of the size limitations of the laboratory rolling mill, these plates were cross-rolled to 60, 70, and 80 percent reductions only, and had a final dimension of 7.5 by 7.5 by 0.55 inch (190 by 190 by 14 mm). It was not possible to use an inserted thermocouple for monitoring the temperature of the plate during rolling; an infrared optical pyrometer was used. The textures of the plates isothermally cross-rolled at 1500°F (816°C) to 60, 70, and 80 percent reductions then water-spray quenched are shown in Figure 5 for the (110) pole figures, and in Figure 6 for the (200) pole figures. We call this texture the *∿(111) type*. This preferred orientation can be more readily recognized with a (222) pole figure, as shown in Figure 7, which was determined from a small-sized specimen

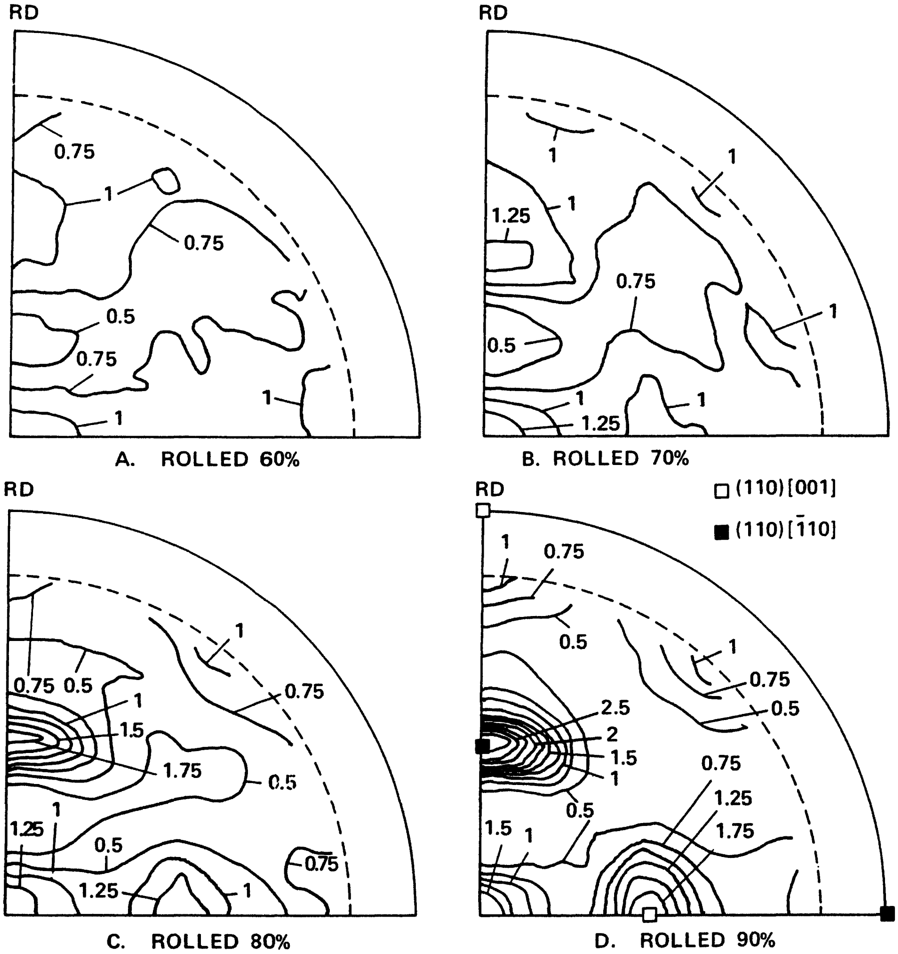


Figure 4. (200) pole figures of plates rolled at 1500°F (816°C) to various reductions, recrystallized, then quenched and tempered.

cross-rolled 90 percent, then quenched and tempered. For reasons unclear at present, the intensity of this texture was also relatively low (about 3 times random) in comparison with that in the straightaway-rolled and quenched plates. We know that the cross-rolling textures of fcc metals or alloys, like copper and brass, are at least as strong as their straightaway-rolling textures.[1] It is possible that cross rolling may induce a greater number of variances in the austenite-to-martensite transformations. As a consequence, the transformation texture may become wider spread and less intense.

HARDNESS AND MICROSTRUCTURE OF THE PLATES

Since all the slabs were reheated to the same temperature and soaked at temperature for the same length of time, the penultimate grain size of the austenite for final rolling was the same. The slabs were all isothermally rolled at 1500°F (816°C) to the same final thickness before quenching, so the

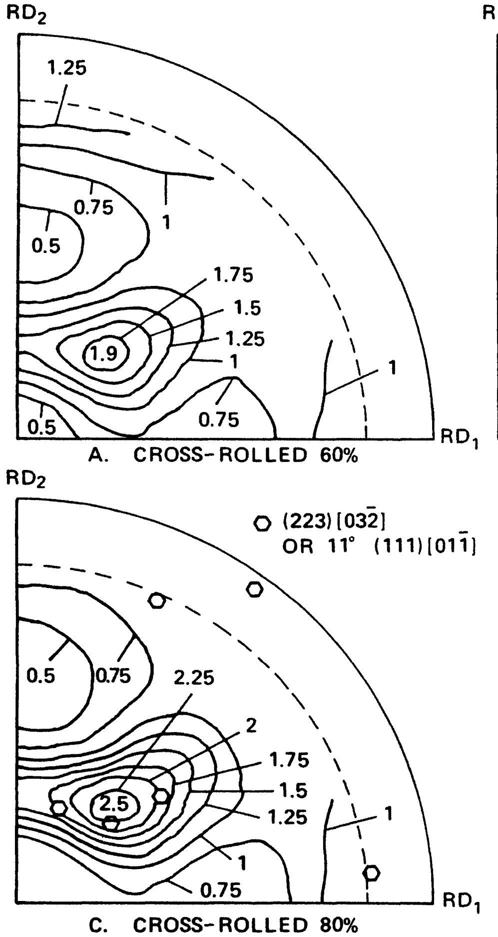


Figure 5. (110) pole figures of plates cross-rolled at 1500°F (816°C) to various reductions, then quenched and tempered.

thermal conditions during rolling and in the immediately followed quenching were the same. After quenching, identical tempering treatment was given to the plates. All the quenched-and-tempered plates had approximately the same hardness, 54 to 56 R_C, the same amount of retained austenite, which was very small (about 3 to 4 percent), and the same martensitic structure. For the straightaway-rolled and quenched plates, the martensitic structure was clearly banded, as shown by the photomicrographs in Figure 8 for the plate rolled 90 percent at 1500°F (816°C). The banding is more clearly shown in the longitudinal section than in the transverse section, and is believed to represent the crystallographically equivalent components of the texture. Such banded structure was equally evident in plates rolled to lower reductions, for example, 60 percent, Figure 9. For the plates processed by quenching the recrystallized austenite, or by quenching the cross-rolled austenite, banding was much less evident, as shown in Figure 10, which is the microstructure of a heavily cross-rolled specimen. There is little difference in the

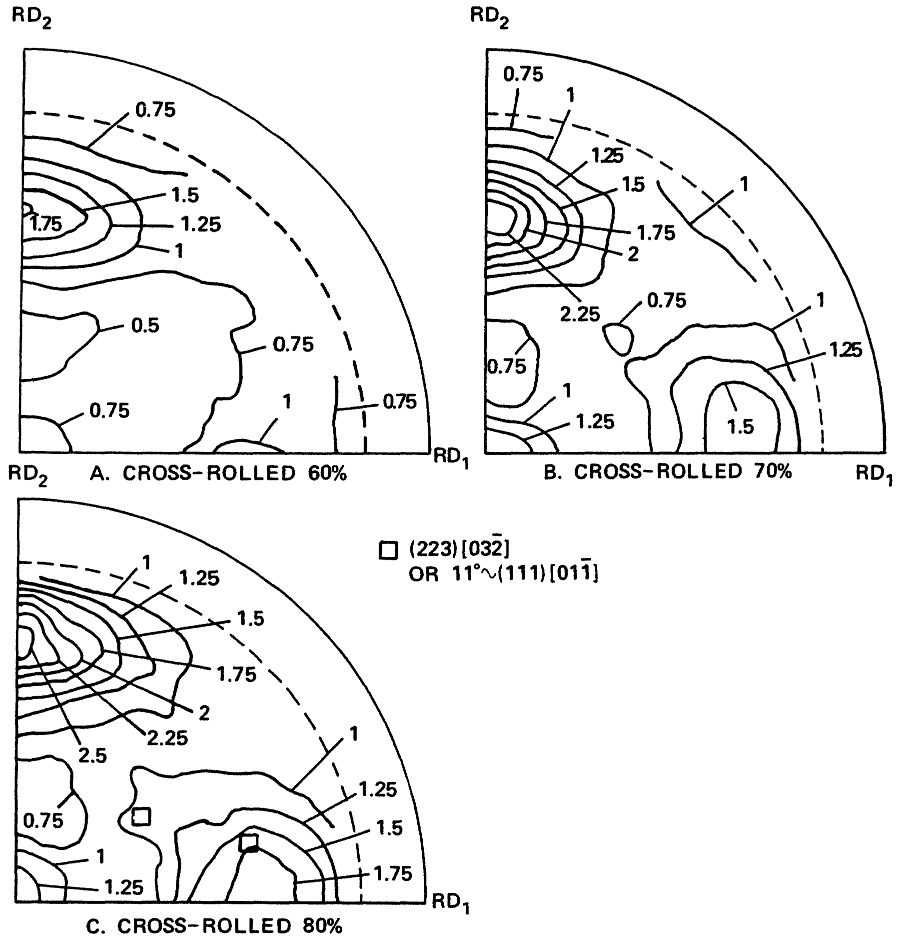


Figure 6. (200) pole figures of plates cross-rolled at 1500°F (816°C) to various reductions, then quenched and tempered.

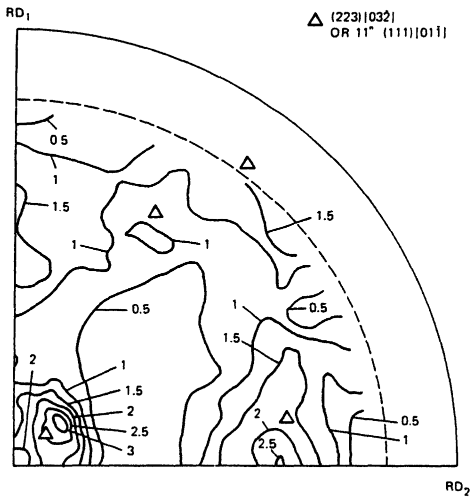
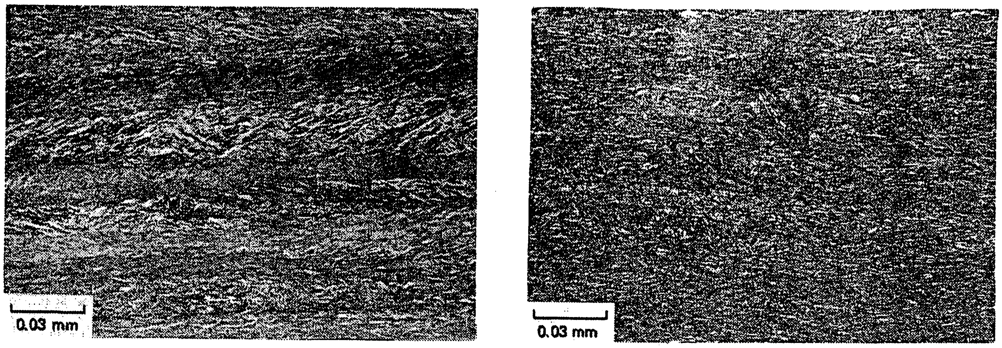
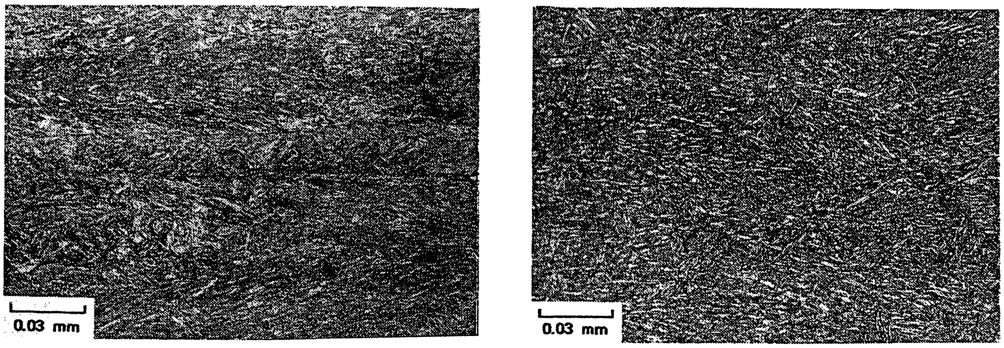


Figure 7. (222) pole figure of the specimen cross-rolled 90 percent at 1500°F (816°C), then quenched and tempered.



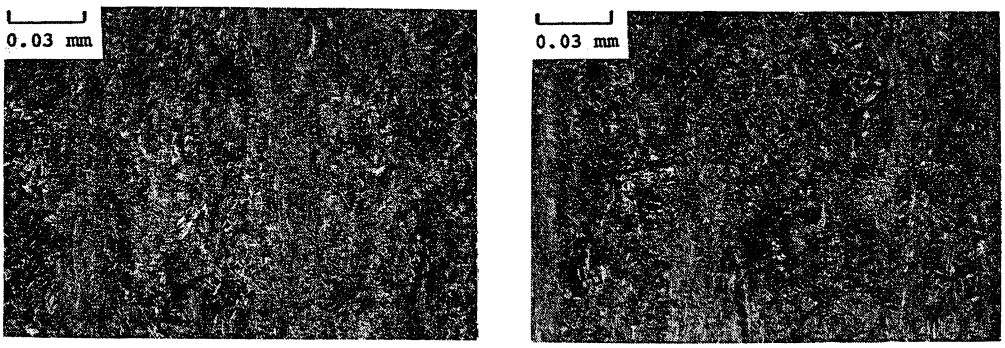
A. LONGITUDINAL B. TRANSVERSE

Figure 8. Microstructure of the plate rolled 90 percent at 1500°F (816°C), then quenched and tempered. X500.



A. LONGITUDINAL B. TRANSVERSE

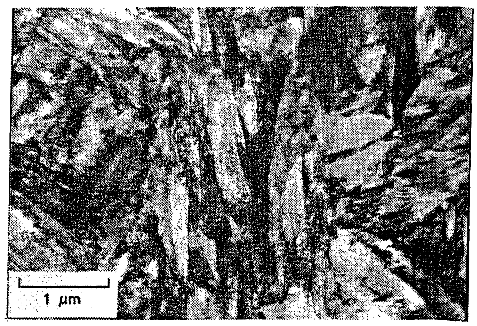
Figure 9. Microstructure of the plate rolled 60 percent at 1500°F (816°C), then quenched and tempered. X500.



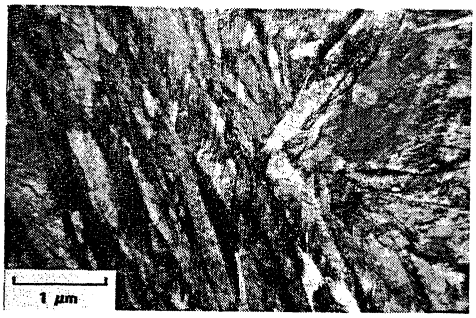
A. SECTIONED PERPENDICULAR (RD_1) B. SECTIONED PERPENDICULAR (RD_2)

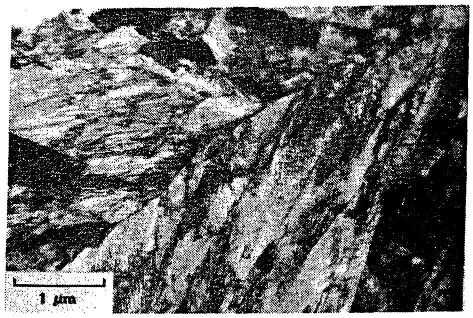
Figure 10. Microstructure of the specimen cross-rolled 90 percent at 1500°F (816°C), then quenched and tempered. X500.

fine structure of the martensite for the plates rolled 60 percent and those rolled 90 percent, as shown by the TEM micrographs in Figure 11.



LONGITUDINAL ROLLED 90% AT 1500°F TRANSVERSE ROLLED 90% AT 1500°F





LONGITUDINAL ROLLED 60% AT 1500°F TRANSVERSE ROLLED 60% AT 1500°F

Figure 11. Transmission electron micrographs showing martensite structures of quenched-and-tempered plates. X19,000.

MECHANICAL AND BALLISTIC PROPERTIES OF TEXTURED ARMOR PLATES

As described in an earlier section, by using three different thermomechanical processing treatments it was possible to produce three different types of textures in the quenched-and-tempered plates. Among these, the (112)+(111) texture, which was produced by quenching straightaway-rolled austenite, was most strongly developed. The other two types of textures, namely the $\sim$(110) and the $\sim$(111), which are produced by quenching the cube-textured recrystallized austenite and by quenching the cross-rolled austenite, respectively, were of considerably lower intensities. As a consequence, the mechanical or ballistic properties of these weakly textured plates were not much different from those of random textured plates. Accordingly, only the properties of the (112)+(111) textured plates will be presented.

Ballistic Performance

The resistance to penetration of the (112)+(111) textured armor was determined by conducting a Protection Ballistic Limit, PBL V_{50} test at obliquities from 0 to 45 degrees. This measures the critical velocity at which the armor target has a 50 percent probability of penetration, with penetration occurring whenever armor or projectile fragments pierce an 0.020-inch-thick aluminum (2024-T351) witness plate located 6 inches behind and parallel to the armor plate.

With the averaged intensity maxima of the (110) pole figure used as an arbitrary parameter, the effect of increasing texture intensity of the (112)+(111) type on the V_{50} ballistic limit for 0 degree obliquity against 0.50 caliber AP M2 projectile is shown in Figure 12*. A 25 percent im-

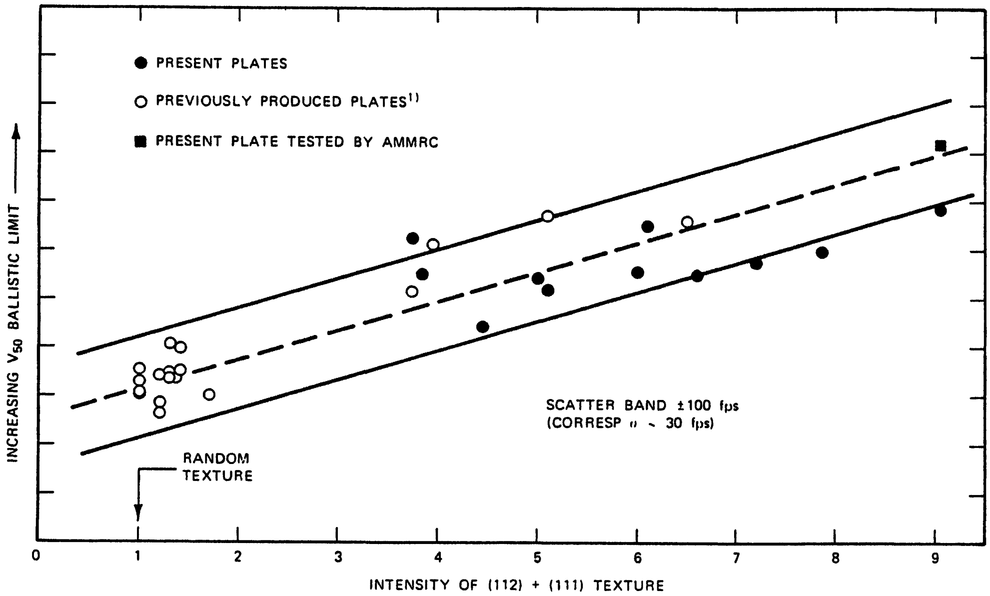


Figure 12. Correlation of the ballistic limit with the intensity of (112)+(111) texture.

provement in ballistic limit is displayed by the textured armor with intensity maxima at about 9.1 over random textured material of equal hardness. The scatter band having ±100 fps corresponds to a standard deviation of $\sigma = 30$. As observed by Abbott,[6] this is an important point for the experimental data, because ballistic limits that have been subjected to statistical analysis by the Test and Evaluation Command at APG (Aberdeen Proving Grounds) for homogeneous steel armor of "uniform good quality" against the caliber 0.50 AP M2 at 0 degree obliquity had a similar standard deviation of about 30 fps. Similar texture dependence of the ballistic limit at 15, 30, and 45 degree obliquities was also established.[7] Theoretical calculations by Ghosh and Paton[8] of the shear and the through-thickness compressive strengths for the ideal orientations of bcc textures appear to be in agreement with the present results.

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*The data represent results from several batches of plates produced at different times.[5] The numerical values of the ballistic limit are withheld because of government security regulations.

Through-Thickness Tension and Compression

As the ballistic limit increases with the intensity of the (112)+(111) texture, the back-spalling tendency of the plates with very high texture intensities, such as the plates rolled 90 percent, appears also to increase. As was suggested by Richmond,[9] the resistance to spalling at a constant strain rate might be determined for plates by testing the through-thickness tensile strength of notched specimens. The geometry of the notched tension-test specimen is shown in Figure 13. The strain conditions in such notched tension-test specimens are similar to those that occur on spalling; that is, the principal strains in the plane of the plate, $\varepsilon_1 = \varepsilon_2 \cong 0$.

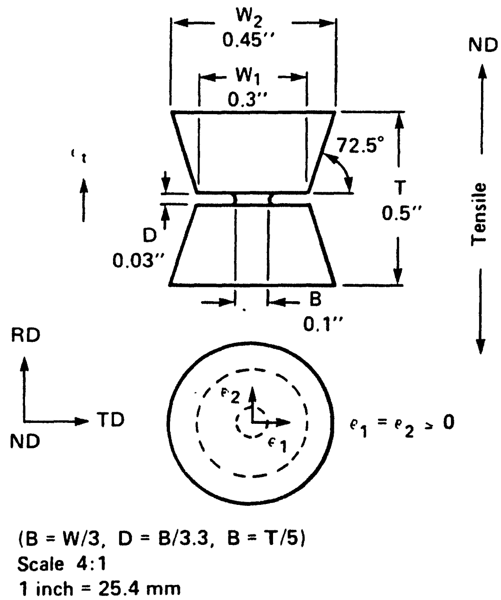

Figure 13. Through-thickness notched tensile specimens for testing spalling resistance of plate (strain rate constant).

Results of such tests are listed in Table II and indicate that the through-thickness tensile strength of notched specimens decreases with increasing rolling reduction or texture intensity, Column (1). For plates quenched from recrystallized cube-textured austenite, there is little difference in the through-thickness tensile strength of the notched specimens for the 90 and 60 percent rolled plates, Column (2). For plates reaustenitized and quenched [from either Column (1) or Column (2)], to essentially random textures, the through-thickness tensile strength of notched specimens is the largest, Columns (3) and (4). This is in agreement with the observation that random plates have a minimal spalling tendency upon ballistic impact. On the other hand, the through-thickness compressive strength of the (112)+(111) textured plates, as shown by the data in Column (1) of Table III, increases with rolling reduction or intensity of the

TABLE II

Through-Thickness Tensile Strength of Notched Specimens from Armor Steel Plates Processed to Various Textures

HR Red. %	Martensite by Quenching (1) Deformed Aust ksi	(MPa)	(2) Recryst Aust ksi	(MPa)	Martensite by Reaustenitizing (3) & Quenching (1) ksi	(MPa)	(4) & Quenching (2) ksi	(MPa)
90	346.6	(2390)	419.8	(2895)	---	---	---	---
80	391.8	(2701)	---	---	---	---	---	---
70	385.7	(2659)	---	---	---	---	---	---
60	415.0	(2861)	424.1	(2924)	434.4	(2995)	435.9	(3006)

TABLE III

Through-Thickness Compressive Strength of Steel Plates Processed to Various Textures

Hot-Rolled Reduction, %	Martensite by Quenching (1) Deformed Austenite, ksi	(2) Recrystallized Austenite, ksi	Martensite by Reaustenitizing (3) and Quenching (1), ksi	(4) and Quenching (2), ksi
90	273.0	254.6	246.5	257.0
80	268.6	258.0	248.0	261.9
70	265.2	256.6	250.0	265.8
60	261.4	251.1	252.9	261.9

1 ksi = 6.895 MPa

texture. For plates having very weak or random textures, the through-thickness compressive strength is nearly the same irrespective of the prior rolling reduction, Column (2), (3), or (4).

Planar Tensile Properties

The planar or in-plane tensile properties of the (112)+(111) textured plates are shown in Table IV. The strength and ductility of the plates varied only insignificantly as a function of either rolling reduction or degree

TABLE IV

Tensile Properties of (112)+(111) Textured Steel Plates

Hot-Rolled Reduction, %	Yield Strength, ksi		Tensile Strength, ksi		Reduction of Area, %		Total Elongation in 1 Inch, %	
	L	T	L	T	L	T	L	T
90	225.5	245.9	298.6	318.1	51.3	31.3	15.0	10.0
	T/L	1.090	1.065		0.610		0.667	
80	230.3	250.0	303.2	315.9	50.0	34.0	16.0	11.5
	T/L	1.086	1.042		0.680		0.719	
70	219.1	231.8	303.2	313.0	51.3	35.0	15.0	12.3
	T/L	1.058	1.032		0.682		0.820	
60	229.5	238.0	293.8	308.1	51.3	36.1	14.0	11.8
	T/L	1.037	1.049		0.704		0.843	

1 ksi = 6.895 MPa

of texture. However, there was a marked anisotropy in yield strength and ductility, which increased with rolling reduction. These are shown in the T/L ratios of the properties for yield strength, reduction in area, and total elongation. These ratios increasingly deviate from unity as rolling reduction, hence degree of texture increases.

Charpy Impact and Transition Temperature

For impact property studies, the standard full-size Charpy V-notch specimens were prepared from the (112)+(111) textured plates. As illustrated in Figure 14, specimen orientations were longitudinal (L-T), transverse (T-L), or 45 degrees (LT-LT) to the rolling direction with the standard notch orientation in the thickness direction of the plate (edge-notched). However, to establish whether there was any effect of notch orientation for the highly textured material, specimens were also notched parallel to the plate surface, such as the (L-S), (T-S), and (LT-S) specimens (face-notched).

The Charpy transition temperature, which is defined as the lowest temperature at which 100 percent fibrosity of the fractured surface still exists, was determined for each orientation and texture intensity by breaking a series of specimens over a range of temperatures. A typical curve of these test results is shown in Figure 15 for the highly textured plate. As is well known, for high-strength materials, the energy curve is fairly flat, and the measurement of fibrosity of the fractured surface requires skill and experience. Larson and Nunes[10] showed that, for steels heat-treated to

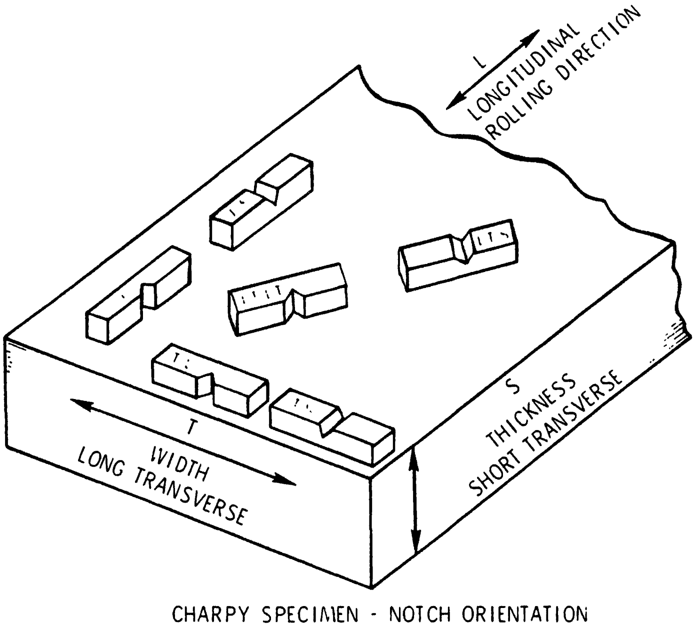

Figure 14. Illustration showing the Charpy specimen and notch orientations.

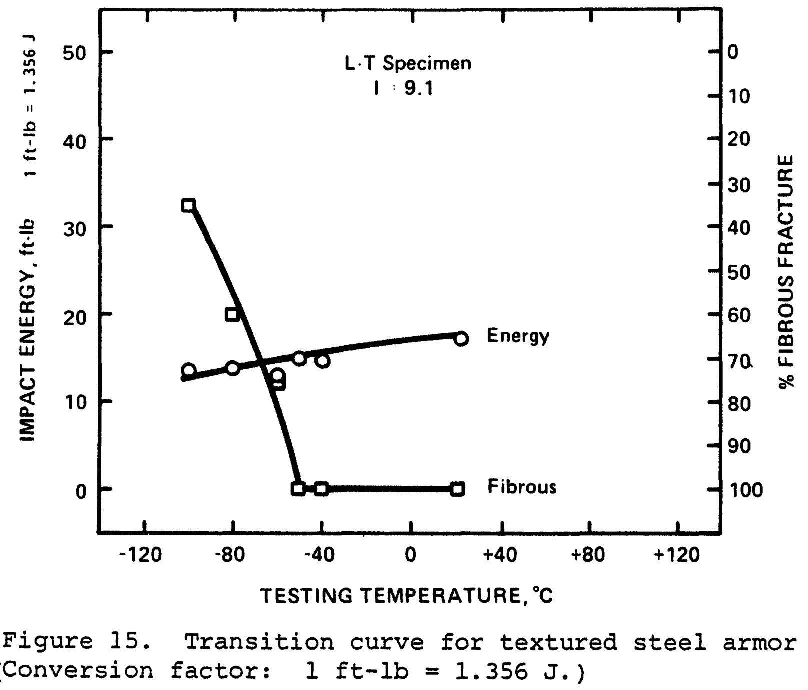

Figure 15. Transition curve for textured steel armor plate. (Conversion factor: 1 ft-lb = 1.356 J.)

various strength levels, there is a linear relationship between fracture surface appearance, fibrosity, and impact energy. It was found that although the transition temperature was not influenced by the specimen and notch orientations, the intensity of the (112)+(111) texture had a marked effect on the transition temperature, as shown in Figure 16. The transition temperature decreases with increasing texture. Similar effects of texture on toughness were observed for low-carbon steel by Bramfitt and Marder,[11] and for pure iron by Kaneko and Terasaki.[12]

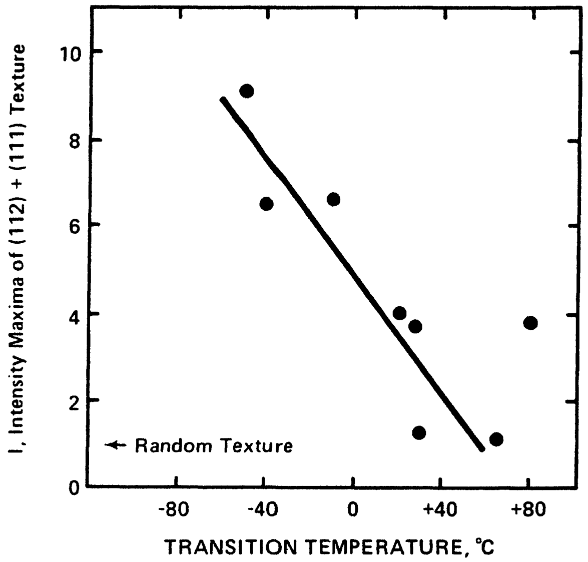

Figure 16. Effect of texture intensity, I, on the transition temperature of steel armor plate.

Fracture Toughness

The influence of texture on the fracture toughness, K_{Ic} plane strain, has received very little attention. To study the textural effects on this property, precracked Charpy specimens of longitudinal, transverse, and diagonal (45°) orientations were tested by three-point bending at a head-speed of 0.05 in. (1.3 mm)/min. For the highly textured and random-textured materials, both edge-notched and face-notched specimens were tested. The K_Q values, which are considered provisional to K_{Ic}, are shown as a function of the texture intensity in Figure 17. The K_Q values of the strongly textured plates are substantially higher than those of the random textured material. The face-notched samples show substantially higher fracture toughness than the edge-notched specimens, up to 30 percent for the diagonal (45°) specimen, which has the highest fracture toughness.

Fatigue

The variation of fatigue life with specimen orientation in textured materials has not been the subject of much investigation. However, recent discoveries have indicated that large improvements in hcp titanium fatigue life are possible and related to the influence of texture upon crack nucleation.

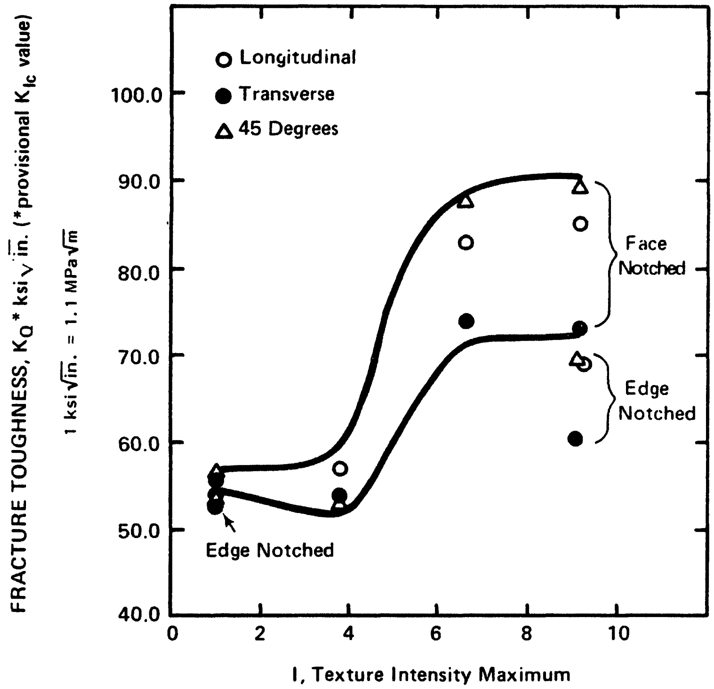

Figure 17. Effect of specimen notch orientations and texture intensity on the fracture toughness of steel armor plate. (Conversion factor: 1 ksi $\sqrt{in.}$ = 1.1 MPa $\sqrt{m}$.)

Fatigue anisotropy was also reported for fcc metals with a high degree of preferred orientation.[14]

To determine whether texture can affect the fatigue life of high-strength steel, a limited number of hour-glass-shaped specimens were machined from the textured plates along the longitudinal, transverse, and diagonal (45°) directions. Samples were tested at room temperature in tension-tension at a stress ratio of R = 0.1 at 1800 cpm. Typical S-N curves were obtained for the plate having a texture intensity of 7.9, as shown in Figure 18. It is evident that large variations have been found for fatigue life in both the high stress region and at the endurance limit. The diagonal or 45° specimen orientation has approximately a one and one-half order of magnitude superiority over the longitudinal orientation in the high stress region, with long cycle life at 85 percent of the yield strength. For this specimen orientation, the endurance limit is high. Taking it as 170 ksi (1172 MPa), the endurance limit is about 57 percent of the tensile strength.

SUMMARY AND CONCLUSIONS

1. By means of appropriate thermomechanical processing treatment in the austenite region of the 5Ni armor steel, at least three different kinds or types of textures, each having various degrees of intensity, can be produced in the quenched

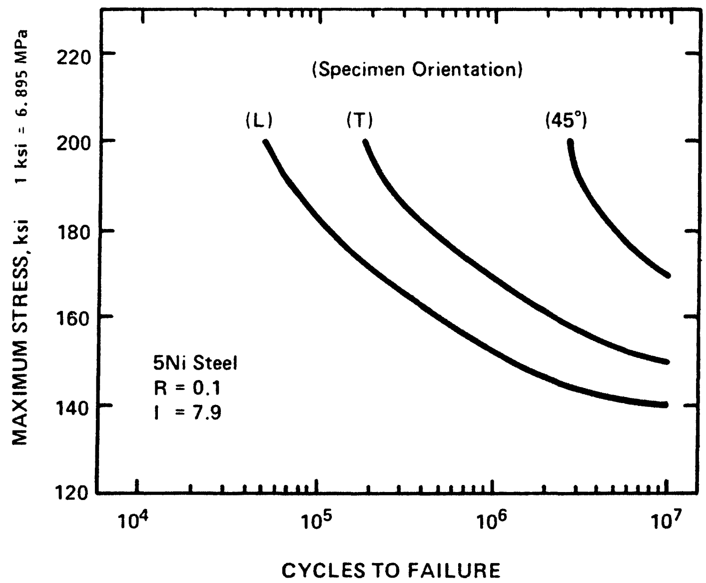

Figure 18. Effect of specimen orientation on the fatigue life of textured steel armor plate. (Conversion factor: 1 ksi = 6.895 MPa.)

and tempered high-hardness steel armor plates. Among the three types of textures, namely (112)+(111), ∿(110), and ∿(111), the (112)+(111) type was produced with very high intensities. For reasons not completely known at present, the other two types of textures were produced with relatively low intensities.

2. The ballistic performance of the (112)+(111) textured plates was substantially superior to that of random-textured plates at the same hardness. The V_{50} ballistic limit increases with increasing texture intensity of the plate at all obliquities from 0 to 45 degrees. A 25 percent improvement in the ballistic limit was observed in the (112)+(111) textured plates with an intensity maximum of I = 9.1 over that of the plate having a random texture.

3. The degree or intensity of the (112)+(111) texture was also found to influence other mechanical properties of the plate. Besides the through-thickness tensile and compressive strengths of the plate, which were affected by the intensity of the texture, the in-plane or planar anisotropy of the plate was established for tensile properties, impact energy, fracture toughness, and fatigue life. In addition, it was ascertained that the notch orientation can significantly affect the fracture toughness and impact energy of the textured material.

4. Although the production of better armor plate which will provide maximum protection of personnel or vital components for a minimum weight penalty is a primary goal, it should be realized that the technology base being built from these research findings could be easily transferred to other applications in which the optimization of mechanical properties can be obtained via "tailor-made" textured materials.

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