DYNAMIC CHARACTERIZATION OF INTERCRITICALLY ROLLED HIGH-HARDNESS STEEL

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METALS RESEARCH DIVISION

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**Dynamic Characterization of Intercritically Rolled High-Hardness Steel**

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- High strength steels
- Armor
- Fracture toughness
- Heat treatment

**Abstract:**

(See reverse side)
Two compositions of intercritically rolled homogeneous steel armor were evaluated by quasi-static and dynamic tests. Cross-rolling just below the intercritical temperature resulted in improved fracture toughness at the high-hardness levels (55 and 58 HRC). Taylor cylinder ballistic impact tests indicated a dynamic stress more than double the quasi-static yield stress. The use of this test for evaluating potential high-hardness armor material is discussed.
INTRODUCTION

Higher hardness in armor plate generally leads to improved ballistic performance. The limiting factor at high-hardness levels is gross plate shattering, which rapidly reduces the ballistic limit. This limitation has led to the use of dual-hard armor with a high-hardness front plate and relatively ductile metallurgically roll-bonded rear plate. The high processing costs of dual-hard armor, however, have led to their replacement by specially processed rolled homogeneous steel armor.

Recently, a comprehensive study was undertaken by the U.S. Steel Corp. to develop steel compositions and processing techniques to attain high-hardness armor with adequate shatter resistance. For the quench-and-tempered steels it became apparent that the optimum rolling temperature was slightly below the ferrite-austenite \( A_\text{3} \) transformation temperature. The interest in intercritical* (IC) rolling was based on earlier work on IC heat treatments that produced increased strength and fracture toughness, along with reduced back spalling during ballistic impact. The resultant microstructure of reduced banding, microstructural refinement, and finely dispersed \( \alpha \) (ferrite) and \( \alpha' \) (martensite) regions is desirable in terms of ballistic performance.

A natural extension of IC heat treatments is the use of IC rolling to further refine the microstructure. This is possible since the low temperatures used essentially prevent recrystallization. The two hypoeutectoid steels (Table 1) that are the subject of this study were obtained from the U.S. Steel Corp. The transformation and processing temperatures are shown in Table 2. A number of microstructural features are a direct result of IC rolling. Intercritical holding time is also a factor since a high-carbon austenite results from the \( \alpha \)-phase rejection of carbon. The finely dispersed \( \alpha \)-regions are refined during IC rolling, producing a layered microstructure of ferrite and austenite. On quenching, after IC rolling, \( \alpha' \) forms in the austenite and the resulting retained austenite and banded \( \alpha+\alpha' \) would be expected to provide improved longitudinal fracture toughness. This microstructure can be undesirable, however, in armor applications where failure by delamination is strongly influenced by microstructural layering. On the other hand, refining the microstructure by thermomechanical treatments should result in spalling resistance at least equivalent to that of conventionally processed rolled homogeneous armor. Crystallographic preferred orientations produced in the austenite at high temperatures are not destroyed on quenching. The high carbon \( \gamma \) (austenite) transforms to high carbon \( \alpha' \).

*The intercritical region is the two-phase \( \alpha+\gamma \) region bounded by \( A_1 \) and \( A_3 \).

Quenching from below $A_3$ reduces the amount of retained $\gamma$. These factors are known to influence strength, toughness, and the resultant penetration resistance.\textsuperscript{1-3} Carson et al.\textsuperscript{2} found that quench-and-tempered IC rolled homogeneous armor plate had improved ballistic performance without plate shattering.

<table>
<thead>
<tr>
<th>Chemical Composition, Weight Percent*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>0.39C</td>
</tr>
<tr>
<td>0.47C</td>
</tr>
</tbody>
</table>

*Material obtained from U.S. Steel Corp. in the processed condition.

<table>
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<th>Transformation and Processing Temperatures*</th>
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</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>0.39C</td>
</tr>
<tr>
<td>0.47C</td>
</tr>
</tbody>
</table>

*Calculated values (Ref. 2).

The two compositions in Table 1 were studied to determine the dynamic characteristics important to armor applications. In addition to tensile and fracture toughness testing, Taylor projectile impact tests were also conducted.\textsuperscript{9,10} Material characterization requires that test conditions be relevant to those encountered in service. This is particularly true for armor applications where strain rates above $10^4$ sec$^{-1}$ are encountered. The Taylor impact test relates the length change of an impacted flat-end projectile to a dynamic flow stress. The test procedure is relatively simple. The projectile is fired at a right angle to a rigid, thick target. Low impact velocities are used to prevent fracture. Contrary to expectations, the measured Taylor stress of moderate strength materials is nearly independent of projectile impact velocity.\textsuperscript{10-13} These expectations are based on tension and compression results in the $10^{-4}$ to $10^3$ sec$^{-1}$ strain rate range. However, a collection of tension and compression results by Soohoo et al.\textsuperscript{14} show the strain rate dependence of yield strength, though significant at low- and intermediate-strength levels, becomes negligible at the high strength levels.

Measurement of the impact velocity and deformed projectile length permit calculation of the Taylor dynamic flow stress $\Delta_0$ from the equation:


\[ \frac{L_f}{L_0} = \exp \left[ -\frac{\rho V^2}{2Y^2} \right], \]

1. \( L_f \) = final projectile length,
2. \( L_0 \) = original projectile length,
3. \( \rho \) = density, and
4. \( V \) = impact velocity.

In Equation 1, \( Y \) represents an "average" flow stress that a cylindrical rod experiences as it decelerates and deforms into a mushroom-shaped rod. The length measurement is made after the impacted end of the projectile undergoes gross deformation with negligible, if any, deformation at the opposite end of the projectile. Therefore, \( Y \) represents neither a yield stress nor ultimate stress (i.e., stress at maximum load).

Tests by Taylor\(^9\) and others,\(^10-13,15\) were performed using low strength materials. In all cases, \( Y \) was higher than the quasistatic value. More recently, Papirno et al.\(^16\) applied the Taylor test to high-strength 4340 steel and found that the dynamic stress was almost double the static compression yield stress.

**MATERIALS**

The rolled homogeneous armor steels tested (Table 1) were received in the IC rolled-and-tempered condition. The higher carbon alloy is a standard armor steel (0.50C-1.1Ni-0.75Cr-0.50Mo) modified with 0.2 percent vanadium. Although the alloys were intercritically cross-rolled with a final rolling ratio of one-to-one, there was still microstructural evidence of a "rolling direction." All mechanical test specimens were oriented with reference to the apparent longitudinal direction of the 5/8-inch-thick plates.

Figure 1 shows the heavily banded structure for both alloys. Areas (dark) of dense carbide precipitation are also evident. At higher magnification, the 0.47C alloy has a finer lath martensite packet size. Rolling conditions and quench rates produced no noticeable difference in microstructure at the surface and midsection planes (Figure 2). The 0.47C alloy has a finer grain structure with carbides strung out along prior austenite grain boundaries. The bands appear as patches when viewed normal to the plate (Figure 2).

**EXPERIMENTAL PROCEDURES**

Selected room temperature tests were performed to complement those reported by the U.S. Steel Corp. Research Laboratory.\(^2,3\) Static tension tests were performed parallel to the plate rolling direction. Computerized instrumented Charpy testing equipment was used to obtain the dynamic fracture toughness data. Charpy impact and dynamic fracture toughness tests were performed in the LT and TL directions.

Taylor impact projectiles, 0.218-inch diameter and 0.436-inch long, were machined from a 5/8-inch plate with the specimen axis in the short transverse and longitudinal directions. The projectiles were fired from a 0.218-inch-diameter smooth bore light gas gun at a thick hardened-steel plate. Precautions were taken to ensure normal impact and accurate final length ($L_f$) measurements.* Velocities were measured with a pair of silver-coated paper screens located close to the target.

![Magnification 100X](image1)

![Magnification 1000X](image2)

(a)

Figure 1. Photomicrographs of the plane normal to the rolling direction (a) for the 0.47C and (b) for the 0.39C homogeneous intercritically rolled steel armor. Picral etch.

*PAPIRNO, et al.\textsuperscript{16} clearly demonstrated that for high-strength materials, where length shortening is small, the uncertainty in $L_f$ can result in a significant error in the calculated Taylor stress.
Figure 2. Photomicrographs of the plane parallel to the rolling direction (a) outer surface plane (b) plane at midthickness of homogeneous intercritically rolled homogeneous armor. Picral etch. Mag. 100X.
RESULTS AND DISCUSSION

The 0.47C steel, as expected, had higher hardness and static strength levels (Tables 2 and 3), lower ductility (Table 3), and lower Charpy impact energy (Table 4). The lack of orientation effects for both steels are a result of cross-rolling. The Charpy energy levels are slightly higher than other high strength steels. Apparently, at these moderate strain rates, IC rolling and the structural refinement are beneficial. Similar results are found for the dynamic fracture toughness specimens (Table 5). Again, fracture toughness is lower at the higher strength level, orientation plays no significant role, and values reported are higher than for comparable high strength steels.

Table 3. LONGITUDINAL TENSILE PROPERTIES

<table>
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<tr>
<th>Material</th>
<th>0.2% YS (ksi)</th>
<th>UTS (ksi)</th>
<th>TFS (ksi)</th>
<th>Elon. (%)</th>
<th>RA (%)</th>
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<tr>
<td>0.39C</td>
<td>226</td>
<td>320</td>
<td>409</td>
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<tr>
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<td>240</td>
<td>317</td>
<td>401</td>
<td>0.09</td>
<td>11</td>
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<td>351</td>
<td>411</td>
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<td>275</td>
<td>353</td>
<td>415</td>
<td>0.08</td>
<td>9</td>
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<td>-</td>
<td>355</td>
<td>420</td>
<td>0.07</td>
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TFS - True Fracture Stress
n - Strain Hardening Exponent

Table 4. CHARPY IMPACT ENERGY

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<th>Material</th>
<th>Orientation</th>
<th>Energy ft-lb</th>
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<tr>
<td></td>
<td>TL</td>
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<td>17.8</td>
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<td>10.3</td>
</tr>
<tr>
<td></td>
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<td>12.1</td>
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<td>11.2</td>
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<tr>
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Table 5. DYNAMIC FRACTURE TOUGHNESS

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<th>Material</th>
<th>Orientation</th>
<th>K_10 (ksi\cdot\text{in.}^{-\frac{1}{2}})</th>
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<tr>
<td>0.39C</td>
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<td>62.3</td>
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<td>TL</td>
<td>52.6</td>
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Two compositions of intercritically rolled homogenous steel armor were evaluated by quasi-static and dynamic tests. Cross-rolling just below the intercritical temperature resulted in improved fracture toughness at the high-hardness levels (55 and 58 HRC). Taylor cylinder ballistic impact tests indicated a dynamic stress more than double the quasi-static yield stress. The use of this test for evaluating potential high-hardness armor material is discussed.
Table 6 lists the cylinder impact test results along with specimen orientations. There is a lower and upper velocity limit that can be used for these tests. The higher velocities produced excessive deformation resulting in specimen fracture along a 45° shear plane (Figure 3). This observation is consistent with the reported cone-shaped fracture observed in cylinder impact tests of high strength 4340 steel. At lower velocities (not shown in Table 6) length shortening was insignificant. The impact data suitable for Taylor model calculations are shown with an asterisk. The harder, higher carbon alloy has the higher dynamic Taylor stress $Y^0$ while both steels show no strong orientation effect. The $Y^0$ is more than double the static 0.2 percent yield stress.

### Table 6. CYLINDRICAL IMPACT DATA

<table>
<thead>
<tr>
<th>Material</th>
<th>Orientation</th>
<th>Velocity (ft/sec)</th>
<th>Original Length $L_0$ (in.)</th>
<th>Final Length $L_f$ (in.)</th>
<th>$L_f/L_0$</th>
<th>$Y^0$ (ksi)</th>
<th>Impact Observation</th>
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<tbody>
<tr>
<td>0.39C</td>
<td>Short Transverse</td>
<td>640</td>
<td>0.440</td>
<td>0.424</td>
<td>0.963</td>
<td>578</td>
<td>Shear Cracking - No separation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>697*</td>
<td>0.441</td>
<td>0.422</td>
<td>0.956</td>
<td>578</td>
<td>Deformation - No cracking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>706</td>
<td>0.441</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Shear Fracture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>730</td>
<td>0.439</td>
<td>-</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>820</td>
<td>0.440</td>
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<td>-</td>
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</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>630</td>
<td>0.440</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Shear Fracture</td>
</tr>
<tr>
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<td>0.425</td>
<td>0.966</td>
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<td>653</td>
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<td>Shear Fracture</td>
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<td>0.959</td>
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<td>Shear Cracking - No separation</td>
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<td>Shear Fracture</td>
</tr>
<tr>
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<td>658</td>
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<td>-</td>
<td>-</td>
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<td>Shear Fracture</td>
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<td>658*</td>
<td>0.442</td>
<td>0.425</td>
<td>0.962</td>
<td>578</td>
<td>Deformation - No cracking</td>
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<td>672</td>
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<td>-</td>
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<td>Shear Fracture</td>
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<td>Deformation - Crack initiation</td>
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<td>Deformation - Crack initiation</td>
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<td>-</td>
<td>-</td>
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<td>0.440</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Shear Fracture</td>
</tr>
</tbody>
</table>

*Data used in Taylor Calculation
The quasi-static yield, Charpy impact, and Taylor impact results are summarized in Figure 4 and compared with published data for quenched-and-tempered AISI 4340 steel.\textsuperscript{16,19-25} The $Y^0$ band\textsuperscript{16} represents two L/D ratios, the L/D = 2 ratio generally having higher values than L/D = 4. The most significant observation is the high value of $Y^0$ for the IC rolled material. At the high-hardness level $Y^0$ for the 4340 steel is double the quasi-static tensile yield strength. This ratio is approximately 2-1/2 for the IC rolled material. The reason for the superior performance of the intercritically rolled material is not known.

The experimental simplicity and ease of calculations make the Taylor test desirable for evaluating potential armor materials. A high dynamic Taylor stress (actually an approximate average flow stress) would give some guidance in the search for increasing hardness and impact resistance. Unfortunately, no studies have been reported relating armor performance and the calculated $Y^0$. In addition, there is only a small body of literature comparing quasi-static and Taylor impact tests for low-strength materials. Only recently have results been reported for high-strength alloys.\textsuperscript{16} Based on experimental and theoretical analysis, Papirno et al.\textsuperscript{16} concluded that Equation 1 is nonconservative when applied to high strength steels. Also included in that paper is a discussion of the experimental sophistication necessary for the Taylor test.

![Figure 3. Cylindrical fracture plane.](image-url)

\textsuperscript{20} Allegheny Ludlum Steel Corp., Extrusion Laboratory. Mechanical Test Results on Various Extruded Materials. January 1956.
Figure 4. Taylor stress, tensile yield stress, and Charpy impact energy of quenched-and-tempered AISI 4340 steel (shaded areas, Ref. 16, 19-25) and intercritically rolled steel.

CONCLUSIONS

1. Intercritically rolled homogeneous armor steel has higher strength and toughness than armor processed by a conventional quench-and-temper treatment.

2. The dynamic Taylor flow stress $Y_0$, obtained from the cylinder impact test, is more than double the quasi-static tensile yield strength of the two steels tested.

3. The relatively simple Taylor impact test is a potential method of evaluating candidate armor materials.

ACKNOWLEDGMENTS

The authors thank Dr. Gregory B. Olson and John Mescall for helpful discussions during the preparation of this report.
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