CRACKING OF COLD DRAWN RESULFURIZED TYPE 303
HEXAGON BARS

by

PAUL ALAN GAULT

SUBMITTED TO THE DEPARTMENT OF
MATERIALS SCIENCE AND ENGINEERING
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MATERIALS SCIENCE AND ENGINEERING

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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submitted to the Department of Materials Science and Engineering on May 7, 1982 in partial fulfillment of the requirements for the degrees of Master of Science in Metallurgy and Bachelor of Science in Materials Science and Engineering

ABSTRACT

Observation and experiments were used to gain an understanding of the causes and potential solutions of a serious cracking problem in cold drawn Type 303 hexagons. The mechanism of this cracking was initiation at surface defects with tangential tensile residual stresses being the driving force. The cracks propagate from sulfide to sulfide, separating the sulfide from the surrounding matrix.

Micro-hardness testing showed a higher overall hardness in cracked bars than in uncracked bars. Scanning Electron Microscopy of the crack surfaces did not show any consistent, significant concentration of foreign elements.

There are a number of potential factors affecting the incidence of cracking including surface defects, size and section, pickling, and heat processing parameters. No single factor can be distinguished as the dominant cause of cracking. Determination of the affect of heat processing parameters was inconclusive due to the number of downstream variables.

Attempts at reduction of cracking can be characterized into three groups: reduction of surface defects, reduction of residual stresses, and reduction of cracking due to pickling. Methods for the reduction of cracking are discussed and compared.

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</tr>
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I would also like to thank Dr. Jeryl Wright, and the rest of the employees at the Crucible Specialty Metals Division of Colt Industries for their assistance in the research of this thesis.

Special appreciation is owed to Mr. William Nesspor for his support and guidance during my three periods of employment with Crucible.
INTRODUCTION

A) STATEMENT OF MANUFACTURING PROBLEM

The research for this thesis was done at Crucible Specialty Metals Division of Colt Industries as part of a cooperative work study program. The problem presented to me was one that had been evident for more than 20 years. The basic problem is that cold drawn hexagonal bars of Crucible Type 303 PLUS have a high rejection rate due to longitudinal cracks. The purpose of this thesis is to identify possible causes for the cracking and suggest possible solutions.

The cracks noted in this product are of variable length, width and depth. The length of the cracks varies from the full length of a 22 foot bar down to a couple of inches. The width of the cracks varies from approximately 1/8 inch down to a crack which is barely detectable to the unaided eye. The depth of the cracks varies from one quarter of the radius to the full radius.

An attempt was made to classify all the cracks found into three types as part of the investigation of this problem. Type A cracks (Figure 1) were identified as short, very tight cracks with little depth. Type B cracks (Figure 2) were identified as long, moderately open cracks with considerable depth, but not to the center of the bar. Type C cracks (Figure 3) were identified as long, wide open cracks which extended to the center of the bar. This effort at classification failed because of the difficulty of making a conclusive distinction in many cases.
Type A - Strain Cracks

Length: Short, straight
Width: Barely
Depth: Shallow

FIGURE 1: Type A cracks
Type B - Strain Cracks

- Length: Long, straight
- Width: Moderately open
- Depth: Varies, not to center of bar

FIGURE 2: Type B cracks
**Type C - Strain Cracks**

Length: Long, jagged, rough

Width: Wide open

Depth: To center of bar

**FIGURE 3: Type C cracks**
All cracks were located near the center of a face of the bars. No cracks were found on the corner of a bar. In most cases cracking was limited to a single face of a bar. The exceptions to this showed cracking on two adjacent faces with one crack ending before the second crack started.

The cracking of this product has a time-delayed character. Although many cracks are noted during processing in the cold drawing area, the final determination of quality is an eddy current test usually performed a few days after the final draw pass. Observation of orders during cold drawing and eddy current testing indicate that cracking can occur anywhere from a few seconds after exiting the die to a few hours later.

The rejection rate for this product varies with the size produced (Table 1). The major problem area is between 0.750" and 1.500".

Examination with a light microscope, (Figure 4), shows that the cracks propagate from inclusion to inclusion. These inclusions are manganese sulfides which are characteristic of this grade. The crack separates the sulfides from the matrix.

Many cracks are noted to follow surface defects on the bars. This leads to the proposed mechanism for cracking being initiation at surface defects which act as stress raisers. The driving force for the cracking is tangential
TABLE 1

Rejection performance of CRU 303 PLUS hexagons for 1980 and the first three months of 1981:

<table>
<thead>
<tr>
<th>SIZE</th>
<th>1980</th>
<th>REJ%</th>
<th>9 months, 1981</th>
<th>REJ%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LBS. SHIPPED</td>
<td></td>
<td>LBS. SHIPPED</td>
<td></td>
</tr>
<tr>
<td>.625</td>
<td>42900</td>
<td>2.2</td>
<td>9286</td>
<td>1.8</td>
</tr>
<tr>
<td>.687</td>
<td>15900</td>
<td>0.0</td>
<td>3483</td>
<td>0.0</td>
</tr>
<tr>
<td>.750</td>
<td>67625</td>
<td>13.9</td>
<td>43095</td>
<td>18.3</td>
</tr>
<tr>
<td>.812</td>
<td>15267</td>
<td>13.5</td>
<td>16930</td>
<td>11.5</td>
</tr>
<tr>
<td>.875</td>
<td>41101</td>
<td>8.7</td>
<td>31556</td>
<td>10.9</td>
</tr>
<tr>
<td>.937</td>
<td>5319</td>
<td>14.5</td>
<td>2314</td>
<td>15.7</td>
</tr>
<tr>
<td>1.000</td>
<td>53997</td>
<td>18.8</td>
<td>32536</td>
<td>7.5</td>
</tr>
<tr>
<td>1.062</td>
<td>12663</td>
<td>28.4</td>
<td>6037</td>
<td>33.9</td>
</tr>
<tr>
<td>1.125</td>
<td>74234</td>
<td>25.9</td>
<td>44090</td>
<td>28.2</td>
</tr>
<tr>
<td>1.187</td>
<td>2720</td>
<td>55.3</td>
<td>2064</td>
<td>47.4</td>
</tr>
<tr>
<td>1.250</td>
<td>36430</td>
<td>12.6</td>
<td>25967</td>
<td>26.9</td>
</tr>
<tr>
<td>1.312</td>
<td>6232</td>
<td>0.0</td>
<td>3690</td>
<td>17.2</td>
</tr>
<tr>
<td>1.375</td>
<td>23114</td>
<td>19.0</td>
<td>11965</td>
<td>16.6</td>
</tr>
<tr>
<td>1.437</td>
<td>1040</td>
<td>0.0</td>
<td>991</td>
<td>18.8</td>
</tr>
<tr>
<td>1.500</td>
<td>59184</td>
<td>3.9</td>
<td>32139</td>
<td>1.7</td>
</tr>
<tr>
<td>1.625</td>
<td>29548</td>
<td>0.6</td>
<td>6161</td>
<td>1.3</td>
</tr>
<tr>
<td>1.750</td>
<td>38252</td>
<td>0.0</td>
<td>19070</td>
<td>1.7</td>
</tr>
<tr>
<td>1.875</td>
<td>4796</td>
<td>0.0</td>
<td>3954</td>
<td>0.0</td>
</tr>
<tr>
<td>2.000</td>
<td>12162</td>
<td>1.7</td>
<td>11693</td>
<td>4.1</td>
</tr>
</tbody>
</table>
FIGURE 4(a)
Microstructure of cracked bar. Cross section 100X unetched

FIGURE 4(b)
Microstructure of cracked bar. Cross section 500X unetched
FIGURE 4(c)

Surface of cracked bar.
50X
unetched
tensile residual stress imparted by cold drawing. The presence of a delay in cracking suggests that stress corrosion cracking or hydrogen embrittlement may be a factor.

B) MATERIAL

The material being studied is a variation is AISI Type 303 stainless steel. Type 303 stainless steel is an austenitic stainless steel with sulfur added to improve the machineability. The basic properties of austenitic stainless steels apply to the material being studied.

Austenitic stainless steels are so named because they retain the face centered cubic (fcc) austenitic structure at room temperature. Interestingly, the Iron-Chromium-Nickel phase diagram shows that austenite is not the stable phase at room temperature for the 18Cr-8Ni composition of this steel. However, the transformation from austenite to ferrite is so sluggish at the temperatures involved that the austenite does not decompose. The stability of the austenitic structure down to room temperature is the basis of the properties found in austenitic stainless steels.

The fact that austenite remains stable down to room temperature means that hardening austenitic stainless steels by thermal treatment is impossible since martensite will not form. However, hardening of austenitic stainless steels is possible through cold working. There are two mechanisms involved in hardening austenitic stainless steels by cold working. The first mechanism is work
hardening due to dislocations and lattice distortion as found in most metals. The second mechanism involves the decomposition of austenite under strain into a martensitic phase. Microstructures of samples of cold drawn material were examined for this strain-induced martensite structure, but none was found. However, magnetic permeability tests show that some strain-induced martensite is present in a few cases.

Magnetic permeability tests are based on the fact that austenite is a non-magnetic phase while ferrite and martensite are magnetic. In theory, austenitic stainless steels are non magnetic since they are composed wholly of austenite. In reality, some magnetic response is noted in austenitic stainless steels due to the presence of some retained delta ferrite. An increase in magnetic response after cold drawing would indicate the formation of strain induced martensite. Using a Severn Magnetic Permeability tester, samples were checked before and after drawing. Some samples showed an increase in magnetic response but the vast majority showed no change. Results of magnetic permeability testing and the absence of any observation of martensitic structure seems to indicate that strain induced martensite is not a major factor in cracking of this product.

The interest in strain induced martensite was due to two thoughts about its possible contribution to the cracking of this material. The presence of this relatively
brittle phase could enhance the initiation and propagation of the cracks. Also, a martensitic phase might be more susceptible to stress corrosion cracking. The indications of the presence of a very small amount of strain induced martensite made this a low priority area of study (Reference 1).

Sulfur is present in AISI Type 303 to improve the machinability. Austenitic stainless steels, due to the high ductility of austenite, are difficult to machine. They are very "gummy" and have a large chip size. This slows down cutting speeds and decreases tool life. The addition of sulfur to the standard 18Cr-8Ni composition of Type 302 or Type 304 produces manganese sulfide inclusions. In the finished product, these sulfides are present as long, thin stringers. These stringers serve two functions during machining: first, they break up the chips into more preferable smaller sizes, and second, they lubricate the tip of the cutting tool. These properties increase cutting speed and tool life.

Three major versions of AISI Type 303 are manufactured at Crucible Specialty Metals Division. They are CRU 303, CRU 303 PLUS, and CRU 303 PLUS X (Table 2). Both CRU 303 and CRU 303 PLUS conform to the AISI chemistry specifications for Type 303 with the major difference between the two being that CRU 303 PLUS has a higher sulfur content that CRU 303. CRU 303 PLUS X has an even higher sulfur content than CRU 303 PLUS and a higher manganese
### TABLE 2

AISI chemistry specification for Type 303 and Crucible aim chemistries for CRU 303, CRU 303 PLUS and CRU 303 PLUS X:

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>AISI 303 specification</th>
<th>CRU 303 aim</th>
<th>CRU 303 PLUS aim</th>
<th>CRU 303 PLUS X aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARBON</td>
<td>0.15 max</td>
<td>0.08</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>MANGANESE</td>
<td>2.00 max</td>
<td>1.75</td>
<td>1.75</td>
<td>2.75</td>
</tr>
<tr>
<td>PHOSPHOROUS</td>
<td>0.20 max</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SULFUR</td>
<td>0.15 min</td>
<td>0.24</td>
<td>0.33</td>
<td>0.39</td>
</tr>
<tr>
<td>SILICON</td>
<td>1.00 max</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>NICKEL</td>
<td>8.00 - 10.00</td>
<td>9.20</td>
<td>8.20</td>
<td>8.30</td>
</tr>
<tr>
<td>CHROMIUM</td>
<td>17.00 - 19.00</td>
<td>17.20</td>
<td>17.20</td>
<td>17.20</td>
</tr>
<tr>
<td>NITROGEN</td>
<td>------------</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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</table>
content than allowed by the AISI specification for Type 303. The grade being studied here is CRU 303 PLUS. Similar product is made with CRU 303 and CRU 303 PLUS X with much lower rejection rates. Data on the physical properties of CRU 303 PLUS is given in Table 3 and Figure 5.

C) PROCESSING OF THE PRODUCT

All sizes of interest are given equivalent processing through the mill.

1) The steel is melted from scrap in Electric Arc Furnaces in heats of 22 or 35 tons. The steel is transferred into an Argon-Oxygen Decarburization (AOD) vessel for alloying. Once the proper composition is reached, the steel is transferred to a ladle from which it is bottom poured into 15 1/2 inch square ingot molds. The standard weight of the ingots produced is 2750 pounds. The ingots are air cooled, then stripped from the molds and sent to the cogging mill.

2) The ingots are cogged to four inch square billets on a 26 inch, two high reversing mill. The ingots are heated to 2300 F and air cooled off the mill. The top portion of the ingot is cropped to remove pipe and the balance of the billet is sheared into nine sections of approximately 700 pounds each.

3) The billets are ground all over to remove surface defects. Fine abrasive wheels are used to reduce the chance of grind pattern being retained in the finished
TABLE 3

Mechanical Properties of Annealed CRU 303 PLUS at room temperature:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>90000 psi</td>
</tr>
<tr>
<td>Yield Strength (0.2% offset)</td>
<td>35000 psi</td>
</tr>
<tr>
<td>Elongation in 2 inches</td>
<td>50%</td>
</tr>
<tr>
<td>Reduction of area</td>
<td>55%</td>
</tr>
<tr>
<td>Izod impact resistance</td>
<td>80 ft. lbs.</td>
</tr>
<tr>
<td>Hardness</td>
<td>170 BHN</td>
</tr>
</tbody>
</table>
FIGURE 5: Mechanical properties of cold worked CRU 303 PLUS. Annealed, 1950°F, water quenched. 3/8 inch round, unstraightened, untempered. From Crucible 303 PLUS Data sheet, issue no. 8.
product. The sections from the tops of the ingots are ultrasonically inspected to ensure that all pipe was removed. The billets are then stocked until they are used for a specific order. It is important to note that after this point, all material from a specific heat is not processed together. Billets may be applied in small lots over a long period of time.

4) The billets are hot rolled into hexagons approximately 1/16 inch over the finish size on Crucible's Rod and Bar Mill. The Rod and Bar Mill consists of a 91 foot barrel type continuous furnace, one 18 inch 2 high reversing roughing stand, three 14 inch stands, two 12 inch stands, and a flying shear for cropping. The billets are heated to 2150 F before rolling and allowed to air cool off the mill. Size tolerance for hot rolled hexagons is specified as ± .010 inches for diameters of 1/2 inch to 1 inch and ± .021 inches for diameters of 1 inch to 1 1/2 inches. The bars are cropped to approximately 20 foot lengths.

5) The bars are given a six inch long point on a turn pointer, then annealed. Annealing is done in a Selas, barrel type continuous furnace at a temperature of 2050 F and water quenched.

6) After annealing, the bars are pickled in preparation for drawing. The bars are immersed in a caustic solution at 900 F. The intended composition of the caustic solution is 90% NaOH and 10% NaNO. The bars
are removed from the caustic, washed with water, and immersed in a sulfuric acid solution. The intended composition of the sulfuric tank is 12% concentrated sulfuric acid. This cycle is repeated until all scale is removed from the surface of the bars. The bars are then coated with lime to improve lubrication in the drawing process.

7) The bars are drawn three at a time through solid convergent dies. The bars are drawn to approximately 1/32 inch over finish size. The lubricant used is either oil or calcium stearate soap.

8) The drawn bars are rough straightened on a Sutton roll straightener, reannealed, repickled, and drawn to the finish size.

9) The bars are cut in half, degreased, and finish straightened.

10) The bars are then inspected with the eddy current probe for cracks. Any bars with cracks are sent to the scrapyard. Good bars are then visually inspected for size and finish, lab tested, and packaged for shipping. Standard time for processing from hot rolled hexagons to shipment is nine weeks.
TESTING

A) MICRO HARDNESS TESTING

Micro-hardness profiles were studied comparing cracked bars with uncracked bars, (Figure 6). Profiles were taken on two cracked samples and two uncracked samples of 0.750 inch finished hexagon bars. Two profiles were looked at. First, micro-hardness tests were done 0.005 inch below the surface at intervals of 0.050 inch across each face of the samples. Second, tests were done starting at the center of a face and running towards the center of the bar.

Results from the first set of profiles indicated two differences: first, the samples that had cracked had a higher overall hardness than the uncracked samples, and second, the uncracked samples had a profile which showed higher hardness at the corners of the faces than the centers of the faces while the cracked samples showed a relatively constant hardness across each face. The second set of profiles confirmed the higher overall hardness of the cracked samples and showed similar profiles for both cracked and uncracked samples.

The profiles found could be due to a number of factors. The difference between the cracked and uncracked samples could be caused by oversized bars off the rolling mill, higher work hardening rate for the cracked bars, or incomplete anneals of the cracked samples.

B) SCANNING ELECTRON MICROSCOPY RESULTS

SEM analysis was done by the Crucible Materials
FIGURE 6(a): Micro hardness profile. Cracked bars.
Profile across face at 0.005 in. depth.
FIGURE 6(b): Micro hardness profile. Uncracked bars. Profile across face at 0.005 in. depth.
FIGURE 6(c): Micro hardness profile. Cracked and uncracked bars. Profile from mid-face towards center of bar.
Research Center on a number of cracked samples (Figure 7). Unfortunately, samples were always gathered at the eddy current tester. This means that the crack surfaces studied were probably exposed to the degreaser and, if the bar cracked after the first draw pass, the pickle cycle.

SEM analysis confirmed that the cracks propagated from sulfide to sulfide, separating the sulfides from the matrix. X-ray analysis of the cracked surface showed a scattering of foreign elements but there was no consistency (Reference 1). Surface chemistry analysis was not significant for two reasons: first, the crack surface may have been affected by processing after cracking; second, if local chemistry was a factor in the initiation of the crack, analysis would have to be done in the region of the crack initiation. Determination and sampling of a crack initiation region has so far been impossible.
FIGURE 7(a) : SEM photograph of crack surface. 170 X
FIGURE 7(b): SEM photograph of crack surface. 900X
FIGURE 7(c): SEM photograph of crack surface. 1700 X
FACTORS AFFECTING CRACKING

A) SURFACE DEFECTS

Since cracking initiates at surface defects, the presence of surface defects is a major factor in the cracking of this product. Surface defects act as stress raisers which increase the local residual tensile stresses and hence the driving force behind the cracking. The major surface defects found in this product are seams, laps and shearings. All three types of surface defects are similar in the finished bar. They are fine, linear defects that run varying depths into the bar. All three are variations of surface openings that are closed during rolling but not welded shut.

Seams usually occur during cogging and are a result of poor ingot surface. They are caused by surface discontinuities in the ingot which are compressed during cogging. Seams should be removed after cogging by the grinding operation but any that are missed will remain through the rest of the processing.

Laps occur when metal is rolled over during the rolling or cogging operation. This can happen as a result of billets or ingots being rolled incorrectly so that the corners are compressed, excessive grinding of billets which causes deep gouges, or gross surface discontinuities in ingots. Again, laps remaining in the billets after grinding will be present in the finished product.
Shearings are the most common defect found in this product. They are the result of bars rubbing against guides or other surfaces during hot finishing. This rubbing creates a gouge which is closed in later passes. Distinguishing between these three types of defects in finished bars is very subjective. A defect that moves laterally as the surface is filed off is usually classified as a lap. A full length defect with no lateral movement is usually classified as a seam and an intermittent defect is usually classified as a shearing. Classification varies from inspector to inspector, and often the result of inspection is a general statement of surface defects of all types.

Seams, laps and shearings have been noted on many cracked and uncracked bars. With cracking dependent on so many variables, the presence of a surface defect does not guarantee that a crack will occur. However, observation of cracked bars indicates that when surface defects are evident on the cracked face, the crack will run along the surface defect.

B) SIZE AND SECTION VARIATIONS

Variations in the size and section of hot rolled hexagons off the Rod and Bar Mill also can contribute to the incidence of cracking in this product. The driving force behind the cracking is the tangential residual tensile stress imparted to the bars by cold drawing. The magnitude of the residual stress is a function of the
amount of cold work performed. An increase in the percent reduction in area increases the residual stresses. The calculated reduction in area for this product varies with the size of the product due to the uniform 1/16 inch over finish size off the rolling mill regardless of finish size, (Table 4). Oversize bars off the Rod and Bar Mill increase the amount of cold work and thus increase the magnitude of the residual stresses in the bars. This increases the chance of cracking.

Variations in the section can also increase the chances of cracking. Excessive off section will cause localized areas of the bar to undergo increased cold work, inducing greater residual stresses.

C) PICKLING

The pickling cycle used for the removal of scale is also a factor in the occurrence of cracking. There are three major ways that chemical descaling can lead to increased cracking: thermal expansion, stress corrosion cracking, and hydrogen embrittlement.

The caustic bath the bars are run through is operated at 900°F. When bars are placed in the caustic tank, the forces generated through thermal expansion added to any residual stresses may be enough to crack the bar.

If a bar with high residual stresses is run through the pickle cycle, the corrosive environment of the caustic or sulfuric acid tanks combined with surface defects may result in stress corrosion cracking.
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Cracking related to thermal expansion or stress corrosion cracking would occur during the pickle cycle. As a test, a cold drawn bar that had not been annealed was run through the pickle cycle. Afterwards, the bar was examined and a crack was found that closely resembled the cracks being studied. Whether the crack occurred due to the caustic or the sulfuric acid was impossible to tell since it is an integrated cycle that is not easy to interrupt.

There may also be some hydrogen pickup by the bars in the sulfuric or caustic tank. This could lead to hydrogen embrittlement. Cracking due to hydrogen embrittlement would probably show up later in the processing.

D) CHEMISTRY AND HEAT PROCESSING

Chemistry is obviously an area that has an influence on cracking. This is evidenced by the substantially lower rejection rates for cold drawn hexagons of CRU 303 and CRU 303 PLUS X. Whether chemistry can be controlled to reduce cracking is questionable, since physical properties may be adversely affected.

There is an indication that some heats have less cracking than others. In an attempt to study this, rejection data were gathered on nine heats processed in 1980 and the heats were ranked according to rejection performance. In the ranking, an attempt was made to take into account the different rejection rates noticed for different sizes by comparing rejection performance for a heat by size ordered to the average rejection rates. This
is by no means a definitive ranking, since other rankings have been done which have many differences from this one. This is caused by different ranking methods and uncertainty in some of the data gathered. Nevertheless, the results of this analysis had the same end result as the work with other lists: there were no significant trends.

The chemistries of the ranked heats as well as all of the processing data available for the processing steps common to a single heat were analyzed, (Table 5), with no significant trends.

The major problem with this type of analysis is that there are so many variables downstream that could affect cracking that a ranking by final rejection performance does not really reflect the tendency towards cracking of different heats. Despite the inconclusive results of this study, it is still felt that there are variables present in the heat processing of this material that significantly affect the cracking tendency of heats.
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Days from melt to cogging: 6, 3, 6, 0
APPROACHES TO THE REDUCTION OF CRACKING

Changes in processing aimed at the reduction of cracking in this product can be separated into three groups. The first group involves reducing the number of surface defects on the bars, thereby reducing the number of cracking initiation sites. The second group involves reducing the tangential residual tensile stress, thereby reducing the driving force behind the cracking. The third group involves reducing the chance of bars cracking due to pickling.

A) REDUCTION OF SURFACE DEFECTS

As previously stated, surface defects produced during cogging and hot rolling act as stress raisers and serve as initiation sites for cracking. Reduction of surface defects should reduce the incidence of cracking.

Since cogging is followed by billet grinding, it should be possible to greatly restrict the number of surface defects present in the finished bar that were introduced during cogging. There are two approaches that can be taken to this problem: first, closer inspection of ground billets could be employed to insure removal of all surface defects; and second, a greater amount of surface could automatically be ground off than at present. Either approach has its drawbacks.

Automatic removal of more material increases the yield loss on this product which decreases the profitability.

But, if the cracking is significantly reduced, the end
profitability may be increased.

Closer inspection of ground billets relies heavily on human operators. As in any process that relies on human control, the chances for error are great. The process of grinding, inspecting, regrinding, etc., may also take a considerable amount of time. Another problem with this type of process is that it may lead to heavily-gouged billets. This can cause more surface defects during hot rolling.

Control of surface defects occurring during hot finishing is more difficult. This arises because of the more complicated rolling setup and the lack of any surface removal after rolling.

Reduction of surface defects could be accomplished by better inspection and control during the rolling. Unfortunately, the mill is very poorly designed for this. The response time for sample inspection is very slow on this mill. Mill control is very human controlled, with operators relying on experience and instinct. It is felt that control of surface defects during hot finishing cannot be relied upon in attempting to solve this problem.

At present there are no facilities to grind the surfaces of hexagons prior to cold drawing. If grinding for the removal of surface defects before drawing is to be implemented as a means of controlling cracking, a grinding machine capable of controlled removal of material from all six faces must be purchased. With a machine like this, the
first drawing pass could be replaced with grinding. This would not only reduce the number of surface defects present, it would also serve as a means of controlling size and section of material to be drawn. There are of course, some drawbacks to this process. First, the yield loss for this product would be increased, since cold drawing involves virtually no loss of material. Second, the cost of a machine of this type would be considerable. But use of a process such as this should reduce the amount of cracking in this product.

B) REDUCTION OF RESIDUAL STRESSES

Reduction of the tangential residual stress imparted to the bars by cold drawing would reduce the driving force behind this cracking. This should reduce the incidence of cracking. There are three approaches for reduction of residual stresses from drawing: thermal treatment, grinding, and changes in die design.

Thermal treatment for the reduction of residual stresses due to cold drawing would involve heating prior to drawing or stress relieving after drawing. Heating before drawing reduces the residual stresses by lowering the yield point of the material. The problem with both of these processes is in the implementation. Crucible does not have proper heat treating facilities located convenient to the cold drawing area and there is no place to install any. A major expansion would be necessary before this would be a viable solution to cracking. There is an additional
problem with stress relieving after draw: some bars crack almost immediately after exiting the die. These bars would not be helped by a stress relief.

Grinding is another method for the reduction of residual stresses from cold drawing. The simplest method would be to eliminate the cold drawing altogether and grind finished hexagons from hot rolled product. This would obviously eliminate any residual stresses from cold drawing. The major problem with this idea is the increased yield loss due to grinding. Desirable physical properties may also be forfeited by the elimination of cold drawing. Since the physical properties of austenitic stainless steels can only be controlled through cold working, product that is ground to size could only be provided with annealed properties.

The other method of reduction of residual stresses through grinding was mentioned previously in the section on the reduction of surface defects. This method involves replacing the first draw pass with a grinding operation and then processing through the second draw pass as usual. This would give better control of the size and section of the bars before drawing. This would ensure that excess residual stresses would not be developed due to oversize of off section bars. As previously stated, the magnitude of the residual stresses is directly related to the percent reduction in area.

A major problem with any process change to include
grinding of hexagon bars is the equipment required. The high cost of this equipment could be prohibitive.

A major study in Crucible Material Research Center's approach to this problem has been the effect of die design on cracking. The premise behind this work is that a reduction in the force applied during drawing will lead to a reduction in the magnitude of the residual stresses present after drawing. By changing the entry angle, (Figure 8), of the die it is possible to decrease the force required to draw this product.

A study of drawing force vs. entry angle, (Figure 9), shows that there is an optimum entry angle which is dependent on the material, the reduction in area, friction, and redundant surface work (Reference 2). CMRC determined that for the conditions involved with this product, a die angle of 9 degrees would provide much better properties than the standard 12 degree dies (Reference 3).

Initial results of mill trials with 9 degree dies were positive, so dies were bought for six sizes of product. After three months of exclusive use of these dies, a decrease in cracking is evident, (Table 6). Data will have to be gathered over a longer time period before any firm conclusions can be drawn, but it does seem that 9 degree dies will have a positive effect. Further study of other variables may lead to other changes in die design which could reduce the cracking of this product.
FIGURE 8: Die geometry.
FIGURE 9: Drawing force vs. die entry angle (1)
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TABLE 6

Rejection performance of sizes with 9° entry angle dies:

12
1980
9 months, 1981
4th qrtr 1981
C) ELIMINATION OF CRACKING DUE TO PICKLING

As previously stated, the pickle cycle the bars are put through can cause cracking due to thermal expansion, stress corrosion cracking, or hydrogen pick up. The simple solution to these problems is the replacement of the pickle cycle with a continuous grit blasting process for scale removal. The major problem with this is the high cost, both for the initial purchase of equipment and for maintenance since this is a self-destructive machine. However, the elimination of pickling problems in this product and others could be worth the expenditure. Another possible benefit for grit blasting instead of pickling is that grit blasting may have a shot peening effect causing compressive residual stresses in the surface of the bars. This would reduce the resultant tensile residual stresses resulting from cold drawing.

A much cheaper method for possible reduction of cracking due to pickling is better quality control in heat treatment. This could be accomplished by checking the hardness of bars after annealing and before pickling. An upper limit hardness could be established to determine whether bars had been properly annealed. Any bars failing this test would be reannealed. As previously discussed, pickling of poorly annealed product can result in cracking. This type of process change will not eliminate all cracking due to pickling. But, it is a relatively easy and inexpensive means of reducing cracking to some extent.
SUMMARY

The implementation of any of these process changes for the reduction of cracking must be analyzed from an economic standpoint. Any expenditure for equipment and increased production costs must be offset by an increase in shipable product. This analysis is complicated by two factors; uncertainty in the benefits of these changes and uncertainty in the amount of business for this product. The uncertainty in the benefits of these changes arises from the fact that many of these changes can not be tested on a trial basis, a full commitment must be made. The uncertainty in the amount of business greatly affects the payback time for any changes. This is not a high volume product and an accurate prediction of future business if difficult to make.

With a good level of business, the use of a grinding sequence in lieu of current breakdown draw pass would be the best alternative. This process change would reduce the concentration of surface defects, help control oversize and off section that could lead to higher residual stresses, and eliminate one of the two pickle cycles. It is a moderately expensive change to make compared to the other possibilities, and the cost for implementation versus the potential benefits is one of the highest for the possible changes discussed in this paper.

Evidence of the potential benefits of replacing the breakdown draw pass with a grinding pass can be found in
the production of cold drawn Type 303 PLUS round bars. Processing of this product includes a grinding operation in place of the breakdown pass found in hexagon material. Rejection rates are lower for round product than for hexagon. This is especially interesting since most of this product is ordered in a high tensile condition which requires cold drawing through a 20 to 30% reduction in area. There may be other factors involved other than surface grinding such as different flow through a round die, but it does seem to indicate that a grinding operation would significantly reduce cracking.
RECOMMENDATIONS FOR FUTURE STUDY

The changes discussed in this paper are all treatments of the downstream variables of this problem. They do not address the potential causes involved in the heat relating processing. This is because of the difficulty of accurately determining the cracking tendency of a heat. These heat related problems must be addressed. If changes are made in the downstream processing which eliminate some of the variables, it may be possible to better identify these heat related variables. Analysis should be done on chemistry, melting variables such as tap temperature and mold temperature, delay times, time and temperature of heating before cogging, and cogging practice.
APPENDIX A

Rejection performances of ranked heats

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REFERENCES

1) Personal communication with Judith R. Hall, Crucible Materials Research Center, 1981


3) B. L. Shakely, "Improved Hardness Uniformity in Cold Drawn Hexagons:, Crucible Materials Research Center report number 619-6, September 16, 1971