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Analysis of Sheet Steel Fracture during Deep Drawing

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Low-carbon steel sheet used for the fabrication of automotive brake components was tearing during deep drawing. The associated mill certificates revealed that the coil met the specified chemical composition and mechanical properties. Metallographic evaluation revealed a severe variation with respect to grain size through the thickness of the steel sheet, as well as a slight segregation of pearlite. Insufficient temperature during hot rolling in combination with a high coiling temperature resulted in the observed microstructural gradient. The anisotropic mechanical properties were amplified by the slight carbon segregation.

Keywords: carbon segregation, deep drawing, hot rolled sheet coil, microstructural gradient

Introduction

In an effort to stay competitive, many metal product manufacturers in the United States have opted for an increased reliance on imported steel. This change in suppliers provides a challenge to the materials specification process and can allow the receipt and use of unacceptable material. The primary driving force behind the decision to change suppliers is generally financial. However, financial savings, while seemingly substantial, can be erased when unforeseen production failure and material deficiencies occur. While the quality and capability of many foreign steel mills meets or exceeds that of domestic mills, the lack of experience in supplying material for a specific operation often translates into the lack of ability to assure the high quality of steel required for the production process. Over the past several years, the authors have observed a significant increase in failures related to steel quality. Product manufacturers that had rarely or never experienced failures on relatively simple components have changed suppliers and are now facing a number and variety of failures; many of these failures can be attributed to the lack of quality (number of defects) in the steel used in the production process. Generally, the material supplied meets the materials specifications but does not meet some unspecified quality requirement that was met by the previous supplier. This paper illustrates this problem for the steel used in the production of a component for an air brake system used on large trailers. The scope of the analysis included visual and metallographic examination, hardness testing, and chemical analysis.

Background Information

Two bladder cups form the housing that encloses a rubber bladder and is a key component in the braking system. This component is equipped with an air fitting on the top for air inlet, and a rod on the bottom that actuates the brake shoes in the axle. The bladder cup manufacturer received four sizes of material for production of the bladder cups. The material was accompanied by the standard mill certifications for chemical and tensile properties. The certifications showed that both the steel chemistry and tensile properties met the specifications of the production manufacturer. The fabrication process consists of slitting, blanking, and finally drawing the bladder cups. Once production was underway, the material was observed to fracture during drawing. By the time the failures were discovered, much of the raw material had already been slit and blanked in preparation for drawing. The slit and blanked material represented a sizable investment, and in an effort to use the prepared material, the manufacturer attempted unsuccessfully to avoid fracture by using different drawing speeds and different drawing oils. Two issues were

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subsequently identified with respect to the raw material. The primary issue involved fracturing of the bladder cups during drawing. A secondary issue involved apparent pitting observed on some of the material. A variety of samples from different stages in the manufacturing process were submitted for evaluation, including a coil sample, circular blanks, and bladder cups.

Visual Examination

The fractured bladder cups were examined first. A photograph of a bin of fractured bladder cups was submitted (Fig. 1). Visual examination revealed a large fracture in the drawn (cup) region of the specimen, which had been sectioned in half prior to submittal. Extensive plastic deformation (necking) was observed in the region of fracture, indicating a ductile overload failure (Fig. 2).

A circular blank that apparently contained pits on the surface was submitted for evaluation of the pitting. Visual examination revealed surface discontinuities associated with an isolated region, denoted by the red lines in Fig. 3. A close-up photograph of the apparent pitting is presented in Fig. 4. Metallographic evaluation of the apparent pitting was also conducted.

Metallographic Examination

In order to determine the role of microstructure in the drawing failure of the bladder cups, metallographic specimens were prepared. The majority of the metallographic evaluation was conducted on the fractured bladder cup half section.

Fig. 1 *Photograph provided by the client that depicts the tearing of the bladder cups*

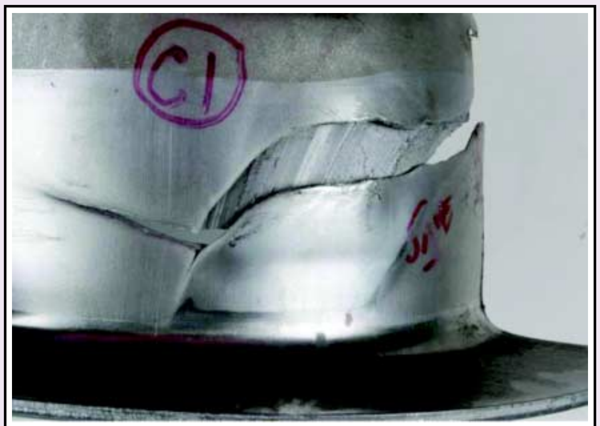

Fig. 2 *Close-up photograph of the fractured bladder cup half*

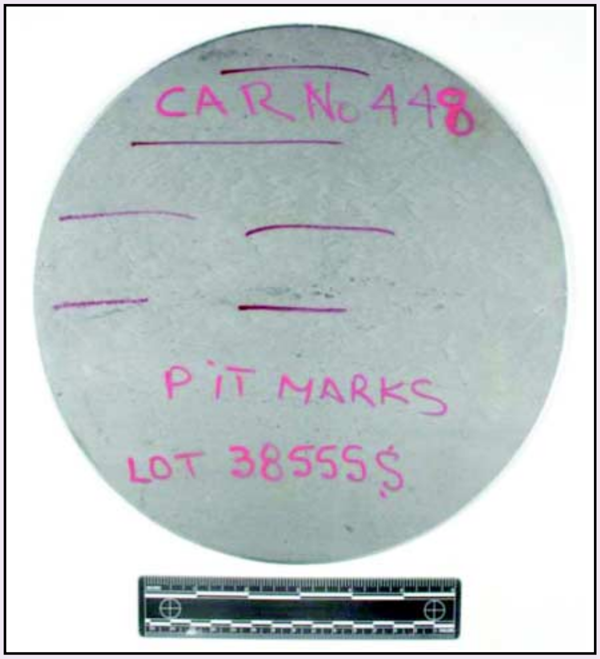

Fig. 3 *Photograph of the apparent pitting observed on the circular blank*

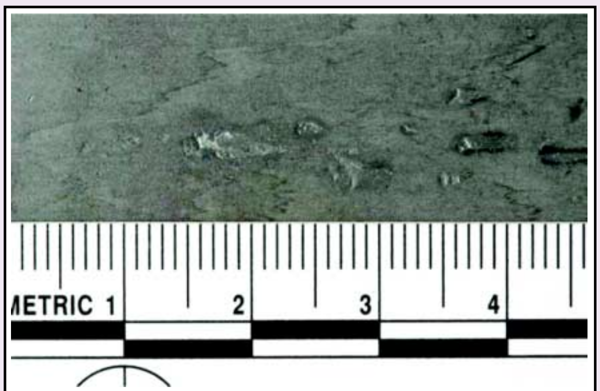

Fig. 4 *Close-up photograph of the apparent pitting observed on the circular blank*

One sample from the flat rim of the draw blank was also examined. Upon etching of the metallographic sample, evidence of a microstructural gradient through the thickness of the material was evident (Fig. 5). Composite micrographs of increasing magnification are presented in Fig. 6 and 7. From these micrographs, the nature of the microstructural gradient is evident. The grain size varies significantly across the specimen thickness, and larger grains are associated with both surfaces.

The variation in grain size resulted from an insufficient hot rolling temperature during fabrication of the steel sheet at the mill. Low finishing temperature results in irregular coarsening of the ferrite grains, particularly at the surfaces of the steel. The variation in grain size becomes more pronounced, as in this case when high coiling temperatures are used.[1] The presence of the grain size variation would be detrimental to any deep drawing operation. Uniform grain size is an important variable, because uniformity is necessary for successful drawing.[2] Anisotropic mechanical properties through the thickness of the material

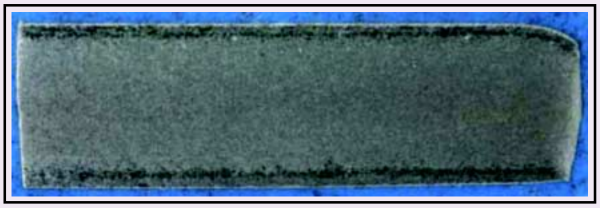

Fig. 5 *Photograph of the microstructural gradient observed on the mounted cross section through the fractured bladder*

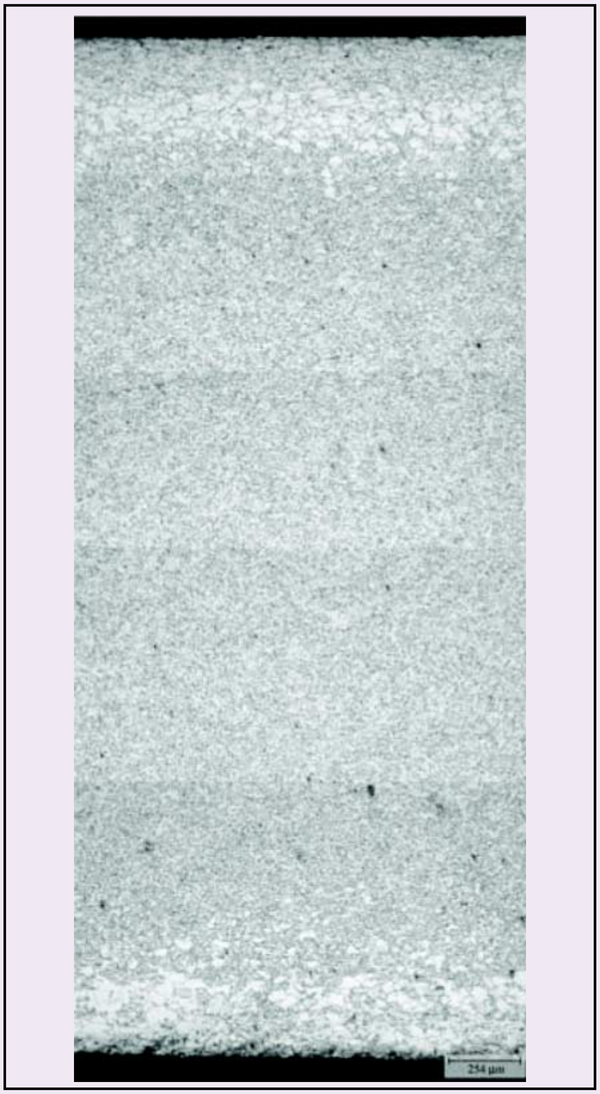

Fig. 6 *Composite micrograph of a cross section through the fractured bladder cup half section. A severe microstructural gradient with respect to grain size variation is evident. The sample was acquired in the flat rim of the bladder cup. Microhardness measurements revealed an approximate hardness of 86 HRB near the surface and 92 HRB near the midthickness.*

Fig. 7 *Higher-magnification micrograph of a cross section through the fractured bladder cup half section. A significant variation in grain size is evident in the depicted region associated with the surfaces. The sample was acquired in the flat rim of the bladder cup. Nital etchant. Original magnification 350×*

would promote a gradient in plastic flow during drawing, facilitating fracture of the component.

In addition to the grain size variation, a slight variation in pearlite content was observed. Examination of the microstructure through the fracture revealed that the material split into two sections (Fig. 8). The division was associated with segregation of pearlite (Fig. 9). The segregation resulted from slight variations in carbon content and is related to steel production.[1] The variation in pearlite would result from carbon segregation during rolling and would contribute to the anisotropy in mechanical properties and drawing difficulties.

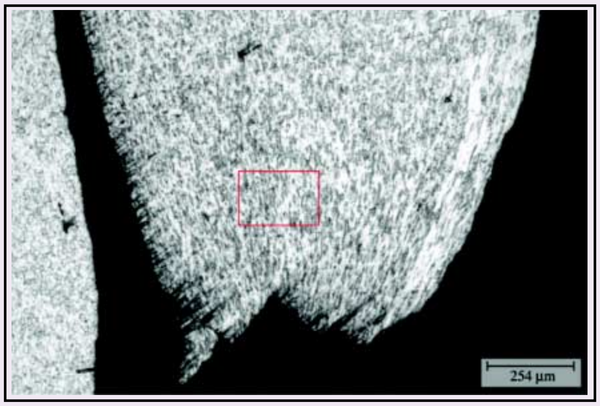

Fig. 8 *Micrograph illustrating the slight segregation of pearlite associated with the fracture in the fractured bladder cup half section. Enlarged grains are visible at the right edge of the sample. Decreased pearlite content is discernible immediately adjacent to the enlarged grains and on the material at the left edge of the micrograph. A higher-magnification micrograph (Fig. 9) was acquired in the highlighted region. Nital etchant. Original magnification 100×*

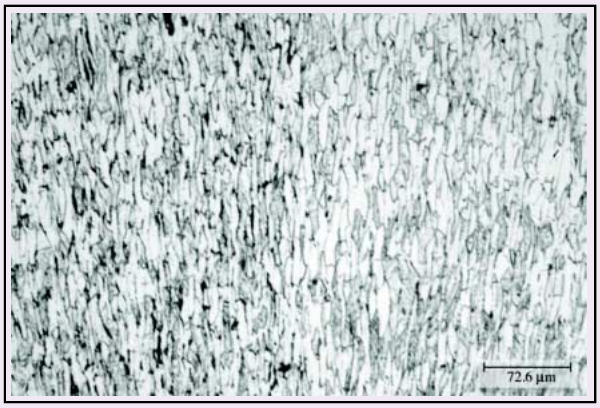

Fig. 9 *Higher-magnification micrograph of highlighted region in Fig. 8, illustrating the pearlite segregation. Nital etchant. Original magnification 350×*

Metallographic specimens were acquired from two circular blanks in order to compare the microstructures. One was from material that was fracturing during the drawing operation. The second was material from another supplier that was able to be successfully drawn. A gradient with respect to grain size was observed within the coil that fractured during drawing (Fig. 10). No evidence of enlarged surface grains was observed in the microstructure of the successfully drawn material (Fig. 11).

Metallographic examination of the apparent pitting depicted in Fig. 3 and 4 was conducted. Examination of a cross section through one of the "pits" revealed evidence of localized plastic deformation. Additionally, enlarged grains were observed at the surface of the blank. The grain flow, which included the larger grains, followed the contour of the "pit" (Fig. 12, 13), thus indicating that the surface defect was not the result of

Fig. 10 *Micrograph from Sample B, a blank from the material experiencing fracture during drawing*

Fig. 11 *Micrograph from Sample C, a blank from the material drawn successfully*

corrosion (no material loss) but was caused by plastic deformation that occurred at some point after the coil was hot rolled. The presence of debris (possibly scale) during the coiling operation is considered the most likely cause of the "pitting" problem. Surface discontinuities serve as stress concentrations and are therefore detrimental to deep drawing operations.

Hardness Testing

In order to verify that the variation in grain size was influencing the mechanical properties, microhardness testing was conducted. Microhardness measurements were acquired on the metallographically prepared cross section of the fractured bladder cup half section. The sample was acquired from the flat rim, a region that would undergo minimal or no plastic deformation during the drawing process. An approximate hardness value of 86 HRB was measured near the surface (large grains), while an approximate value of 92 HRB was measured near the midthickness (small grains).

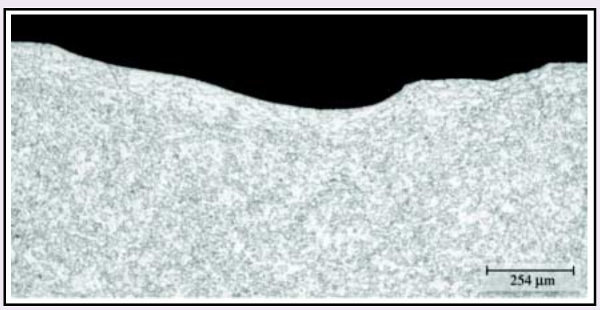

Fig. 12 *Micrograph through an apparent pit observed on the circular blank*

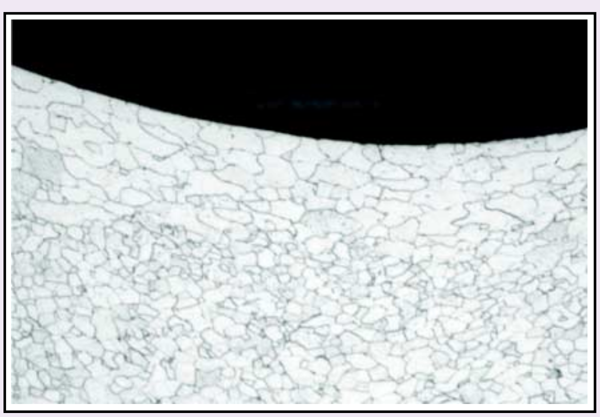

Fig. 13 *Higher-magnification micrograph through an apparent pit observed on the circular blank*

Chemical Analysis

Optical emission spectroscopy and combustion techniques were used to verify the chemical composition and AISI designation of several of the materials. All of the tested materials met the requirements of AISI 1009 and 1010 carbon steel. No evidence that chemical composition contributed to the failure was observed. This is of particular importance with respect to the observed carbon segregation, which cannot be attributed to improper chemical composition based on the test results.

Discussion, Conclusions, and Recommendations

Visual examination of the submitted bladder cups revealed that failure was manifested in the form of ductile overload fracture. A high degree of plastic deformation (necking) was associated with the fractures. Metallographic evaluation of the fractured bladder cup, as well as blank material known to fracture during drawing, revealed a significant microstructural gradient in the form of grain size variation. The grains adjacent to the surface were significantly larger than those associated with the midthickness of the material. The increased grain size resulted during hot rolling of the material. Insufficient temperature during finishing results in irregular coarsening of the ferrite grains. This characteristic was likely amplified in combination with high coiling temperatures. The observed carbon segregation contributed to the anisotropic mechanical properties of the material.

Metallographic evaluation of the apparent pitting revealed that no material loss had occurred. Evidence of localized plastic deformation (indentations) in the surface was observed. The indentations likely resulted from the presence of surface debris during coiling of the steel sheet.

The bladder cup drawing failures resulted from strain localization associated with the significant grain size variation observed at both surfaces of the steel coil. The variations in grain size resulted in varying yield strength (confirmed via microhardness testing) and drawing behavior. The grain size effect on strength generally follows the Hall-Petch relationship, where strength increases with decreasing grain size in an inverse square root proportionality.[3,4] The decrease in strength furthers strain localization and, ultimately, fracture by requiring more of the plastic strain to be accommodated by the larger grains.

As part of the failure investigation, recommendations were sought regarding the remainder of the material that had been partially prepared for drawing. It was recommended that it be returned to the supplier based on both the grain size gradient as well as the observed surface discontinuities, neither of which could be feasibly rectified by the component manufacturer.

As mentioned previously, the material that fractured during drawing was accompanied by a mill certification for tensile properties. While the material supplied was in accordance with the specification, it was not suitable for production of the deep-drawn bladder cups because of the grain size gradient. This apparent conflict between specification and suitability is a common problem associated with the transition from long-standing, domestic suppliers to new, foreign suppliers of steel. Adherence and attention to the tensile property specification alone is not adequate to ensure raw material that will perform successfully during product manufacture. Had materials qualification articles been submitted for analysis prior to production coils, the microstructural anomaly may have been identified and the failures avoided. In-depth materials qualification or ongoing metallographic sampling to ensure raw material quality should be considered as part of the overall cost of production, as should the costs of failure investigations. These hidden costs, in addition to the lost time and other indirect expenses resulting from the failures, illustrate the pitfalls associated with transitioning suppliers to minimize apparent cost in the absence of rigorous specifications that ensure material suitability.

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