Penny-shaped Central Bursting Defect in the Cold Drawing of High Chromium Ferritic Stainless Steel

By Muneaki Shimura*

The phenomenon of central bursting during cold drawing of a high-purity high-chromium ferritic stainless steel has been investigated, and it is well established that the defect forms periodically in the drawing direction and does not have the usual chevron or arrow shape but a penny shape. The defect is generated by cleavage fracture at the centerline of the billet, depending on the stress state when plastically deformed during drawing. In drawing the hydrostatic stresses are most tensile in the slipline field analysis, and the damage at a critical tensile stress is most severe at the centerline despite the small amounts of deformation and strain-hardening. The growth of defects takes places in a direction perpendicular to the highest tensile stress by discontinuous cleavage propagation to form the penny shape. Blunting of the crack tip occurs in the region directly under the die and then the crack propagation rate is retarded to stop. Mechanical properties of the high-purity high-chromium stainless steel play a very important role in the damage formation process.

(Received March 9, 1978)

I. Introduction

Central bursts, or chevrons, are the internal arrow-shaped defects that are occasionally encountered in the cold-drawn wire or cold extrusions. It is of great concern because the phenomenon occurs internally. The holes are in the interior of the product where they may not be readily detected but may then cause unexpected failure in service. When central bursts are detected, the quality of the raw material is often examined. However, as early as 1930 a study of wire drawing by Jennison(1) showed that the geometrical features of the deformation process are a major cause for central bursting. Since then many other workers(2)–(4) have reported qualitative methods for eliminating central bursts. In earlier work little was known about the occurrence of central bursting in the billet with relatively small reductions, relatively large die angles, and subsequent to prior severe cold working. Recently, the problem has been studied in some detail by Avitzur(5), who suggested that the phenomenon may be better understood if one considers velocity fields that are likely to develop. Also, Hoffmanner(6) has attempted to quantitatively relate the basic material performance of workability data with the observations during deformation processing. He concludes that the Cockcroft and Latham analysis(7) provides an accurate working procedure for defect prediction during extrusion, but the reason why this empirical procedure does work is not understood. Furthermore, Rogers(8) has proposed that in any deformation process the degree of structural damage generated locally in a wrought metal should depend strongly on the hydrostatic component of the stress acting there while the metal is being plastically deformed. In strip drawing the hydrostatic stresses are most tensile and so the damage is most severe at the midplane of the strip.

Since metals are not normally processed in a temperature range in which cleavage failure occurs, fracture occurring as a result of such processing has been usually made to relate the fracture with what is known as the mechanism of fracture in normally ductile materials under a simpler condition. The fracture in ductile metals initiates by the development of voids at a number of sites and proceeds by the growth and coalescence of these voids to form an internal crack. All arguments referred earlier to the central bursting have been presented on

* The Research Institute for Iron, Steel and Other Metals, Tohoku University, Sendai, Japan.
the basis of such a ductile fracture mechanism.

Recently, however, the present author has found that in drawing a high chromium ferritic stainless steel has been damaged in an unusual form of central bursting with a different shape and a fracture mechanism. In this report the results of observations on the defects are presented and discussed.

II. Experimental

The high chromium steel investigated was vacuum-induction melted to obtain the required low levels of carbon and nitrogen, chemical analysis of which is given in Table 1. This material, originally in the form of a 30-mm thick sheet bar as hot-forged, was machined to a billet of 26.5 mm diameter. Heat treatment at 950°C for 10 min, followed by water-quenching, was carried out to provide grain sizes of 1000 μm in average diameter. Uniaxial tensile properties of the steel thus treated are shown in Table 2. The steel has high ductility.

The billet was drawn at a low speed of 5 m/min on a draw bench. Seven different drawing dies were used, made up of the die angle 14.5°. (Die sizes; 26.0, 25.5, 25.0, 24.5, 24.0, 23.5, 23.0 mm in diameter) Commercial lubrication, “Houghto-Draw” (E. F. Houghton Co.) was used. To study the microstructure of the drawn samples, both transverse and longitudinal sections were taken out and the etched in Vilella's reagent which has been proved to be the most effective solution for revealing the ferritic substructure. Fracture surfaces were examined in a scanning electron microscope.

III. Results

1. External appearance

Photograph 1 shows the external appearance of the drawn after a reduction of 1.15 (initial radius/final radius of billet). Lustrous annular bands appear periodically on the external sur-

Table 1 Composition of material.

<table>
<thead>
<tr>
<th>Cr</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Mn</th>
<th>O</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29.6</td>
<td>1.71</td>
<td>0.004</td>
<td>0.13</td>
<td>0.011</td>
<td>0.003</td>
<td>0.023</td>
<td>0.0012</td>
<td>0.0097</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 2 Uniaxial tensile properties.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Proof stress, MPa</td>
<td>438.3</td>
</tr>
<tr>
<td>Ultimate tensile strength, MPa</td>
<td>546.2</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>30.5</td>
</tr>
<tr>
<td>Reduction of area, %</td>
<td>54.3</td>
</tr>
<tr>
<td>Strain hardening exponent</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Photo. 1 External appearance of the drawn. Arrows show lustrous annular bands on the surface of the drawn.

Photo. 2 Radiograph of the drawn by γ-rays. Full size. Arrows show the positions of central burst defects.

face of billet. In general, however, the visual observation of drawing is not sufficient for detecting the internal defects.

2. Radiograph

The radiograph by γ-ray in Photo. 2 illustrates the central burst defects which have been observed after the seventh pass. The defects are relatively large and affect the external surface of the drawn as indicated by the annular bands.

3. Direct observation of defects

Samples were taken from the transverse and longitudinal sections of the billet. There were
Penny-shaped Central Bursting Defect in the Cold Drawing of High Chromium Ferritic Stainless Steel

4. Hardness distribution in the vicinity of the cavity

Figure 1 shows the hardness distribution in the vicinity of cavities in the longitudinal section. Hardness along the centerline is about 225–230 Hv near the border of the cavity and about 230–250 Hv far from the border, and the hardness in the region between the surface of the billet and the brim of the cavity is about 270–280 Hv.

5. Microfractography

Examinations of the cavity surfaces demon-

large cavities at the positions detected by γ-rays in the interior of the drawn. No defects could not be detected in the part between the cavities.

The shape of the cavity is different from the chevron, which is a usual shape in the central burst and resembles a pancake with an un-sharpen brim, as shown in Photo. 3. (The typical central burst is in the chevron or arrow shape, with the head point in the drawing direction and a sharp tip.)
strate that the fracture mode is cleavage fracture in most cases. Photograph 4 is a result of the precision matching technique applied to the mating fracture surface of cavity. Figure 2 illustrates the location of mating fracture surfaces in Photo. 4. Convex parts and the concave parts correspond to each other in both surfaces and the degree of correspondence is very high in the central region of the cavity. This fact suggests that the cavities have been initiated by cleavage fracture in the central part of the billet during the drawing and those parts are not largely deformed by the formation of the defects. Photograph 5 shows a river pattern on the cleavage fracture surface. Judging from the river pattern, the propagation of cleavage is discontinuous.

6. Metallography

Metallographic examination was carried out in the neighborhood of cavities under polarized light. Grains are almost equiaxed in the vicinity of the centerline of the billet but elongated near the brim of the cavity, the surface of the billet and far from the border of the cavity even though in the region of the centerline. Photograph 6 indicates that many deformation-twins are in the grain near the border of the cavities in the vicinity of the centerline. The plane of cracks does not necessarily correspond to the plane of twins. Photograph 7 shows the microstructure near the brim of the cavity in the longitudinal section. Twins are relatively few and stripe patterns which are representative of the substructure appear in the grains. The stripe patterns have a tendency to align in the direction of drawing. Such a stripe pattern does not appear in the grain near the border of the cavity at the centerline. The brim of the cavity, e.g., the crack tip is remarkably blunted. This fact suggests the formation of a large plastic zone ahead of the crack. Photograph 8 shows the microstructure near the brim of the cavity in the transverse section. The characteristic stripe pattern structure is observed in the vicinity of the brim of the cavity. A small number of deformation twins appear and the region of crossing of the stripe pattern and twins is evident, too. Photograph 9 shows the
Penny-shaped Central Bursting Defect in the Cold Drawing of High Chromium Ferritic Stainless Steel

Photo. 7 Microstructure near the brim of cavity in the longitudinal section of the drawn. Stripe pattern appears in the grains.

Photo. 8 Microstructure in the vicinity of the cavity brim in the transverse section.

IV. Discussion

The high chromium ferritic stainless steel has been damaged in an unusual form of central bursting during cold drawing. The micromechanism of the fracture is typical cleavage on the cavity surface and the correspondence exists between the mating surfaces (especially in the central part), and the hardness is relatively low near the border of the cavity at the centerline. Those facts indicate that the cleavage fracture has initiated at the centerline of the billet in the early stages of drawing. This conclusion is also supported by the result of metallography, that the grains do not elongate near the border of the cavities.

Photo. 9 Microstructure near the surface of the drawn in the longitudinal section.
in the region of the centerline and the stripe pattern is not observed there. Moreover, the fact that many deformation twins are observed may be related to the above conclusion.

The shape of defects is different from the usual shape of central burst in this experiment. However, the studies made hitherto on the typical central burst are useful for the investigation of this case. The flow process in drawing can be extremely nonhomogeneous\(^9\). Rogers\(^8\) proposed that the degree of structural damage generated locally should depend strongly on the hydrostatic component of the stress. According to this concept, he analyzed the deformation process of strip drawing using the slip line field method. The distribution of hydrostatic pressure in the strip, measured by the angular change of the slip line indicates that the greatest hydrostatic compression is in the region directly under the die while at the midplane the hydrostatic stress has its lowest algebraic value. Some conclusions shown by the analysis is that (1) the structural damage generated locally depends on the nature of the hydrostatic component of the stress prevailing there while it was being plastically deformed during drawing, (2) the magnitude of the structural damage increases as the hydrostatic stresses become increasingly tensile, (3) the nature and magnitude of the hydrostatic stress generated locally in the region where deformation is occurring depends on the process parameters, and (4) in strip drawing, the hydrostatic stresses are most tensile and the damage is most severe at the midplane of the strip.

It seems quite probable that the defects generated locally in the present billet are related closely to the hydrostatic component of the stress acting there. However, considerations should be given to the difference in micromechanism of fracture. In terms of the micromechanism of fracture, the usual type of central burst occurs by "microvoid coalescence"\(^{10}\), but the defects observed in the experiment occurs by cleavage. In general, the onset of microvoid coalescence demands a critical strain level and the growth may be affected by the hydrostatic component of the stress state\(^{11}\). The concepts of Rogers and other workers\(^{(5)\text{-}(7)}\) are based on the above context. However, the cleavage fracture occurs at a critical value of tensile stress and so does the propagation\(^{11}\). Consequently, the distribution of tensile stress in the billet has to be calculated in this case. The distribution of the tensile component in the drawing direction is plotted in Fig. 3 after modification of Rogers' result. It should be noted that the highest tension exists at the midplane. The analysis described above is predicted under the condition of zero friction between the die surfaces and the strip being drawn. According to the detailed analysis by Coffin and Rogers\(^{(12)}\), the effect of friction is to make the hydrostatic component of stress more negative than would be expected under frictionless conditions. For the conditions of this experiment (approximately 5\% reduction per pass; die semi-angle 15°, coefficient of friction 0.3), this amounts to an increase in midplane tensile stress.

\[\text{Fig. 3 Distribution of the tensile stress components in billet in the drawing direction in passing through the die. Reduction=}8.5\%. \text{ Numbers refer to the tensile stress components (negative value)/tensile yield stress.}\]
stress of about 0.3 (× tensile yield stress). The highest tension at the midplane may be equivalent to a severely notched bar. Although the slip line field approach is applicable under the restrictions of plane strain for a plastic-rigid material of constant yield stress, the results of the analysis of their plane strain analogs would be directly applicable to simple, axisymmetric deformation processes such as wire drawing.

Avitzur’s analysis of the energy balance, leading to an expression relating the drawing stress and geometry of the system, establishes a criterion of central bursting⁵. Furthermore, Hoffmanner’s prediction based on the Cockcroft and Latham criterion and visioplasticity results are presented⁶. Criterion derived by Zimerman and Avitzur(13) takes into consideration the effect of the strain hardening capacity of the deformation material. However, the result of this experiment does not agree very well with other criterions. It is very likely that the discrepancy is dependent on the difference in micromechanism of fracture.

The shape of defects in this experiment is different from the usual one. There has not been any detailed investigation on the growth of the central defect, but it seems quite probable that the chevron or the arrow are formed by the ‘void sheet mechanism(10) from the defect at the centerline of the billet in the usual central bursting. The cleavage type defect generated at the centerline seems to grow by a discontinuous propagation of cleavage depending on the tensile stress below the crack tip. In the case of usual central bursting, crack growth takes place along a narrow region of heavy deformation (void sheet) running at an angle of 30° to 40° to the tensile axis to form an arrow shape. However, in the case of the cleavage type defect the crack growth perpendicular to the direction of tensile stress takes place to form a penny shape.

The shape of the brim of cavities, the metallography in the vicinity of the brim and the hardness distribution shows that a large plastic zone is formed ahead of the crack tip, the blunting of the crack tip occurs, and then the crack propagation rate is retarded to stop. Those facts can be explained by inhomogeneity of the stress state and the flow. The greatest hydrostatic compression is in the region directly under the die, so that the fracture behavior by cleavage or microvoid coalescence is prevented in the region. The examinations of the microstructures indicate that the deformation by slip takes place mainly in the region and the stripe pattern are formed and strain hardening is relatively high in the region, while the deformation by twins takes place in the region of the centerline of the billet and the strain hardening is low there.

Material properties play a large role in the damage production process, as suggested by Rogers(8). The ductility of high chromium stainless steel has been improved by the high refinement, but the results of the experiment indicate that the notch toughness, in other words, the tendency of this alloy to suffer structural damage under an unfavorable state of stress is still a problem which cannot be ignored. Rogers has reported that materials which have a low inclusion content or without hard second phase particles to act as void nuclei show minimal damage. However, the inclusion content is extremely low in the case of alloys refined highly and the second phase particles are scarcely contained in the specimen heat-treated as mentioned in Sec. II.(15) Ferritic stainless steels are subject to a ductile to brittle transition temperature (DBTT) which is dependent on many factors. Some data have indicated a significant influence of the
interstitial component\(^{(14)}\) and the microstructure\(^{(15)}\). The grain size is important for notch toughness\(^{(16)}\). It can be considered that the microstructure containing large grains enhances the sensitivity to the state of stress in this case. As far as the present author investigated the high chromium stainless steel is sensitive to the state of hydrostatic tensile stress\(^{(17)}\). For example, the failure strain of the material as a function of stress state in the circumferentially notched tensile specimen is shown in Fig. 4\(\dagger\). Furthermore, it seems that the work required to initiate fracture is lowered by the high yield stress compared with the ultimate tensile strength and by the relatively low work-hardening rate in the specimen\(^{(20)}\).

The mechanical properties of this alloy are dependent on the thermomechanical processing and final heat treatment. The relations has been investigated and the results are to be reported in a separate paper\(^{(18)}\).

As regards the microstructure, special attention should be paid to the stripe pattern in the vicinity of the cavity brim. The stripe pattern reveals the ferritic substructure under polarized light. The substructure is deformation zones within a grain of a polycrystalline body and formed by "Compartmentalization" of the grain\(^{(19)}\). They may correspond to boundaries of zones of differing orientation within the grain. Subgrains are often seen in the bands of alternating orientation. The difference in orientation between the alternating stripes is fairly large, judging from the configuration of crossing of stripes and twins. The fine substructure consisting of the stripes affects to prevent the twin-nucleated cleavage fracture.

The periodicity of the occurrence of central bursting seems to be attributable to the periodicity of occurrence of a non-steady state of flow, as suggested by Avitzur\(^{(5)}\). That is, as the drawing proceeds, the fracture will grow in size and will be displaced axially until it leaves the die, thus leading to a non-steady state of the flow as mentioned above. The situation may therefore bring about the periodicity and also affect the frictional condition in such a way as to induce the periodicity of the lustrous annular bands on the external surface of the drawn. In general, however, the visual observation is not sufficient for detecting the internal defects. Particularly, the difficulty of detection is increased by the special characteristics in the case of penny-shaped central bursting defects from cleavage. This is partly due to the fact the defects do not necessarily occur subsequent to prior severe cold working as in usual cases and occur with a relatively small reduction.

The condition for the occurrence of central bursting in question also depends on the process parameters, that is, die angle, reduction per pass and coefficient of friction. The correlations and the data will be presented elsewhere.

Finally, this study confirms the following advice of Rogers\(^{(13)}\). The working ranges for the new materials of the body-centered cubic crystal structure must be determined experimentally, even though the principles and general understanding exist, since the brittle transition temperature may not be known for such materials, especially under the some complex stress systems which arise in some deformation processes.

V. Conclusions

An unusual form of central bursting has been found during cold drawing of a high chromium ferritic stainless steel. The conclusions obtained by the analysis are:

1. The defects form periodically in the drawing direction and do not have the usual chevron or arrow shape but a penny shape.
2. The defects are generated by cleavage fracture at the centerline of billet.
3. The defects depend on the nature of the stress state prevailing there while it is being plastically deformed during drawing.
4. In drawing the hydrostatic stresses are most tensile in the slip line field analysis, and the damage caused at a critical tensile stress is

\(\dagger\) The chemical composition of the specimen in Fig. 4 is different from the composition in Table 1. The difference is carbon content 0.002% and niobium content 0.2%. The grain size is about 500 \(\mu\)m. The stress states in circumferentially notched tensile specimens were estimated by using an analysis originally applied to the neck of tensile specimens by Bridgman\(^{(21)}\).
most severe at the centerline even though the quantity of deformation and the strain-hardening are small.

(5) The growth of defects takes place in a direction perpendicular to the highest tensile stress by discontinuous cleavage propagation to form a penny shape.

(6) Blunting of the crack tip occurs in the region directly under the die and then the crack propagation rate is retarded to stop. Those facts can be explained in terms of the inhomogeneity of the stress state and the flow.

(7) Mechanical properties of the high-purity high-chromium stainless steel play a very important role in the damage production process. That is, the high ductility of the alloy in the unidirectional tensile stress or hydrostatic compressive stress as well as the tendency of the alloy to suffer relatively easily structural damage under an unfavorable state of stresses has a strong effect on the damage production process.

Acknowledgments

The author wish to thank his colleagues at Industrial Research Laboratory of the Research Institute for Iron, Steel and Other Metals, Tohoku University, for their experimental cooperation and Dr. Kamigaki for helpful nondestructive examination and Prof. E. Tanaka for the guidance and encouragement. Experimental materials was kindly supplied by Research Laboratory for Metals, Showa Denko Co. Ltd.

REFERENCES


(3) J. V. Russel: Metal Engineering Quarterly, 2 (1962), No. 1, 49.


(9) L. F. Coffin, Jr.: Fundamentals of Deformation Processing, Syracuse Univ. Press, Syracuse, N.Y. (1964), Chap. II.

(10) H. C. Rogers: ibid., Chap. IX.


(17) M. Shimura: to be published.

(18) M. Shimura, H. Tokuno and E. Tanaka: to be published.

