Effect of Groove Shape on Closure of Center Defects in Symmetric Rolling of Round Billets

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Although the closure of defects at the center of round billets on rolling such billets is an important subject, a method of quantity evaluation for such closure has not yet been clarified. Therefore, to explain the effect of rolling conditions including grooved shape, we carried out the experiments with round billet which has an artificial defect and finite element analysis, especially with respect to the integration of the hydrostatic stress Gm. The results showed that grooved shape affected the closure of center defect, and Gm could express the relationship between closure and rolling conditions without the consideration of the difference in the ratio of defect size and roll size. However we found that original Gm could not express the influence of the grooved shape, at the same time.

KEY WORDS: rolling; bar rolling; deformation behavior; defect; closure; hydrostatic stress; grooved roll; equivalent strain.

1. Introduction

As distinctive features of the steel materials which support social infrastructure, a wide range of mechanical properties are available and products with different cross-sectional shapes can be manufactured with comparative ease. In many cases, a large-sized slab or billet manufactured by the continuous casting or ingot casting process is rolled as the material for manufacturing these products.

The semi-finished products which are used as material are manufactured by applying plastic working such as rolling or forging to still larger continuous casting materials or ingots. The use of large material is advantageous, in that the dimensions of the semi-finished products can be produced with considerable freedom, but on the other hand, inclusion of casting defects and the size of those defects tend to become large due to the increased material cross-sectional area. Therefore, reduction of this type of defect is an important issue.

It is known that elimination of internal defects by closure or pressure bonding of defects, as is done in forging, generally achieves a larger improvement in internal quality as the degree of working increases. However, in heaving working with a flat die, the Mannesmann effect occurs in the central part of the material, and this causes cracks reduces the closure effect. To solve this problem, the FM forging method was developed, as described in this paper. The closure conditions in this case are also discussed.

In rolling, it has been reported that a large rolling reduction is effective. However, in rolling and forging processes, it has been found that defects can be closed more efficiently by providing a temperature gradient between the surface and center of the material.

Many reports have indicated that the closure of defects in rolling can be arranged by the roll gap shape factor \( L_d/H_m \), where, \( L_d \) is the roll contact arc length and \( H_m \) is average thickness. Although this result was obtained by an experimental technique and is suitable for actual operation, its mechanism had not been clarified. On the other hand, with progress in numerical analysis, comparison of deformation analysis by FEM and the closure behavior of defects can now be performed with good accuracy, especially in the case of forging. Moreover, quantitative evaluation of closure behavior by using a parameter was attempted in a report which stated that closure behavior can be arranged by the stress and strain fields obtained from these analyses.

In rolling, quantification of closure behavior is influenced by the arc-of-contact length or average plate thickness, so that estimation from the roll gap shape factor is also possible. Therefore, estimation of the closure effect by using the arc-of-contact length as a parameter is proposed. Based on the fact that a smaller average plate thickness is effective in defect closure, the stress and strain produced by rolling reduction are effective in closure of the central part of material, a hydrostatic stress integration parameter, which is obtained by dividing the hydrostatic stress by equivalent strain and integrating the result by strain is proposed by forging analysis, and application of this parameter to rolling is examined. As the hydrostatic stress integral equation takes a form similar to the well-known Oyane’s formula as an expression of ductile fracture, it can be said that this equation expresses the closure of a defect produced by the volumetric strain caused by deformation. In comparison
with the real phenomenon in this formula, it is thought that hydrostatic stress integral equation can also express the phenomenon with good accuracy, since it expresses the same tendency as the knowledge that a high hydrostatic stress is effective in closure of defects. Therefore, this equation is also applied to study of the actual manufacture process.22)

On the other hand, in forging application of the closure behavior given by hydrostatic stress integration, it has been reported that closure behavior changes depending on the dies being used.23) As the main factor in this difference, based on the results of calculation of the influence coefficient by multiple regression, it is thought that equivalent strain has the largest influence on the deviation of the hydrostatic stress integration value Gm.24) In a study of the application of hydrostatic stress integration which considered a defect, it was reported that the stress-strain distribution surrounding the defect influenced Gm in the surrounding region.25) It is supposed that differences in the processing method also greatly influence the distribution of Gm, and this in turn has a large influence on defect closure; however, in rolling, the influence of differences in rolling conditions on defect closure has yet not been clarified.

Accordingly, this report compares the experimental and analytical results of the closure behavior of a defect in the central part of a billet. At the same time, the results of an attempt to quantitatively evaluate the applicable range of the hydrostatic stress integration value Gm, which is currently applied comparatively broadly, are also presented.

2. Experiment Method

2.1. Closure Behavior Investigation of Defect Arranged at Center of Material

In order to investigate the closure of an axial center defect depending on changes of the groove shape, which is the purpose of this research, an artificial defect was created in the rolling stock. Assuming a billet with a circular cross section as the rolling stock, the shape of the defect was a bored hole, with a similar circular cross section, in the longitudinal direction of the material. The material used the pure lead.

Cold rolling was performed at room temperature, in this case, 25°C.

As shown in Fig. 1, the groove shapes used in this experiment were oval, box, diamond, or flat. Pairs of rolls which comprising these shapes were used. The groove shape used in the experiment was designed so that the face in contact during rolling could be set from 2, 2 to a maximum of 6, 4 with increased rolling reduction. The diameter of the roll was designed so that the diameter was 150 mm at the flange part as the maximum value. The dimensions of the stock were a billet outer diameter of 50 mm or 30 mm, the size of the defect in the center of the material was 5.13, 2.55 or 3.10 mm and the length was 150 mm. The geometries of the specimens used these experiments are shown in Table 1.

To investigate the effect of rolling reduction, in these experiments the relationship between the specimen reduction in area and the defect closure rate was investigated by adjusting the roll gap.

In the following, reduction in area of the material Rm and the defect closure rate Rd are defined as shown by the following equations, respectively. A cross section in the part in the steady rolling state was used for the dimensions of the defect after rolling.

\[ R_m = \frac{1}{A_{rolled}} \frac{A_{initial}}{A_{material}} \]

\[ R_d = \frac{1}{A_{defect}} \frac{A_{initial}}{A_{material}} \]

2.2. Solver and Analysis Conditions Used in Analysis of Defect Closure Behavior

As described in the previous report, in order to estimate the closure behavior of a defect by analysis, the influence of defect dimensions should be considered. Therefore, this analysis was performed using the rigid plasticity finite-element analysis solver CORMILL26) using the Lagrange multiplier method. As the stress field used in the discussion of defect closure, the value in the roll bite outlet section was used. This value was used because stress reaches its maximum value near the roll bite outlet when material with a circular section is rolled with diamond-shaped grooved rolls. As rolling was symmetrical in four directions, the analysis was conducted with a 1/4 section. Within the section, the material was divided into 20 meshes in the radial direction and 9 meshes in the circumferential direction; 8 meshes were provided in the rolling direction and meshes for the deformation zones before and after the roll bite were also provided. Number of meshes in circumferential direction was considered by the analyses with different number of mesh division. The results of analyses for diamond groove rolling at \( R_m = 24\% \) by use of the material with the outside diameter of 30 mm and inside diameter of 3.10 mm as defect are shown in Fig. 2. It was found that there were little change of Rm and Rd in 9 meshes and over, namely obtained results became steady state, therefore number of circumferential division was decided 9. Accuracy of the

![Fig. 1. Dimension of roll and grooved shape for experiments and FEA (from top to bottom, Oval, Box and Diamond).](image-url)

**Table 1. Dimension of material for rolling test.**

| diameter of center defect/mm | 5.13 | 2.55 | 3.10 |
|-----------------------------|------|------|------|
| outer diameter/mm           | 50   | 30   |      |

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FEA was proved in the H-beam universal rolling by comparison with lead and steel material, and also provided in bar rolling using plasticine for stress field.\(^25\) The element used in the analysis was defined as an 8-node hexahedral isoparametric element with reduced integration, and was analyzed in three dimensions.

Flow stress was given by flow stress \(\sigma_{eq}\), which was used the results of the single axis compression experiment for pure lead as a parameter of the average deformation resistance equation\(^28\) of the formula of Inoue\(^29\) and Misaka\(^30\) as follows.

\[
\sigma_{eq} = 33.81e^{0.3e^{0.07}} \text{ [MPa]}
\]

The temperature distribution was assumed to be uniform. The coefficient of friction between the roll and the material was assumed to be approximately 0.5 in cold rolling by Coulomb friction. This was adopted because the surface was intentionally roughened with sandpaper in order to secure the gripping ability of the roll in the experiment. The hydrostatic stress integration value \(G_m\), which is discussed in the following, was calculated from the stress and strain calculated in this manner, and quantitative evaluation was discussed.

In the following, rolling by a pair of flat rolls without grooves is called F-F rolling. Similarly, rolling by an oval groove pair is called O-O rolling, box rolling is called B-B rolling, and diamond groove rolling is called D-D rolling.

3. Results and Discussion

3.1. Influence of Dimension of Defect on Closure Rate

The materials with the outside diameter (OD) of 50 mm and the defect dimensions 5.13 mm and 2.55 mm were used in the rolling experiment. The ratio of defect diameter/material OD is defined as the defect dimension ratio. That is, defect dimension ratios of 0.1 and 0.05 are compared in this experiment.

Cross-sectional photographs of the specimens after rolling with the different defect dimension ratios are shown in Figs. 3 and 4, respectively. The defect closure rates for each groove shape and rolling reduction are shown in Figs. 5 and 6, respectively. In these figures, the error bar shows the range of the data \(R_d\) which may happen due to accuracy in mechanical working to make the straight hole as the defect. The defect closure rate increases with increasing rolling reduction, independent of the defect dimension ratio. However, the closure tendency changes depending on the groove shape. As shown in Fig. 5, with the defect dimension ratio of 0.1, the closure rate is the highest in flat rolling when reduction in area exceeds about 0.1. Moreover, the region exceeding 0.2 shows a tendency in which the defect is closed by flat rolling and the closure rate in diamond rolling becomes the lowest. The obtained width by analyses was confirmed by comparing to experimental results with errors of less than 2%. The cause of this low closure rate in diamond rolling is attributed to the large deformation of the material in the rolling direction\(^31\) with this groove shape.

In addition, the superiority of closure by flat rolling is also recognized when the defect dimension ratio is 0.05, as shown in Fig. 6, although this is not clearer than with the dimension of defect ratio 0.1.

This comparison showed that the dimensions of a defect do not have a large effect on closure behavior within the range of rolling conditions in this research, and flat rolling is most advantageous for closure.

![Fig. 2. Influence of number of circumferential division on change of reduction in area.](image)

![Fig. 3. Cross sections after rolling with 50 mm O.D. and 5.13 mm I.D. billets.](image)
Fig. 4. Cross sections after rolling with 50 mm O.D. and 2.55 mm I.D. billets.

Fig. 5. Relationship obtained by experiments between the reduction in area of billet Rm and the one of defects with 50 mm O.D.-5.13 mm I.D. billets.

Fig. 6. Relationship obtained by experiments between the reduction in area of billet Rm and the one of defects Rd with 50 mm O.D. -2.55 mm I.D. billets.

Fig. 7. Cross sections after rolling with 30 mm O.D. and 3.10 mm I.D. billets.
3.2. Influence of Roll Diameter on Defect Closure

Next, the influence of the roll diameter ratio of a roll was investigated by changing the material OD. The roll diameter ratio is expressed by the numerical value obtained by dividing the OD of the roll by the OD of the material.

Figure 7 shows cross-sectional photographs with the defect dimension ratio of 0.1 and the roll diameter ratio of 5; Fig. 8 shows the relationship of reduction in area and the closure rate under the same conditions. In Fig. 7, it could be found that the shape of deformed hole between F-F and B-B rolling are different while the reduction rate are similar. The cause of that was guessed the restrain of sidewall with box caliber.

From a comparison with Fig. 3, in which the roll diameter ratio was 3, it can be understood that the influence of reduction in area on the closure rate is great. That is, in flat rolling, the reduction in area $R_m$ was approximately 0.1 and in this case, the defect was closed. In contrast, the defect closure rate $R_d$ was roughly 0.6 in rolling on the same order with the other groove shapes. The closure rate is clearly higher compared with the closure rate of approximately 0.4 in Fig. 5, in which the defect dimension ratio is the same. Regarding this result, it is considered that the tendency shown by these results is similar to the phenomenon in which the hydrostatic stress increases because the rolling condition approaches forging as the larger roll diameter ratio increases.

Therefore, the influence of the roll diameter on closure was analyzed by numerical analysis. Using oval-shaped grooved rolls in which the OD of the roll at the flange was set to the 150 mm in the experiment or double that diameter, i.e., 300 mm, $R_m$ was changed and this parameter was compared with the reduction in the cross-sectional area of the defect. These results are shown in Fig. 9. When compared at the same $R_m$, it can be understood that the cross-sectional area of a defect is effectively reduced when a large OD roll is used. Furthermore, the change of the hydrostatic stress within the roll bite in the analytical result, which showed $R_m$ of approximately 9% in Fig. 9, was compared at the caliber bottom and the flange part. This is shown in Fig. 10. Although the hydrostatic stress in the caliber bottom does not change greatly when the roll diameter is changed, the hydrostatic stress in the flange part increases when the large diameter roll is used. This is thought to suggest that hydrostatic stress and its distribution have a large influence on defect closure.

Next, the influence of the groove shape on defect closure was clear when the roll diameter ratio was large. For example, in the range of $R_m$ of 0.1–0.15, the closure rate was highest with flat rolling, followed by oval rolling, box rolling and diagram rolling. Although the closure performance of diamond rolling was inferior, as mentioned previously, neither the superiority of oval rolling nor the difference between oval rolling and box rolling was necessarily clear.

3.3. Evaluation of Closure by Using Hydrostatic Stress

As described in the previous paragraph, in conventional practice, defect closure in rolling has frequently been evaluated by using hydrostatic stress. However, while there have been many studies on plate rolling, there are virtually no examples which considered the influence of groove shape. Therefore, the defect closure rate obtained in these experiments was compared with the hydrostatic stress obtained by FEM analysis.

As rolling conditions, flat rolling and diamond rolling with $R_m$ of approximately 0.15 and different roll diameter ratios were compared. In addition, when a defect was provided, this analysis found that stress was distributed...
along that edge of that defect. Therefore, the analysis was performed assuming a round bar as the material in order to eliminate that influence.

For the stress field, as it was thought that the hydrostatic stress just after the exit plane of the roll bite was a value representing the stress field, this was compared. The result is shown in Fig. 11. In this figure, the effect when the roll diameter ratio was changed in flat rolling showed a high hydrostatic stress when the roll diameter ratio was large, proving that the conventional view is correct. However, in the comparison of diamond rolling and flat rolling, the experimental defect closure rate was clearly large in the case of flat rolling. In spite of this, the closure ratio predicted by the hydrostatic stress becomes larger in diamond rolling. In other words, when the groove shape is different, it is difficult to discuss defect closure only in terms of hydrostatic stress.

In forging, it is known that equivalent plastic strain has a large influence on defect closure. Therefore, equivalent plastic strain, including that in the vicinity of a defect, which is presumed to have a direct effect on the defect closure, was compared by analysis. The results are shown in Fig. 12. In flat rolling, equivalent plastic strain becomes large near the outside surface, which is in contact with the roll, and comparatively high strain with a dead metal shape is distributed in the direction of an axial center where a defect exists. This result confirmed that one of the main factors which influence closure of an axial center defect is equivalent plastic strain.

### 3.4. Discussion of Defect Closure by Using Hydrostatic Stress Integration Value \( G_m \)

Based on the discussion on Section 3.3, defect closure was investigated by using the hydrostatic stress integration value \( G_m \) as a parameter which can consider these factors of hydrostatic stress and equivalent plastic strain. The influence of the groove shape on \( G_m \) was studied by using the \( G_m \) obtained from the stress field and strain field at the on the edge of the defect in the FEM analysis, conditioned on the existence of a defect, as investigated in a previous report.

\( G_m \) is expressed by the following formulas using the hydrostatic stress \( \sigma_m \), equivalent stress \( \sigma_{eq} \) and equivalent strain \( \varepsilon_{eq} \).

\[
G_m = \int \sigma_m \varepsilon_{eq} \, d\tau 
\]

\[
\sigma_m = (\sigma_x + \sigma_y + \sigma_z) / 3 \quad \text{................. (2)}
\]

Here, \( G_m \) in the rolling direction streamline in a roll bite was calculated as an approximation by the trapezoid method between the longitudinal direction nodes on a streamline.

Furthermore, an analysis prior to this discussion confirmed that there is no significant difference in terms of the correlation of \( R_m \) and \( R_d \) acquired in the experiment. As an example, Fig. 13 shows the results for the defect diameter ratio 0.1 and roll diameter ratio 3. By comparing Figs. 5 and 13, experiments and analyses show almost good agreement except for the condition with flat rolling in \( R_m > 0.2 \). In our analyses, \( R_m \) value in a large reduction range, i.e. \( R_m > 0.2 \) in flat rolling, with the perfect defect’s closure was not used because of the uncertainty of the obtained data. In addition, the size of artificial defect had small variation at mechanical working about the range of 0.1 mm in the diameter, therefore it was considered that the deference was appeared.

Figure 14 shows the difference in the influence of the groove shape on the distribution of \( G_m \) obtained in the anal-
ysis under the rolling conditions of $R_m$ of 0.13, roll diameter ratio of 5 and defect dimension ratio of 0.1. As in the results in the previous report,$^{25)}$ which investigated asymmetry, $G_m$ displays a distribution in the circumferential direction of the defect edge. Moreover, in diamond rolling, $G_m$ was distributed comparatively uniformly in the circumferential direction, but with the other groove shapes, there was a large difference in its position. Therefore, as $G_m$ which has a correlation with defect closure, the authors decided to use the average value of the defect perimeter, and conducted the analysis by adjusting the value of $R_m$ to be approximately equal with the range of the experimental conditions.

Figures 15 and 16 show the results with the roll diameter ratio of 3.0 and the defect dimension ratios of 0.1 and 0.05, respectively. As with the results of the rolling experiments, a comparison of these results shows that the effect of the defect dimension ratio is negligible. On the other hand, although the groove shape which is used affects the defect closure rate, it seems that this can be arranged systematically by the $G_m$ value within a certain region. Accordingly, in the range of $G_m$ values up to about $-0.1$ in Fig. 15, the value of $G_m$ is independent of the groove shape. However, from a comparison of the results when the closure rate is from 0.7 to 0.8, it is estimated that closure is performed in the order of flat rolling, box rolling and diamond rolling, even with smaller $G_m$ values. Regarding this threshold value, as the result of oval rolling at around $-0.07$, $R_m$ is on the order of 0.13. From a comparison with the experimental results in Fig. 5, this is the region where the effect of the groove shape has already begun to appear. Therefore, as mentioned above, the threshold value is considered to be approximately $-0.1$. The opposite tendency in the hydrostatic stress shown in Fig. 11 and the distribution of equivalent plastic strain shown in Fig. 12 is obtained depending on the groove shape. However, because $G_m$ is the product of these two factors, it is considered that defect closure of a comparable degree is obtained at $G_m$ values of $-0.1$ and less, at which $G_m$ influences defect closure.

A similar analysis was conducted for the rolling conditions of the roll diameter ratio of 5 and the defect dimension ratio of 0.1. The results are shown in Fig. 17. It can be understood that the influence of the groove shape is shown still more clearly by the results in this figure. Therefore, as $G_m$ is considered to have high flexibility, defect closure given by $G_m$ was summarized for all the rolling conditions as shown in Fig. 18. This figure shows that defect closure does not depend on rolling conditions and can be arranged by $G_m$ with comparatively little deviation. Furthermore, when multiple regression of the obtained result was carried out, the difference in the $G_m$ value depending on the groove shape was small up to $-0.08$, as stated previously, but it was clear that the groove shape had begun to influence defect closure after exceeding $-0.1$. In explaining this, it is conjectured that the influence of the groove shape becomes obvious in the region exceeding $-0.1$, for example, when rolling the $\varphi 30$ material in Fig. 12, because the equivalent plastic strain due to deformation of the dead metal shape becomes relative large at the edge of a defect.

To investigate the difference in the deformation of this defect in greater detail, the mode of deformation in the roll bite during flat rolling and diamond rolling was traced from the viewpoint of the dependence of closure on the groove shape. This is shown in Fig. 19, and the equivalent strain distribution of the area surrounding the defect is shown in Fig. 20. In Fig. 19, the dotted line shows the deformation near the starting point of contact between the roll and the material, and the solid line shows the deformation on the delivery side at a slight distance from the center of roll bite.
From this comparison of deformation, in flat rolling, it was found that a center defect is first flattened, and this is followed by width spread and closure of the defect. In contrast, in diamond rolling, the entire defect contracts uniformly. The difference in these closure phenomena can also be understood from the equivalent strain distribution shown in Fig. 20. It is considered that these differences in the equivalent strain distribution appear as shown in the distribution of Gm in Fig. 14 and become differences in closure behavior.

As mentioned above, the closure of center defects can be expressed with good accuracy by using the hydrostatic stress integration value Gm. However, in the region where Gm exceeds -0.1, it is difficult to express differences depending on groove shape systematically by Gm in its present form.

4. Conclusion

In order to examine the defect closure effect of grooved
rolling on defects in the center of billets with a circular section, experiments were performed with various groove shapes using pure lead material, and simultaneously with the experiments, a numerical analysis was conducted by the rigid plasticity finite element method analysis solver CORMILL. The knowledge obtained as a result of this study is summarized below.

(1) The selection of the groove shape has a large influence on the defect closure effect. When compared at the same material reduction in area $R_m$, the highest closure effect is obtained by flat rolling, followed by oval rolling, box rolling, and diamond rolling in that order.

(2) The effect of rolling conditions on defect closure can be expressed by using the hydrostatic stress integration value $G_m$, independent of the roll diameter ratio and the defect dimension ratio. However, when the influence of the groove shape exceeds a certain value expressed by $G_m$, the influence of those factors still remains. Development of a unified expression for this is a subject for future research.

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