Analysis of Alligatoring Behavior During Roll Pressing of DRI powder with Flat Roller and Indentation-type Roller

S.-H. Joo1, a, H.-J. Chang2, b, W.H. Bang2, c, H. N. Han3, d and K. H. Oh4, e

1 POSCO, Pohang, Gyeongbuk, 790-785 Korea
2 School of Materials Science and Engineering, Seoul National University, Seoul 151-742, Korea.
3 Materials Processing Department, Korea Institute of Machinery and Materials, Changwon, Kyungnam, 641-010 Korea

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Abstract. A computational model for roll pressing of powder was developed based on an elastoplastic finite element method, and was applied to predict the alligatoring behavior at roll nip during powder compacting process. The yield criterion for powder has been implanted for the simulation of the roll pressing of Direct Reduced Iron powder with both flat roller and indentation-type roller. Calculated results could well explain the experimental observation that the indentation-type roller is more useful to hinder in alligatoring.

Introduction

In the roll pressing [1] of powder (Fig. 1a), enlarging the thickness of compacted sheet offers more economical efficiency. However over-enlargement of the sheet thickness may give rise to the alligatoring phenomenon at the end of roll pressing (Fig. 1b). Alligatoring mechanism based on residual stress was proposed by Backofen [2]. In the model, the sheet splitting is caused by a RD stress, which represents tension in surface and compression in center. In this work, it was evidenced that during roll pressing with flat roll (Fig. 2a), RD stress states are compression in and tension in center, after exit of the pressing the RD residual stress state is reversed. These may split the compacted powder sheet. Making indentations on the surface of rollers (Fig. 2b) has been suggested as the solution against the alligatoring problem [3].

Several mathematical models for porous material have been proposed for the numerical approach. Drucker and Prager [4] suggested the generalized Mohr-Coulomb model into three-dimensional
situations. Park et al. [5] modified the yield criterion, suggested by Doraivelu et al. [6], to analyze the compaction of powder particles.

In this paper, the experimental result on a critical sheet thickness that leads to the alligatoring is compared with the analysis by the finite element method based on the yield criterion of powder suggested by Park et al. [5]. We present an interesting conclusion that indentations type roller offers larger quantity product than flat roller because the indentations increase the critical sheet thickness.

**Numerical model**

The yield criterion of a porous material can be generalized in a following form

\[
(2 + R^2)J_2' + \frac{1 - R^2}{3}J_1^2 = \left(\frac{R - R_T}{1 - R_T}\right)^m
\]

where \( J_2' \) is second deviatoric stress invariant, and \( J_1 \) first stress invariant, \( R \) relative density, \( R_T \) tap density, \( K \) a strength coefficient, \( n \) a strain hardening exponent and \( \varepsilon_0 \) an accumulated plastic strain in incompressible base metal. The parameters \( m, K \) and \( n \) can be obtained by the best fitting of the uniaxial compaction data. The equation for uniaxial powder compaction is expressed by [5]

\[
P = \left[ \frac{2 - R^2}{(2 + R^2)(1 - R^2)} \right]^{n/2} \left( \frac{R - R_T}{1 - R_T} \right)^{m/2} \times \left[ K \int_0^R \frac{1}{(2 + R^2)(1 - R^2)} \left( \frac{R - R_T}{1 - R_T} \right)^{m/2} dR \right]^{1/2}
\]

**Experiments**

Uniaxial die compaction was used to find out the parameters \( K, n \) and \( m \) of DRI powder, which has the circular type shape with rough surface and 2.2 mm average size and was used for the roll pressing, in Eq. (2). After compaction, the change of the average density of powder compact offered a pressure-density diagram with increasing the pressure. As shown in Fig. 3. From the experimental data and Eq. (2), the parameter values in Eq. (1) could be given as \( K=333.93 \text{MPa}, n=0.188, m=2.683 \) and \( R_T=0.45324 \). These values were used in the FEM analysis for roll pressing of the powder. The critical thickness of compacted sheet was obtained by checking the alligatoring with increasing roll gap during roll pressing of the DRI powder. Two kinds of roll pressing with the flat roller, which has flat surface, and the indentation-type roller, which has indentations on the roller surface, were carried out. Both rollers have 1000mm diameter and 145mm width. The volume of indentations is 20 cc. The specific sheet thickness is defined as the ratio of final sheet thickness to

<table>
<thead>
<tr>
<th>Specific sheet thickness</th>
<th>1.00</th>
<th>2.16</th>
<th>2.66</th>
<th>3.50</th>
<th>4.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat roller</td>
<td>Fine sheet</td>
<td>Fine sheet</td>
<td>Split</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Indentation-type roller</td>
<td>-</td>
<td>Fine Sheet</td>
<td>Fine Sheet</td>
<td>Fine Sheet</td>
<td>Split</td>
</tr>
</tbody>
</table>

Table 1. Pressing results with both kind of roller
initially roll gap. While good quality of compacted sheet with specific sheet thickness of 2.16 was obtained when the flat roller pressed the DRI powder, the compacted sheet with over 2.66 thickness caused the alligatoring fracture. On the other hand, the indentation-type roll pressing offered the fine quality of compacted sheet up to 3.5 sheet thickness. Just changing the shape of the flat roller into the indentation-type roller makes it possible to increase sheet thickness by about 60 percents. These are illustrated in Table 1.

FEM modeling

The DRI powder was assumed to behave like continuum matter after the critical length between the rollers as shown in Fig. 1b. The critical length was set as (60+roll gap)mm for the flat roll and (70+roll gap)mm for the indentation-type roll, respectively. Sheet thickness was defined as roll gap for the flat roll and (roll gap+20)mm for the indentation-type roll, respectively. A minimum length between two rollers defined the roll gap. An adaptive mesh technique and a user subroutine (UMAT) for the yield criterion of Eqn. (1), which are supported in a commercial finite element code of ABAQUS, were used for FEM simulation. Only half of the calculation system was analyzed using symmetric boundary condition. The other conditions are detailed elsewhere [7].

Results and discussion

When the flat roller pressed the DRI powder, the RD stress distributions along the distance through the rolling direction were shown in Fig 4. The small sheet thickness of 30mm in Fig 4a gives the...
compressive stress during pressing and the tensile residual stress after exit of pressing in both surface and center. In case of the large sheet thickness of 60mm in Fig 4b, during roll pressing the RD stress of the surface is compressive, that of the center is tensile, and at exit of the pressing the RD residual stresses become reverse; These stress distribution is similar to the alligating condition based on Backofen’s [2] models. It is proved that the sheet thickness must be under 60mm to hinder in alligating.

Fig. 5 shows RD stress distribution along the distance through rolling direction in the indentation-type roll pressing. In the sheet thickness of 60mm in Fig 5a, overall compressive stress in surface is observed during pressing but there is high sharp tension peak right before exit of the pressing. The RD tension residual stress in surface after the exit of the pressing is not reversal stress state. This stress pattern may not induce alligating. As the sheet thickness increase up to 100mm as shown in Fig 5b, the tension peak before the exit of the pressing become low and broad. Therefore, an assumption can be made that after the exit of the pressing the RD residual stress in surface could become the reversal stress of the compressive RD stress during roll pressing. This stress state resembles that of 60mm sheet thickness with flat roller, which may split the compacted sheet. We expect that the indentation in roll surface hinder in alligating phenomenon by making high sharp tension peak before exit of the pressing. Hence, the indentation could enlarge the critical sheet thickness by over 60% as illustrate in Fig 6; this is in good accordance with the experimental results.

Conclusion

The experimental result on a critical sheet thickness that leads to the alligating is compared with the analysis of the finite element method based on the yield criterion for powder suggested by Park et al. [5]. Numerical analysis shows that the indentation-type roller can offer the critical sheet thickness 60 percents thicker than the flat roller. The indentation-type roller could offer larger quantity of the product in the roll pressing process by enlarging the sheet thickness.

Reference