Investigation of the Microscopic Aspect of the Stress Distribution in the Accumulative Roll Bonding Process Using the Slab Method

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Received: September 24, 2016; Accepted: February 3, 2017

Abstract
The accumulative roll bonding (ARB) as a severe plastic deformation (SPD) procedure aimed at enhancing the mechanical properties of metals and alloys. In the present study, a new slab method is proposed for estimating the forming stress field for cold extrusion of metals cross the alumina interlayer powder particles by accumulative roll bonding process. Plastic deformation behavior of the metal at the interfaces of the strips was investigated. Distinctive particles arrangements are used for different zones in the extrusion channel in the present models and the forming stress during the extrusion process affected. The corresponding results have also been determined analytically and by using the finite element software, ABAQUS. It was found that the theoretical prediction of the forming stress of the extruded metal cross the interlayer particles is in good compliance with the numerical measurement. Moreover, the interfaces of laminates have been studied to investigate the behavior of particles by scanning electron microscopy (SEM).

Keywords
Slab Method, Roll bonding, Interlayer Particles, Aluminum

1. Introduction
Roll bonding (RB) has been used as a novel method to produce particle reinforced metal matrix composites (MMCs) [1-5]. This method is carried out to embed appropriate reinforcement interlayer particles into the base metal. It is obvious that the generation of suitable bonds at the roll bonding step has an important role in the properties of the product. A schematic illustration of the bonding process continuing interlayer particles is presented in Figure 1. According to Figure 1, one of the key factors on bond strength in roll bonding in the presence of powders at the interface is the bonding pressure[1, 6- 9].

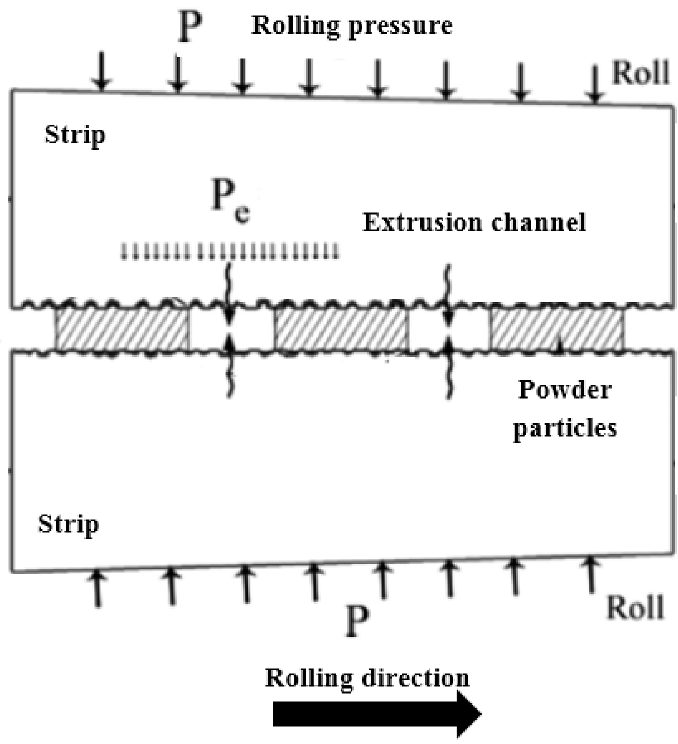

Figure1.Schematic outline of the bonding mechanism between strips with the presence of the powder particles at interface

There are several methods to analyze the metal forming processes which are contributed to the slab method, slip line filed, upper bound and so on. The slab method is a very important model due to its accuracy and independency of forming modes. In the sophisticated problems, the other solving contributed to the slip line field and upper bound theorems. The slip line field theorem is based on the stress field and its variations during the metal forming process while the upper bound theorem is contributed to the velocity variation of metals during the forming process.These models are popular due to their simplicity in solving. For example Samoly et al. used the slip line field theorem to investigate the filling mechanism of the forging die during the forging process [10,11]. Presenting a new slip line field model and simulating the process, they improved the forging parameters. Chenot et al. investigated the numerical application of the slip line field theorem for the extrusion process in a conic die. Presenting a new accurate slip line field model, they calculated the extrusion pressure during the process [12]. Das et al. used the slip line field theorem for analyzing the extrusion process in a wedge die in a slippery friction condition [13]. Celik et al. used the upper bound theorem to investigate the forging parameters in an out of axial extrusion with rectangular cross section die[14]. Alexandrov et al. proposed a new accurate upper bound theorem in the plane strain conditions with a wedge die. They compared their new model with the slip line field theorem [15].However, the bonding mechanism has not yet been characterized very well and no theoretical study has been conducted to predict the forming pressure cross the interlayer particles. Therefore, the aim of this work is to introduce theoretical models to predict the forming pressure at the interface in presence of the powders.

2. Methods

One of the popular models to investigate the metal forming processes is the slab method which is based on the forming fields that are compatible to its geometrical aspects[16, 17].

Through the analysis, the following assumptions are applied:

- The metal of strip is isotropic.
- The metal is considered as perfect plastic material.
- The effects of thermal and strain variations are negligible.
- The deformation of the strip is in a plane strain condition.
- The powder particles have rectangular cross section.Based on the mentioned assumptions in the x-y plane, there are

$$d\varepsilon_z = 0, \quad d\varepsilon_y = -d\varepsilon_x \tag{1}$$

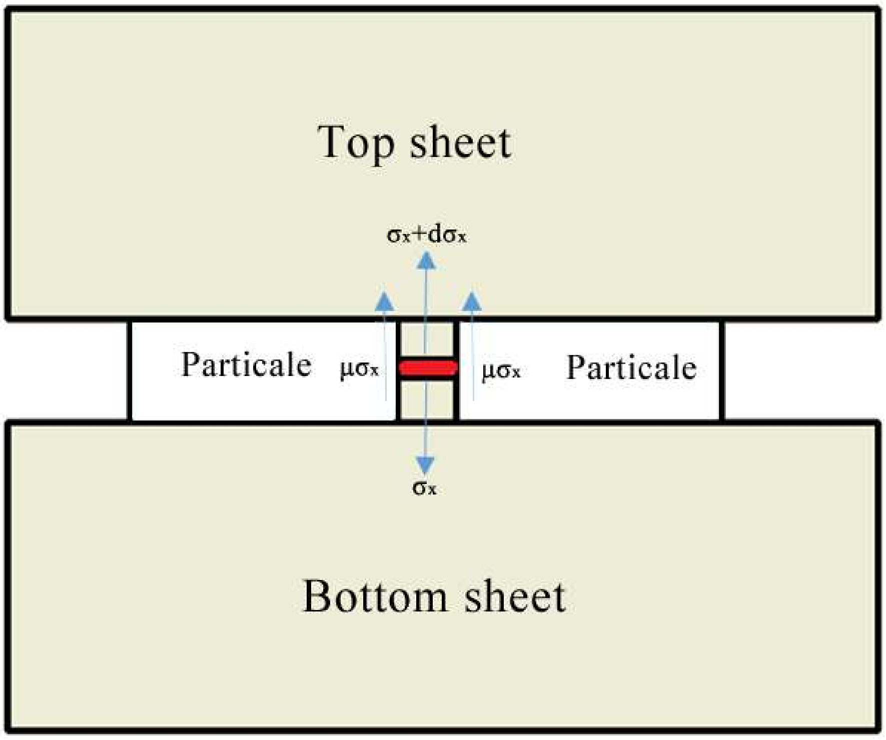

Figure2. The stress contribution on a small element of the extrusion system

According to Figure 2, considering a hydrostatic state in the extrusion process, the frictional force can be written as $\mu\sigma_x$ and we have:

$$\sum f_x = 0 \rightarrow (\sigma_x + d\sigma_x)\lambda\text{-}\sigma_x\lambda - 2\mu\sigma_x dx = 0 \tag{2}$$

By integration the eq. 2, it gives

$$d\sigma_x\lambda dx - 2\mu\sigma_x = 0 \rightarrow \frac{d\sigma_x}{\sigma_x} = 2\frac{\mu}{\lambda}dx \rightarrow \ln\sigma_x = 2\frac{\mu}{\lambda}x \rightarrow \sigma_x = c\mathrm{e}^{\frac{2\mu}{\lambda}x} \tag{3}$$

The boundary conditions are used to determine the coefficient c and 2K is the pressure which is needed to extrude the virgin materials amount the interface particles. Then, it gives

At $x = 0; \sigma_x = 2k \rightarrow c = 2k$

By expanding e^x as $e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \cdots$, then it gives

$$\sigma_x = ce^{\frac{2\mu}{\lambda}x} \to \sigma_x = 2k(1 + \frac{2\mu}{\lambda}x + \frac{\left(2\frac{\mu}{\lambda}x\right)^2}{2!} + \cdots) \to \sigma_x = 2k(1 + \frac{2\mu}{\lambda}x) \quad (4)$$

Finally eq. 4 becomes

$$\sigma_1 = 2k(1 + \frac{2\mu}{\lambda_1}x) \quad (5)$$

Equation 2 is an estimation and linear relation to determine the force required for extruding the virgin material through the interlayer particles. The rolls carry out this force. By continuing the rolling process the virgin metals begin to extrude through the upper and lower strips and bonding occurs. Finally the entire extrusion channel among the particles will be filled by the virgin material.

2.1 Determination the rolling pressure required through the interlayer particles with rectangular cross section

Always in actual conditions, virgin materials extrude through the clusters of particles. By increasing the rolling process, the virgin material extrudes through theses clusters, Figure 3.

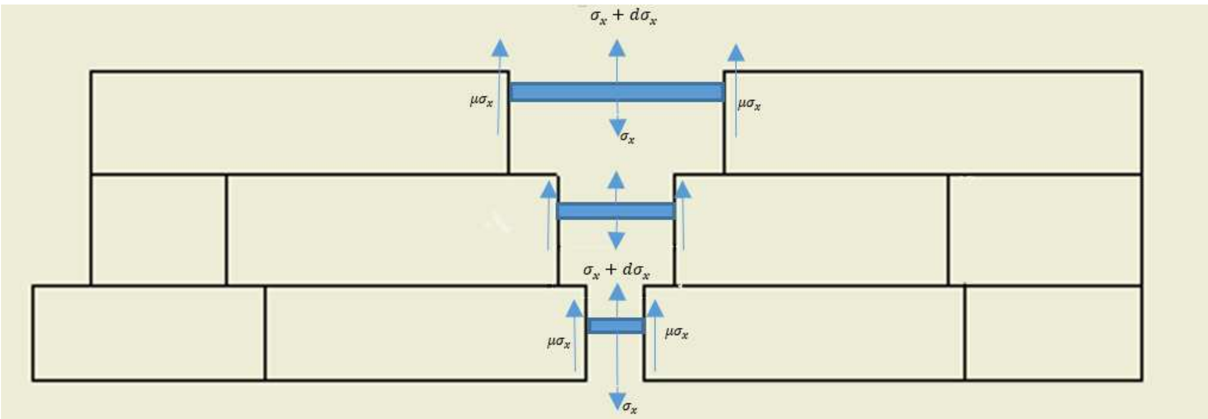

Figure3. Effective stresses on a particle of material during the extrusion process between two particles.

According to Figure 3, the material flows through different extrusion channels and the extrusion pressure required depend on the number of these channels. By increasing the number of channels, the pressure requires increase.

In this state, if σ_2 be the stress of the virgin material while extruding through channel 2, by driving the equations and using the boundary conditions at $x = x_1$, $\sigma = \sigma_1$, the rolling pressure required will be

$$\sigma_2 = \sigma_1 + c_2\left(1 + \frac{2\mu}{\lambda_2}(x - x_1)\right) \quad (6)$$

At $x = x_1; \sigma_x = \sigma_1 \to c_2 = \sigma_1$

So, Equation 6 gives

$$\sigma_2 = \sigma_1 + \sigma_1\left(1 + \frac{2\mu}{\lambda_2}(x - x_1)\right) = \sigma_1\left[1 + \left(1 + \frac{2\mu}{\lambda_2}(x - x_1)\right)\right] = 2k\left(1 + \frac{2\mu}{\lambda_1}x_1\right)\left[1 + \left(1 + \frac{2\mu}{\lambda_2}(x - x_1)\right)\right] \quad (7)$$

So, the rolling pressure required to flow through three extrusion channel becomes

$$\sigma_3 = \sigma_2 + \sigma_2 \times \left(1 + \frac{2\mu}{\lambda_3}(x - x_1 - x_2)\right) = 2k\left(1 + \frac{2\mu}{\lambda_1}x_1\right)\left[1 + \left(1 + \frac{2\mu}{\lambda_2}(x - x_1)\right)\right] \times \left[1 + \left(1 + \frac{2\mu}{\lambda_3}(x - x_1 - x_2)\right)\right] \quad (8)$$

And finally, the rolling pressure required to flow through n extrusion channels becomes

$$\sigma_n = \sigma_{n-1} + \sigma_{n-1} \times \left(1 + \frac{2\mu}{\lambda_n}(x - x_1 - x_2 - \cdots - x_n)\right) = 2k(1 + \frac{2\mu}{\lambda_1}x_1) \times \left(1 + \frac{2\mu}{\lambda_2}(x - x_1)\right) \times \left(1 + \frac{2\mu}{\lambda_3}(x - x_1 - x_2)\right) \times \cdots \times \left(1 + \frac{2\mu}{\lambda_{n-1}}(x - x_1 - x_2 - \cdots - x_{n-1})\right) \times \left[1 + \left(1 + \frac{2\mu}{\lambda_n}(x - x_1 - x_2 - \cdots - x_n)\right)\right] \quad (9)$$

2.2 Determination of the threshold rolling pressure for dispersion the interlayer particles during the rolling process.

If the virgin material can flow through the particles during the roll bonding process, the clusters must disperse and break. According to Figure 4, interlayer particles are laying together in two states.

1. The particle between the upper/ lower strip and other particles
2. The particle in the cluster and among a group of particles

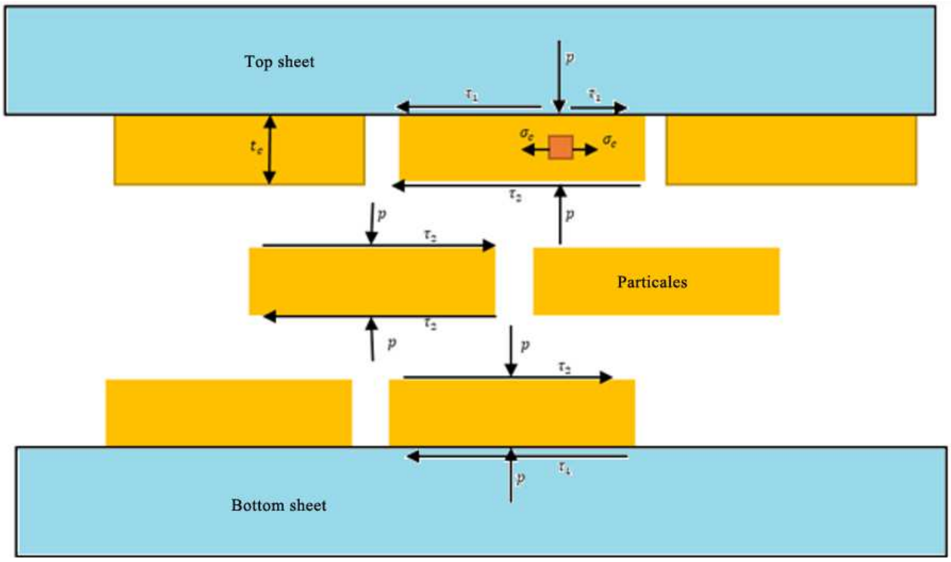

Figure4. Effective stresses on the particles in a cluster.

According to Figure 4, by writing the equilibrium equation, it gives

$$\tau_1 l_{BC} + \tau_2 l_{BC} = \tau_2 \lambda \quad (10)$$

By writing the equilibrium equations in the neutral point c, then it gives

$$\sigma_c t_c = (\tau_1 + \tau_2) l_{AC} \rightarrow l_{AC} = \frac{\sigma_c t_c}{(\tau_1 + \tau_2)} \quad (11)$$

Finally equation 10, gives

$$\sigma_c = \frac{(\tau_1 + \tau_2)\lambda}{1 + t_c} \quad (12)$$

Considering plan strain conditions, $\sigma_c + P = 2K$ and k is the shear strength of the strip and p is the rolling pressure.

Finally according to Equation 9, the threshold rolling pressure for dispersing the particles in adjacent with the strips becomes

$$P_1 = 2K + \frac{(\tau_1+\tau_2)\lambda}{1+t_c} \tag{13}$$

By writing the equilibrium equations for the particle through the clusters, the pressure needed for dispersing the particles will be

$$P_2 = 2K + \frac{\tau_2\lambda}{t_c} \tag{14}$$

Finally, the threshold rolling pressure for beginning the extrusion through the clusters will be

$$P_{treshhold} = MAX(P_1, P_2) \tag{15}$$

So, to produce a two layer reinforced laminate, the rolling pressure must be greater than $P_{treshhold}$.

$$P_{treshhold} \gg MAX(P_1, P_2) \tag{16}$$

3. Experimental procedure

3.1 Specimen Preparation

The RB techniques are used to fabricate metal matrix composites. The RBed sample was sheets of annealed commercial aluminum alloyAA1050 strips with initial dimensions of 100 × 30 × 1 mm where annealed at 400°C for 1 hour to ensure consistent specimen hardness. The detailed chemical compositions AA1050 are given in Tables 1. Also, the mechanical and physical properties of alumina particles as interlayer particles are presented in Table 2.

Table 1.The chemical composition of AA1050

Element	Al	Cr	Si	Fe	Mn	Zn	Ti	Cu	Ni
Wt%	balance	0.0016	0.12	0.222	0.032	0.01	0.005	0.12	0.0014

Table2. The mechanical and physical properties of Al_2O_3 particles

hardness	Rapture module	Compressive strength	density	Particle size	Purity %	material
1650 kgf.mm^{-2}	330 MPa	2200 MPa	3.9 gr.cm^{-3}	2µm	99.9%	Al_2O_3

To produce a satisfactory metallurgical bond by RB, it is essential to remove contaminants from the Surfaces of the strips to be joined. These layers are composed of greases, oxides, adsorbed ions and dust particles. Then aluminum strips were degreased in acetone bath and scratch brushed with a stainless steel circumferential brush in order to remove the oxide layer on the surfaces of strips. In order to remove the oxide layer from the surfaces of strips, two strips of AA1050 were stacked together to achieve 2 mm thickness. Proper alignment of the two strip surfaces prior to rolling is necessary. Then, according to Figure 5, the stacked strips were fastened at both ends by steel wires and were roll bonded with different thickness reductions at the ambient temperature. The roll welding experiments were carried out using a laboratory rolling mill with 170 mm roll diameter, 36 rpm of rotational speed and a power capacity of 35hp.

After surface preparation, the handling of strips was performed carefully to avoid renewed contamination. The time between surface preparation and rolling was kept to less than 120 seconds to avoid the formation of a thick and continuous oxide layer on the bond surfaces of the strips.

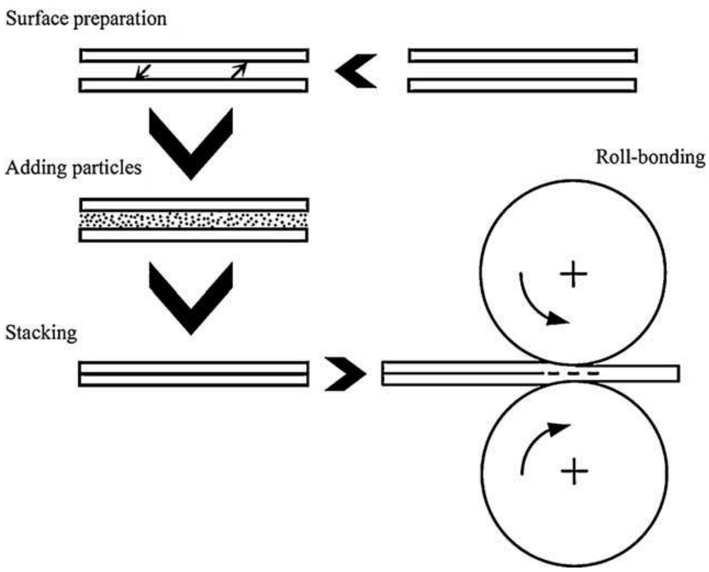

Figure 5.Schematic illustration of the bimetal roll bonding process

According to Figure 6, by increasing the amount of surface expansion, the clusters begin to disperse and the distance among the particles increases which leads to generation of wider extrusion channels. So, the contact is established between the highest asperities of the virgin material of the two opposing surfaces to form a metallic bond. With a considerably larger surface expansion, the extensive areas of the base metal are uncovered and numerous bonds are formed. So, the unbounded regions of the brittle surface layer at the interface are confined to small isolated islands [5].

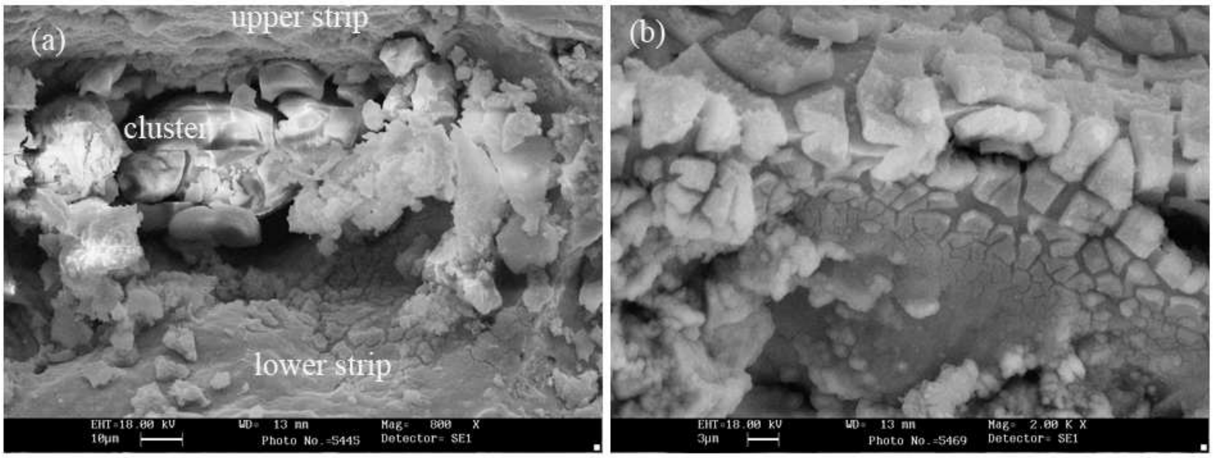

Figure6. Particles arrangement during the roll bonding process: (a) particle cluster and (b) dispersion of clusters and generating the extrusion channels

4. Numerical simulation

In the present study, the extrusion process among the powder particles is investigated by the ABAQUS software, Figure 7. In the two dimensional FE model of the RB process set up in ABAQUS, the initial thickness of both layers (AA1050) was 2 mm which was performed in the experiment. The isotropic material model was used for modeling the AA1050 layers. Temperature change and sheet width spread were neglected. The friction coefficient between the metal and the alumina particles is set to 0.75. The explicit solver is used to model the metal forming process. Figure 7 shows the stress distribution for the extrusion process among the particles that are assumed to be rectangular.

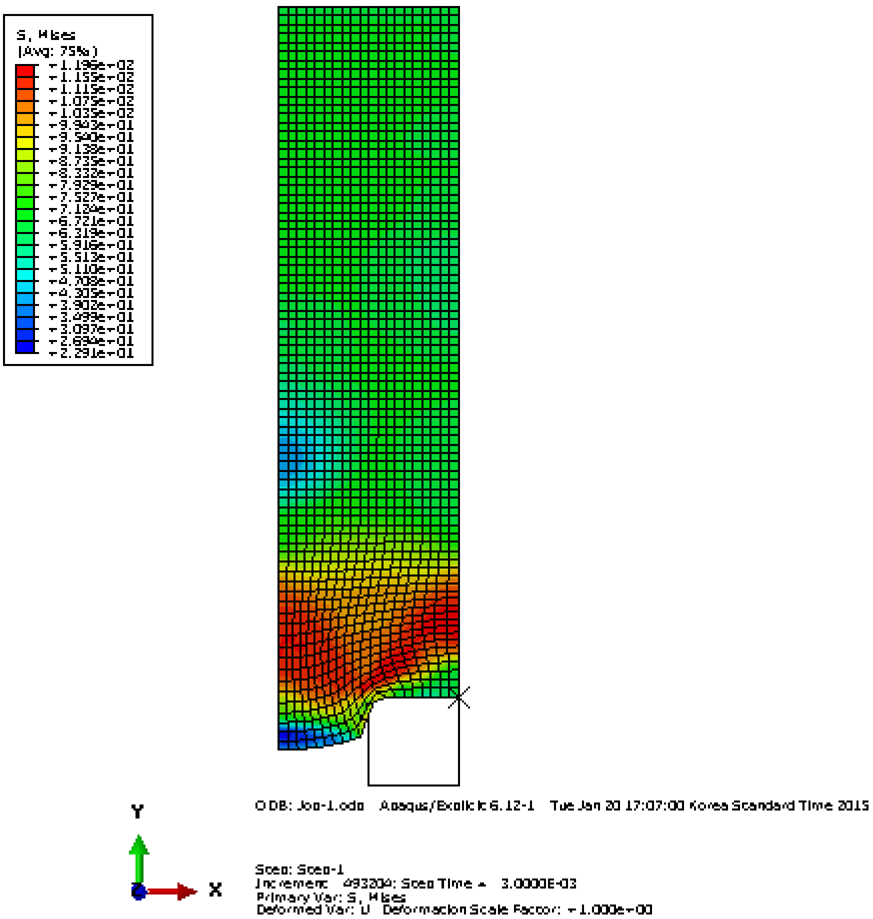

Figure7. The extrusion of metal cross the powder particles: Due to the symmetry to the y axis, the half of the extrusion channel is modeled.

The results obtained by the upper bound, slip line field and the numerical simulation are presented in the Table.3.

Table.3.the pressures measured along the extrusion channel

Solving method	Average stress(Mpa)
Slab method	109.38
Numerical simulation	108.92

5. Conclusion

In this research, the upper bound and slip line field theorems were applied to the analysis of the extrusion process cross the interlayer powder particles (alumina in this study). The following conclusions can be highlighted briefly:

- The slab method estimated the pressure needed for the extrusion process with an acceptable error less than 1%.
- By increasing the rolling pressure, the clusters of alumina particles break which facilitates the bonding process.
- According to the results obtained, the presented mathematical model is capable of successfully predicting the bilayer cold rolling process and is efficient to give a better insight into the manufacturing and production of bimetal sheets and strips.

Nomenclature and subscripts

σ	Normal stress [Mpa]
μ	Friction coefficient
p_e	Extrusion pressure [Mpa]
k	Shear strength of the base metal [Mpa]
h	Thickness of the base metal [mm]
h_i	Initial thickness of strip [mm]
h_e	Final thickness of strip [mm]
R	Work roll radius [mm]
Y	Yield strength of the base metal [Mpa]
r	Reduction ratio [%]
K	Resistances to the deformation of strip before and after rolling [Mpa]

6. References

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