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Research paper

Finite Element Modelling of a Hot Roll Forging Process with Emphasis on Role of Grip

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Abstract

In this paper, a finite element model of grip in roll forging is presented, which has a deep influence on both finite element predictions and real process. It is considered as a tool possessing two roles, that is, force exerting role and velocity imposing role on the material. A fraction of roll separating force is exerted on the front end of the material to be pulled, which is defined by minimum value between allowable grip pulling force of the grip and roll separating force multiplied by a grip constant. Effect of the grip constant is examined, revealing that the predictions of final length and plastic deformation in major deformed region have a distinct function of the grip constant, which can be a characteristic property of the process. The approach is applied to roll forging of manufacturing a stepped bar and the predictions are compared, revealing that they are in a good agreement with each other. It is also emphasized that the new approach not only improves flexibility of adopting the difficult-to-model actual roll forging processes but it also enhances numerical stability and reliability of the finite element analysis of them.

Keywords: *Finite element model, grip force, grip constant, roll forging, roll separating force.*

1. Introduction

Roll forging [1] is a sort of rolling, which is employed for fabricating long bars with non-uniform cross-sections using two oppositely rotating irregular rolls of which profiles are varying with their orientation. Roll forging is usually utilized to manufacture preforms of forgings or parts with sound metal flow lines and reduced scrap [2, 3].

It has been known that the roll forged preforms can contribute to enhancing mechanical properties of irregularly shaped long products because of their sound metal flow lines. It is also advantageous to economically manufacture larger and slender parts because forming load is relatively small and thus roll forging machine is small as well.

Recent requirement on green manufacture and reduced weight of auto parts makes the roll forging technology more attractive to application researchers because it cannot only maximize the yield rate of the material but it can also improve the structural rigidity and strength of the parts. In particular, this technology is considerably beneficial in the case of mass consumption of expensive material including aluminum. However, academic research works have been limited in spite of industrial importance of roll forging and related process design engineers are still relying on the traditional trial-and-error approaches. The reason includes its geometric and mechanical complexity. Due to geometric complexity, some analytic approaches cannot be easily applied to analysis of roll forging processes. From standpoint of finite element analysis, there is a difficulty in dealing with boundary conditions especially when the material starts to contact with rolls or to separate from them. In addition, there is a problem of how to describe the grip which pulls the material in the rolling direction and thus plays an important role in actual process for stabilization of material.

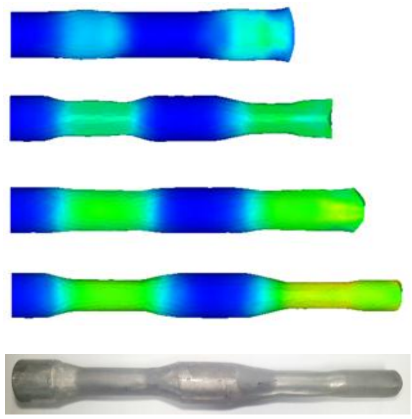


Fig. 1: Comparison between predictions and experiments of an aluminum roll forged product [5]

Cai [3] proposed a roll-profile design scheme based on a kinematic contact analysis between the material and rolls. Liu et al. [4] conducted an isothermal analysis of a simple round-to-ellipse roll forging process using a commercialized software. Eom et al. [5] conducted a non-isothermal analysis of aluminum bar roll forging process and compared the predictions with experiments, showing that they are in a qualitatively good agreement with each other. However, some detailed examination showing that there are existence of distinct local discrepancy between the predictions and experiments. It has been assumed that numerical treatment schemes of the rigid-body movement zone and the slipping zone where the material starts to contact with rolls or to separate from the rolls as well as the pulling tool of the grip have a great influence on the predictions. There have been no research works which reflect the role or effect of the grip.

In this paper, a reasonable model of the grip is established and its validity is verified, which can also solve the problem of the numerical schemes to deal with rigid-body movement or slipping zone of the material.

2. Grip model

Roll forging process is composed of material, two oppositely rotating dies or rolls and the grip manipulating the material. In roll forging, the material to be being formed can be contacting with the rolls or it can be moving only with the grip. In general, the material keeps contacting with the rolls once it contacts with them especially when the shape of product and process geometries are simple, for example, in a single-step round bar roll forging. However, the material may separate instantly from the rolls when the cross-sectional area varies with bar length as shown in Figure 1. When the material is separated from the rolls, the material motion cannot be accurately described, which is affected by inertia, etc.

It should be noted that precision simulation of a roll forging process is very important because its predictions have a great deal of influence on the consecutive forging process design based on finite element simulation technique. For example, the predicted preform in Figure 1, which is more or less different from the experimental result, can be meaningless from standpoint of precision forging of a lower arm of passengers' car because it causes much bigger difference in shape between predictions and experiments of the final forging of lower arm [5].

The grip also has a great deal of influence on the motion and deformation of material especially around the time interval when the material initially contact with rolls or it separates from them. The force exerting on the grip changes drastically during the time interval, which can cause slipping between the material and rolls. The pulling force exerted on the material by the grip also affects the mechanics of the roll forging process during plastic deformation interval. The velocity of material when it is contacting only on the grip between two plastic deformation intervals is of great importance. Therefore, an engineering model for the grip is needed to obtain the best solution of roll forging processes.

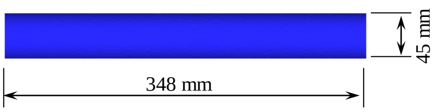
This study propose a scheme of force exerting roll forging grip which imposes on the material a grip force defined by the minimum value between allowable grip pulling force given and the roll separating force multiplied by a grip constant. The pulling force exerted on the material by the grip, denoted as F_G, is calculated as follows:

$$F_G = Minval(F_{Limit}, fF_{RS}) \tag{1}$$

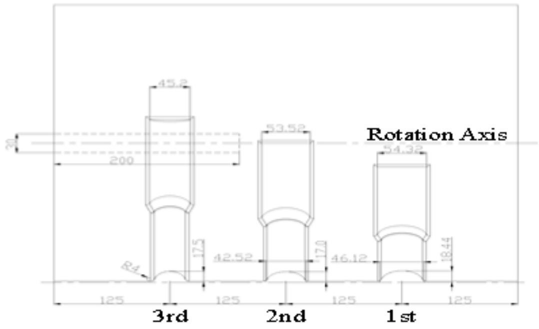
where the roll separating force is denoted by F_{RS}, the grip constant f is one of process parameters which can be empirically determined by comparison of predictions with experiments and FLimit means the allowable maximum grip pulling force. Minval in equation (1) is a function which selects smaller value of the two numbers in the bracket. It is also assumed that both the grip and material move constantly with the given grip velocity or the material velocity at the instant when the material is separated.

2.1. Test process design

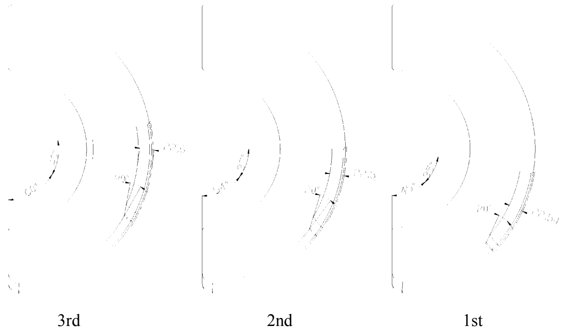
Figure 2 shows a test process. This is such a geometrically simple roll forging process producing a stepped rod that it can be effectively used to develop and explain the grip model.



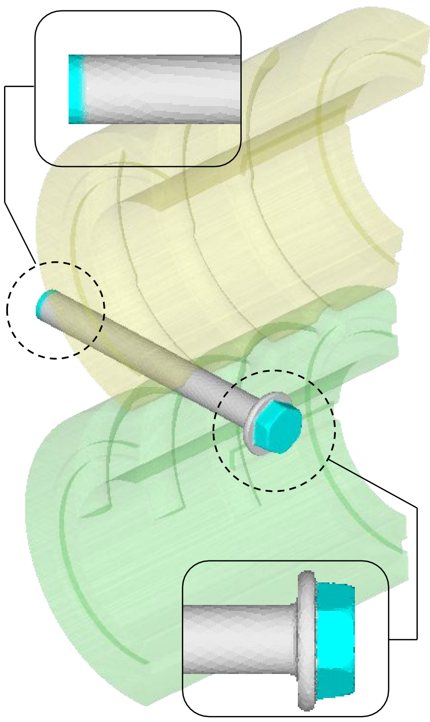
(a) Initial material



(b) Front view of roll



(c) Side view of roll



(d) Bird's view

Fig. 2: Initial configuration of rolls and material

2.2. Flow stress of the test material

Figure 3 shows flow stress of the test material which was obtained by hot compression test and curve fitting scheme based on the following material model, $\bar{\sigma} = C(\varepsilon, T)\dot{\bar{\varepsilon}}^{m(\varepsilon,T)}$. The coefficient of Coulomb friction is assumed 0.2 for all the material-roll interface. Angular speed of rolls are all 50 rpm. Maximum allowable pulling force is assumed 2000 N. Number of tetrahedral elements is around 40000.

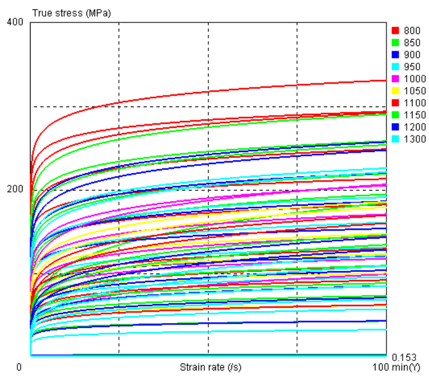
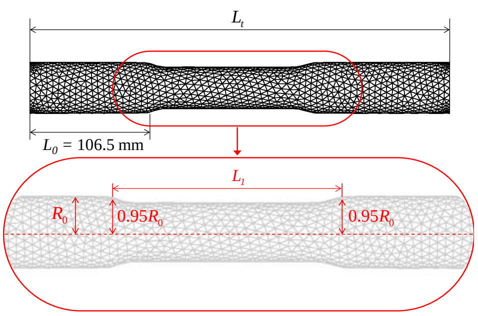


Fig. 3: Flow stress curve

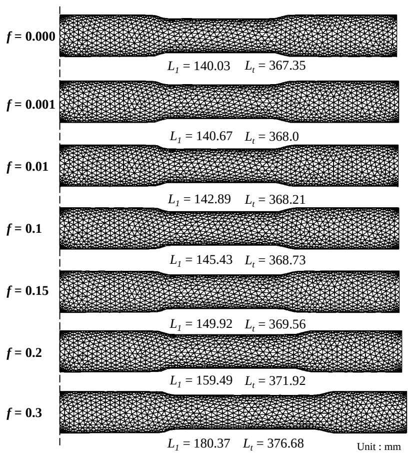
3. Results and discussion

3.1. Effect if the constant *f*

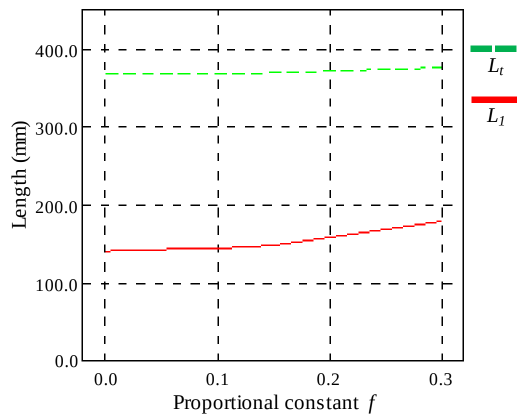
First, effect of the constant f on the process is examined using the first pass of a two-pass roll forging process. We conducted finite element simulations under various grip constants with the other process parameters fixed and summarized the predictions in Figure 4. Figure 4(a) defines the total length L_t of deformed material and the measured length L_1 of a major deformation zone of which diameter of the cross-section of deformed material is less than 95% of that of the initial material. Note that the measured length L_1 is used to evaluate the grip model and effects of grip constant.
As seen in Figure 4(b), the distinct difference in the deformed shape from the grip constants in the left side, that is, in the entry side cannot be observed. However, it should be noted that the change of L_1 in the main deformation region is relatively great, even though the total length does not change much with grip constant. This fact reveals the possibility of controlling or adjusting the finite element predictions based on experiences in order to reflect the actual situations which are very hard to be scientifically known.



(a) Definition of measures L_1 and L_t



(b) Definition of measures L_1 and L_t



(c) Proportional constant *f* against length curve.
Fig. 4: Effect of grip force on the roll forged bar

Therefore, it is desirable to evaluate the effect of the grip constant f in terms of the length of major deformation zone denoted as L_1. The major deformation zone is defined by the length of the deformed rod of which diameter reduces by more than 5%. Figure 4(c) shows the relationship of total length L_t and L_1 with the grip constant f. This figure showing that the increase in L_1 with that of grip pulling force becomes very clear after f reaches 0.15. Therefore, considering numerical stability or liability, the value of 0.1 for the grip constant is appropriate for the test process. To the contrary, it can be said based on experiences that the grip parameter of around 0.1 with the allowable maximum grip pulling force of the equipment enhances numerical stability of the solution even though it incurs negligible deformation of material. Of course, the grip constant is a parameter of the process which should be experimentally determined for the specific roll forging process.

3.2. Roll separating force with time

Figure 5 shows the variation of roll separating force with time. It can be seen that the linearity between roll separating force and the grip pulling force was applied for only small portion of time near entry and exit side because the allowable maximum grip pulling force of 2000N is quite small compared with the roll separating force.
Figure 6 shows the history of deformation, implying that roll forging gives us sound metal flow lines, which are friendly to increasing strength of the roll-forged products.

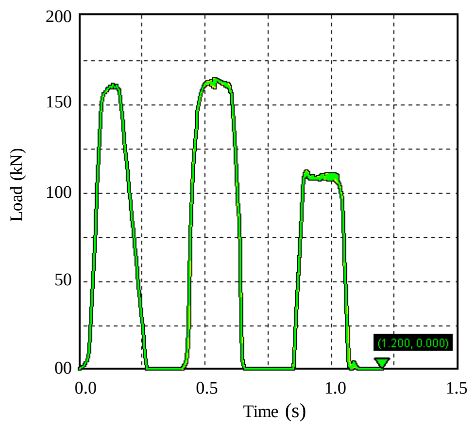
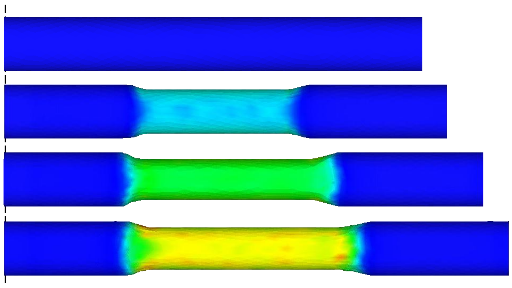
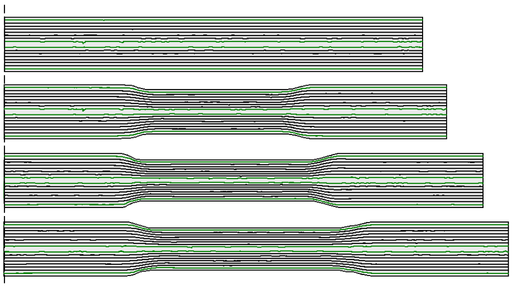


Fig. 5: Roll separating force when *f* = 0.1



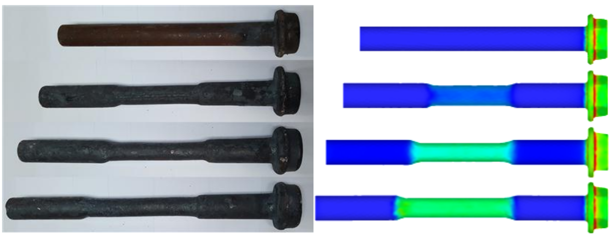
(a) Effective strain



(b) Metal flow lines

Fig. 6: History of deformation when $f = 0.1$

3.3. Comparison of experiments with predictions



(a) Experiments **(b) Predictions**

Fig. 5: Roll separating force when $f = 0.1$

The predictions were compared with experiments as shown in Figure 7, revealing that they are very close to each other. It is noted that the difference in the grip constant may cause negligible difference when it is sufficiently small around $f = 0.1$. However, the grip model is very useful in real situations because it can remove the problem of slipping between the material and rolls and alleviate numerical instability in finding converged solutions. Note that some numerical instability exists in rolling simulation because of drastic change of relative motion around friction hill [7], which makes it difficult to obtain strictly converged solutions.

4. Conclusion

In this paper, a grip model for roll forging was presented. The model moves a material constantly with the given grip model when the material does not contact with rolls. While the material contacts with the rolls, the grip exerts pulling force on the material of which the magnitude is calculated by the roll separating force multiplied by a grip constant. The pulling force plays a role of preventing numerical slipping between the material and the rolls. The grip constant should be determined based on comparison of experiments and predictions because it has an influence on the predicted length of roll forged bar or rod.
The approach was verified through comparison of the predictions and experiments, showing a quantitative agreement with each other. It has been revealed that the proper determination of the grip constant can make it possible not only to control the deformed bar length and the deforming zone critically because of its clear dependence on the grip constant but also to enhance numerical stability in simulating roll forging processes.

Acknowledgement

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