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Title: Identification of a friction model for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

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Abstract: A physically-based friction model is developed based on the ball-on-disc test results. The model is verified by using double action extrusion tests. Good agreements between the FE predictions and experiments have been obtained, in terms of the extrudate length and steady-state extrusion load, indicating that ball-on-disc test is an effect way of characterizing the friction for the bearing channel of extrusion dies and the nature of friction in the bearing channel can be summarized as a pressure dependant process: formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

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May 15, 2011

Dr. Philippa Cann
Imperial College
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Dear Dr. Cann,

Enclosed please find the manuscript entitled: *Identification of a friction model for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests* submitted for publication in Tribology International. The authors are: L. Wang, J. Zhou, J. Duszczyk and L. Katgerman. The basic findings are as follows.

(1) Short sliding distance ball-on-disc tests can be used to characterize the friction in the bearing channel of the hot aluminium extrusion dies.
(2) The tribological conditions of hot aluminium extrusion process cannot be reflected by using one single friction testing technique, and a combination of different friction testing techniques should be used. For the bearing channel of the hot aluminium

extrusion dies, the short sliding distance ball-on-disc test is recommended, with the disc made from the workpiece material and ball made from the die material.

(3) Strong adhesive friction occurs between the hot aluminium and steel and the nature of friction in the bearing channel can be summarized as a pressure dependant process, *i.e.* formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

This is an original paper which has neither previously, nor simultaneously, in whole or in part been submitted anywhere else.

Kind regards,

Liliang Wang.

May 15, 2011.

TRIBOLOGY INTERNATIONAL

Statement of Originality

As corresponding author, I Liliang Wang, hereby confirm on behalf of all authors that:

1) The paper has not been published previously, that it is not under consideration for publication elsewhere, and that if accepted it will not be published elsewhere in the same form, in English or in any other language, without the written consent of the publisher.

2) The paper does not contain material which has been published previously, by the current authors or by others, of which the source is not explicitly cited in the paper.

Research highlights

Ball-on-disc tests can be used to characterize the friction in the bearing channel of aluminium extrusion dies.

The friction in the bearing channel is a pressure dependant process:

At low contact pressure: formation of isolated adhesive junctions

At medium contact pressure: adhesive junctions growth

At high contact pressure: coalescence of adhesive junctions

Yours sincerely,

Liliang Wang (corresponding author), on behalf of the authors

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Revision notes (TRIBINT-D-11-00177)

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Title: Identification of a friction model for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

1. Changes and explanations in response to the comments of Editor

The advice of Editor has been followed and the changes have been made to the manuscript accordingly.

(1) Please try to improve the English grammar and style throughout the paper.

The advice of Editor has been followed and the paper has been revised carefully and the English grammar and style throughout the paper has been improved.

(2) The reference listing should conform to the Journal style - see Advice to Authors.

The advice of the editor has been followed and the reference style of Tribology International has been followed.

2. Changes and explanations in response to the comments of Reviewers

The advice of Reviewers has also been followed and the changes have been made to the manuscript accordingly. The added/revised text and explanations are given below.

(1) The bibliography is primarily focused on simulation tests and critical analysis of them. It lacks a summary review of the results obtained in the literature, the nature of tribological phenomena involved in the hot extrusion of aluminium, and a brief description of the process.

All the three suggestions have been followed and changes were made accordingly.

For the field tests, the friction test results are summarised in Table 1.

For the simulative friction tests, the friction test results are indicated in the text:

"high values of friction coefficients ($1<\mu<1.5$) were observed"

"The results obtained from the DAE tests indicate that full sticking friction occurred at the extrudate/die interface when a 15' choke angle was applied in the extrusion dies"

For the tribological tests, the friction test results are indicated in the text:

"The steady-state friction was found to be greater than 1.0 when the testing temperature was higher than 150°C and the magnitude of friction increased with increasing temperature."

As the reviewers suggested, the nature of tribological phenomena involved in the hot extrusion of aluminium has been reviewed and added into the introduction part, although the fundamental understanding of the friction phenomenon in the bearing channel of hot aluminium extrusion dies is still insufficient.

"In the meanwhile, high values of friction coefficients ($1<\mu<1.5$) were observed and this was attributed to a high degree of aluminium to aluminium contact"

"The presence of a continuous transfer layer was thought to be responsible for the high magnitude of the frictional force."

As the reviewers suggested, a brief introduction of extrusion process has been added into the introduction part:

"Extrusion is a process in which a cast billet of solid metal is converted into a continuous length of generally uniform cross-section by forcing it to flow through a shaped die opening. Generally, the extrusion process is a hot working operation, in which the metal billet is heated to a proper temperature, at which a relatively high ductility and low flow stress can be achieved."

(2) No friction curves measured from the ball/disc test are presented. Why? There should be and if so, they should be discussed. Moreover, the advantage of using a pin on disc test should be more clearly proved.

As the reviewers suggested, the friction curves measured from the ball-on-disc tests are presented (Figure 1and 5 in the revised manuscript) and the results have been discussed. The ball-on-disc test results have clearly proved the advantage of using a ball-on-disc test, because the friction stresses at different testing temperatures are reasonable and constant. Moreover, the good agreement between the FE simulation results and experimental (DAE) results has proved the advantage of using a ball-on-disc test.

“Figure 1 shows the evolution of the friction coefficient over a sliding distance of 10 laps at different temperatures. It is of interest to note that friction coefficient increases with the sliding distance. At 500 °C, in particular, the friction coefficient increases even by 50%. The increase of the friction coefficient with sliding distance, leads to the uncertainty as to the exact value to be put into FE simulation.”

“Figure 5 shows the evolutions of the calculated shear friction stress at different temperatures and over a sliding distance of 10 laps. It is interesting to see that the shear friction stress starts from a relatively low value, and then becomes stable at different temperatures, while the friction coefficient increases considerably (Figure 1). The low shear friction stress at the initial stage may be due to the oxide layer on the disc and ball surfaces, which tends to lower the adhesion between aluminium and steel. After the initial stage of sliding, the oxide layer may be broken up and metal-to-metal contact occurs, leading to the increases in friction stress. In addition, the severe plastic deformation on the surface material may generate a considerable work-hardening effect, which may also lead to the rise of shear friction stress.”

(3) p. 9, line 43: specify the distance of sliding.

The reviewers’ suggestion has been followed and the sliding distance (1, 5 and 10 laps of sliding) has been specified in the text.

(4) p. 13, line 29: clarify what is meant by "transition from a slippery patch and adhesive zone"

The reviewers’ suggestion has been followed and the explanation and the microstructure of a transition zone have been added into the manuscript:

“At this stage, an in-continuous tribo-layer might be visible on the die land, and the so-called transition zone between the slipping and sticking zone may be observed, as shown in Figure 6 (b) and (c). According to, the transition zone is normally observed when extruding with low die temperatures, and this region is composed of a sportlike aluminium deposit.”

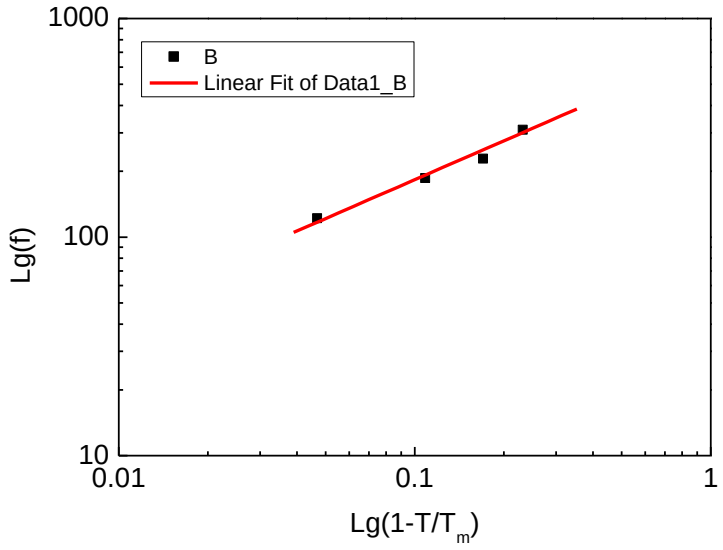
(5) p. 13, line 34: the authors describe a mechanism of coalescence of junctions (does it occur at the entrance of the die?) accompanied by the formation of a continuous transfer layer (is this layer homogeneous?).

Yes, the coalescence of adhesive junctions occurs at the entrance of the extrusion die, because the contact pressure in this region is much higher compared to that of the other regions in the extrusion die. This layer is a continuous layer and is homogeneous. The microstructure of the worn extrusion die (Figure 6 in the revised manuscript) shows that the worn die surface in the sticking zone is very smooth,

suggesting that a homogeneous layer of surface material has been removed by the extrudate.

(6) p.14: the authors should justify the physical origin of a power law to model the resistance of the junction in equation 6.

The physical origin of the power law is indicated in the figure shown below. In this figure, the friction stresses and temperature are both plotted in the Log scale, and a liner fitting can fit the experimental data very well, then we normally select a power law in the model.



(7) What conclusions the authors can draw from the calculations presented in Figure 6. The latter are not exploited. Why?

Figure 6 shows the FE model used in the present research. The simulation results were not exploited explicitly, but presented in Figures 10-13 in terms of the extrudate lengths and extrusion loads. The results obtained from the FE model shown in Figure 6 has led to the conclusions that the proposed physically based friction model can be used to model the friction in the bearing channel of hot extrusion dies.

(8) The authors observed a correlation between the length of the bearing area and the possibility of growth of the area of contact (and friction). They should clarify the interpretation. Is it connected to the possibility of junctions to be formed?

In the current research, choked dies with 15' die angle were used to apply contact pressure to the extrudates and full sticking friction was observed in all the DAE tests

conducted in the present research. In the manuscript, the correlation between the length of the extrudates and bearing area has been explained:

"The length difference of the extrudates increases with increasing ram displacement. At the initial stage of the DAE, the workpiece is extruded at the same extrusion speed in both of the dies. As the ram displacement increases, the friction force increases at the same rate in the two dies due to the increasing contact area. When the extrudate lengths are greater than 2 mm, the contact area in the 2 mm bearing cannot be further increased. Thus a constant friction force is achieved in the 2 mm bearing. In the 6 mm bearing, however, the contact area is further increased due to the increase of the extrudate length, thus the friction force increases and the material flow in the 6 mm bearing is restricted, consequently the extrusion speed slows down. In the meanwhile, the rate-dependant property of the billet material becomes explicit. In the severe deformation zone of the 2 mm bearing, the material is enhanced due to the higher extrusion speed and becomes more difficult to be deformed. In the severe deformation zone of the 6 mm bearing, however, the low extrusion speed results in lower material strength, thus the material becomes easier to be extruded. As such, a dynamic balance is maintained throughout the DAE process: the friction between extrudates and bearing surfaces increases the length difference of the extrudates; on the other hand, the effect of rate-dependent material behaviour decreases the length difference."

(9) Pictures of worn surfaces that correspond to different stages the model ASFM should be shown. This would allow the author to demonstrate more clearly the validity of their model.

The reviewers' suggestion has been followed and the microstructures of worn surfaces that correspond to different zones in the extrusion die have been added into the manuscript (Figure 6 in the revised manuscript).

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The authors sincerely thank the reviewers for their contributions to the improvement of the manuscript and for sharing their thoughts.

Identification of a friction model for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

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Abstract

A physically-based friction model is developed based on the ball-on-disc test results. The model is verified by using double action extrusion tests. Good agreements between the FE predictions and experiments have been obtained, in terms of the extrudate length and steady-state extrusion load, indicating that ball-on-disc test is an effect way of characterizing the friction for the bearing channel of extrusion dies and the nature of friction in the bearing channel can be summarized as a pressure dependant process: formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

Keywords: FE Simulation; Friction model; Hot aluminium extrusion; Bearing channel

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1. Introduction

FE simulation of the extrusion processes is widely used in both scientific research and industrial practice. The selection of friction models and the assignment of friction coefficients or factors for the FE simulations of extrusion processes remain an essential issue, because the accuracy of the simulation results is strongly affected by the flow stress of workpiece material (thermo-viscoplastic behavior at elevated temperatures) and the assignment of boundary conditions, *e.g.* friction boundary conditions. The uncertainty of flow stress is low when the constitutive equations determined from thermo-mechanical testing are implemented. However, unreliable FE simulation results could be obtained if the friction boundary conditions are not assigned correctly.

Hot aluminium extrusion is a complex thermo-mechanical process, which involves highly complicated chemical and tribological interactions between the workpiece and tooling. It was found that many practical problems in the hot extrusion industry, such as wear of the extrusion dies [1-4], surface quality of the extruded profiles [5], die lines and pick up [6] *etc.,* are related to the strong adhesion between the hot aluminium and the die due to strong chemical and atomic interactions between hot aluminium and steel, which is the main reason for the excessively high friction observed during hot aluminium extrusion [1-3, 7].

In the past years, efforts have been made to study the tribological phenomenon of the extrusion process and the developed friction testing techniques can be classified as three different groups, namely, field tests; simulative tests (or physical simulation tests) and tribological tests.

In general, field test is to estimate the friction coefficient or factor by using extrusion friction tests. According to the material flow response to the friction force, some novel extrusion friction tests have been developed, including double backward extrusion [8], combined forward rod-backward can extrusion [9] and combined forward conical / straight can-backward straight can extrusion [10]. These tests were designed with highlighted friction sensitivity in extrudate lengths. Lubricants can be evaluated and the global friction coefficient or factor on the workpiece/tooling interface can be determined quantitatively with the aid of FE simulations. In addition, the friction sensitivity of extrusion load [11, 12] was used for friction characterization, in which the average friction over the container wall was estimated. For the regions of particular interest, specialized techniques are employed. For instance, the direct stress measurement techniques, *e.g.* stress transmitting pins [13] have been used to measure the pressure distribution on the die face during hot aluminium extrusion. Extrusion friction tests for extrudate/bearing interface [4, 14, 15] was used to characterize friction in the bearing channel of extrusion dies, in which a transition from full sticking to sliding was experimentally observed and the friction coefficients were therefore determined from the lengths of sticking and sliding zones [14-16].

Field tests are normally time consuming, expensive and difficult to control. In most of the field tests, the local contact conditions vary significantly throughout the whole operating cycle, and the individual effect of each factor is rather difficult to be discriminated. Therefore, there is a need for simplified friction testing techniques, in which, more stable contact conditions can be achieved. Hence, simulative tests have been proposed and conducted. The block on cylinder tests [1, 7] were developed to simulate the contact between the workpiece and extrusion die, and the wear mechanisms in the bearing channel region were studied. The results revealed that adhesive wear and abrasive wear were dominant wear patterns of the extrusion dies. In the meanwhile, due to the strong chemical bonding between the hot aluminium and steel, high friction coefficients were observed. Most recently, a novel simulative friction test method highlighting the friction in the bearing channel of the die, double action extrusion (DAE), was developed [17, 18]. In the DAE, an aluminium billet was pressed against two extrusion dies with different bearing lengths and two indirect extrusions took place simultaneously. The lengths of the extrudates were found to be highly friction sensitive due to different friction in the two dies, and thus the friction between the extrudate and bearing channel of the die during hot aluminium extrusion can be characterized.

In the field tests or simulative tests, it is rather difficult to study the effects of individual factor, such as temperature, sliding speed and contact pressure *etc.*, on the friction. The tribological test is a sensible technique to understand the physical fundamentals of the friction under hot aluminium extrusion conditions. In the past, tribological tests (pin/ball-on-disc tests) have been employed to identify the friction coefficients for metal cutting

process [19-22]. Recently, the first attempt to determine the friction coefficient for hot aluminium extrusion process by using ball/pin-on-disc tests has been conducted [23, 24]. However, the tribological test results have not been implemented into the FE simulations of hot aluminium extrusion yet, probably due to the lack of knowledge about the evolution of the contact interface during ball-on-disc tests.

The aim of this research is to understand the fundamental of friction phenomenon in the bearing channel of the extrusion die from a tribological point of view. Moreover, based on the ball-on-disc test results, a physically-based friction model has been developed and implemented into the simulation of hot aluminium extrusion process.

2. Selection of friction testing techniques for the friction characterization of hot aluminium extrusion processes

During the friction tests, the large variety of contact conditions, such as temperature, contact pressure, sliding distance, sliding velocity and oxidation scale should be considered very carefully [25], because these factors influence the friction coefficients considerably. In general, it is very unlikely to emulate all the contact conditions or reflect all the tribological conditions by using one single friction testing technique, because one friction testing technique is only able to reflect one specific or a few tribological conditions, *i.e.* the tribological conditions of a particular region of the workpiece / tooling interface. Therefore, in order to characterize the friction of extrusion processes, a combination of different testing methods should be used, for instance, the combination of extrusion friction tests (to determine the friction between the billet and container) and

short sliding distance ball-on-disc tests (to determine the friction of the bearing channel region).

The extrusion friction tests were developed to estimate the global friction coefficient at the billet/container interface. During the tests, high contact pressure and intensive surface enlargement can be achieved [9, 10, 12, 26, 27]. Most recent research results have shown that different contact conditions in the extrusion friction tests can be achieved by adjusting the extrusion ratio[27]: low contact pressure and surface enlargement can be achieved when low extrusion ratio is used, thus a high friction sensitivity can be obtained. If a high extrusion ratio is used, high contact pressure and surface enlargement are obtained, which resemble the real contact condition of forging or extrusion processes, but sacrifice the fiction sensitivity. The combination of extrusion friction tests and FEM simulations is an effective way of estimating global friction at the billet and container interface.

Ball/pin-on-disc test is a widely used laboratory testing technique for the quantitative study of tribological behavior of materials. During ball-on-disc tests, a high contact pressure can be achieved in a small contact area between the ball and the rotating disc. If a soft material is sliding over a harder one, severe plastic deformation may occur, which could lead to the removal of oxide layers and the contact of pure metals. In the meanwhile, the contact pressure may drop with the increasing sliding distance. Therefore, ball-on-disc tests are favorable to the friction characterization of the regions, in which local contact pressure is high and new surface generation is severe, such as the bearing

channel of hot aluminium extrusion dies. During hot aluminium extrusion, fresh aluminium is extruded from the container, and in the die bearing, a pure metal contact takes place. It is well known that the presence of chemical stable surface oxides or scale prevents the strong atomic interactions [28]. Therefore, in order to reproduce the friction conditions in the bearing channel, it is vital to choose a friction testing technique being able to remove the surface oxides. Obviously, short sliding distance ball-on-disc test is one of the best friction testing techniques over the other ones, because during the ball-on-disc tests, severe plastic deformation occurs at the ball / disc interface [19, 20, 23], especially during the run-in period. Short sliding distance ball-on-disc test is highly suitable for the study of the friction between fresh metals, which emulates the contact condition in the bearing channel or welding chamber of the extrusion dies. However, the friction test results obtained from ball-on-disc tests cannot be transferred into FE simulations of extrusion processes directly as the friction boundary conditions, due to the complicated nature of the evolution of contact conditions during the tests. Therefore, the selection of testing parameters, such as pin and disc materials, sliding distance and size of the ball has to be considered carefully. Furthermore, friction data processing has to be conducted through FEM simulation or theoretical analysis.

The selection of the pin and disc materials affects ball-on-disc test results. If the pin is made from a soft material, and the disc is made from a hard one, severe plastic deformation and wear would occur on the tip of the pin, which leads to a significant enlargement of the contact area. After the run-in period, a steep decrease of contact pressure occurs and the contact pressure during the steady-state sliding is close to the

yield strength of the soft material. On the other hand, if the disc is made from a soft material, while the pin is made from a hard one, plastic deformation tends to occur in the disc, but the material flow is most likely constrained by the remainder disc material, which is much larger than the size of the wear track. Hence a relatively high hydrostatic pressure which is greater than the strength of the disc material would be imposed onto the spherical pin head. Therefore, different materials combinations would result in different contact pressures, and the selection of pin and disc mating materials need to be considered carefully prior to testing, especially when the strengths of the pin and disc materials are different. In the meanwhile, the selection of ball size and sliding distance is of great importance. In general, the contact pressure increases with decreasing ball size [29] and decreases with increasing sliding distance [30].

When a hard pin is sliding over a soft disc, the apparent friction coefficient obtained from the test is normally composed of plowing and shearing (adhesive) friction [20, 21, 31]. The plowing friction is caused by the plastic deformation of the disc material in front of the pin, which depends on the size of the ball, sliding distance and the material strength. Consequently, the test results cannot be transferred into a metal forming operation directly, because the existence of plowing friction leads to an overestimation of the friction between the mating materials. The plowing and shear friction have to be discriminated by means of FEM simulations [20, 21] or theoretical analysis [24, 32], and only the shear component of apparent friction representing the real friction between the two mating materials should be used in the FE simulations of metal forming operations as boundary conditions [20, 21]. However, when the material combination of soft pin and

hard disc is used, the friction coefficients obtained from the tests are mainly attributed to the shearing (adhesive) friction. Therefore, with the knowledge about the contact pressure evolution, the results can be transferred into the FE simulations as friction boundary conditions. To simulate the tribological conditions in the bearing channel of the hot aluminium extrusion die, the short sliding distance ball-on-disc test is recommended, with the disc made from the workpiece material and ball made from the die material.

3. Determination of friction coefficient for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

A CSM® high-temperature tribometer with a ball-on-disc configuration was used for the friction characterization. To emulate the extrusion process, the disc was made from AA7475 aluminium alloy, which was the same as the billet material used in the extrusion tests. The hardened H11 steel was selected as the mating material, which was the same material as that of extrusion dies. The tests were carried out under a constant normal load of 6 N at 350, 400, 450 and 500°C [24]. In order to achieve a high contact pressure between the mating materials, short sliding distance ball-on-disc tests were employed to represent the friction condition of the bearing channel of the hot aluminium extrusion process. The friction coefficients between AA7475 and H11 steel were determined.

In order to transfer the friction test results of ball-on-disc tests into FE simulations as friction boundary conditions, it is of great importance to understand the evolution of the contact conditions during the tests. A previously developed model being able to characterize the evolution of contact interface during high-temperature ball-on-disc tests

was used to determine the mean friction stresses at different temperatures [24], which will be used for friction modelling in this research.

Figure 1 shows the forces acting on an elemental area during ball-on-disc testing, which are given in Equation (1).

$$\begin{cases} dF_x = \left(pr^2 \sin^2\beta\cos\gamma + fr^2 \sin\beta\sqrt{\cos^2\gamma\cos^2\beta + \sin^2\gamma} \right) d\gamma d\beta \\ dF_z = \left(pr^2 \cos\beta\sin\beta - fr^2 \dfrac{\cos\gamma\sin^2\beta\cos\beta}{\sqrt{\cos^2\gamma\cos^2\beta + \sin^2\gamma}} \right) d\gamma d\beta \end{cases} \quad (1)$$

First lap of wear

The aluminium disc was assumed to behave as a viscoplastic material at elevated temperatures and the elastic recovery of the disc at the rare part of the ball was omitted. Figure 2 schematically shows the contact interface during the 1st lap of wear. Equation (2) can be used to calculate the tangential and normal forces acting on the ball surface.

$$\begin{cases} F_x = 2\int_0^{\xi_1}\int_0^{\pi/2} dF_x \\ F_z = 2\int_0^{\xi_1}\int_0^{\pi/2} dF_z \end{cases} \quad (2)$$

where ξ_1 is the upper integral limit of angle β (see Figure 2a where W_1 is the width of the wear track after the first lap of wear).

Arbitrary $(i+1)th$ lap of wear

The contact interface of an arbitrary lap of wear is schematically shown in Figure 3. The tangential and normal forces acting on the ball can be calculated by Equation (3).

$$\begin{cases} F_x = 2\int_0^{f_i(\gamma)} \int_0^{\pi/2-\omega_i} dF_x + 2\int_0^{\xi_i} \int_{\pi/2-\omega_i}^{\pi/2} dF_x \\ F_z = 2\int_0^{f_i(\gamma)} \int_0^{\pi/2-\omega_i} dF_z + 2\int_0^{\xi_i} \int_{\pi/2-\omega_i}^{\pi/2} dF_z \end{cases} \tag{3}$$

As shown in Figure 3b, in the area COD, $f_i(\gamma)$ is the upper integral limit of β, and in the areas AOD and COB, ξ_i is the upper integral limit of angle β. ω_i is the angle for locating the position of the front contact boundary during the $(i+1)th$ lap of wear.

To determine the constants in the model, three tests with different wear laps (1, 5 and 10 laps) were conducted at each temperature. The friction coefficient was continuously recorded during the test. Thereafter, wear tracks were examined using an optical microscope. The average width of the wear track in each lap was determined from 12 measurements.

4. A physically-based adhesive strength friction model (ASFM) for the bearing channel of hot aluminium extrusion die

According to the classic theory of tribology, the friction force mainly stems from ploughing (due to hard asperities and trapped wear debris) and adhesive (due to atomic or chemical interactions) forces [33-35]. At elevated temperatures, the adhesive friction plays a dominant role, due to the strong atomic or chemical interactions, especially under

high contact pressures [1-3, 36]. This is mainly due to the following reasons: at elevated temperatures, the atoms in both materials in contact are highly activated, which aids the interdiffusion at the surface layers of the materials and a strong chemical bonding tends to be established. The mating materials and surface oxides are relatively soft and easy to be deformed or penetrated, which thus leads to the contact of pure metals. In addition, the high contact pressure (several times greater than the flow stress of the workpiece material) further aids the severe plastic deformation of the asperities or oxidation scale, and brings the faying material highly close to each other to a distance of atomic level. Therefore, in the bearing channel of hot aluminum extrusion, the strong chemical or diffusion bonding is the dominant friction mechanism, which has been verified experimentally before [2, 3]. Also, the strong interactions between hot Al and steel have been observed in the forge welding process [37-39]. From a micro-scale point of view, the influence of the contact pressure is to change the real contact area, *i.e.* the number of asperities in contact. Therefore, the nature of different friction modes within the bearing channel could be summarized as:

Formation of isolated adhesive junctions → Adhesive junctions growth → Coalescence of adhesive junctions.

Formation of isolated adhesive junctions. At low contact pressure conditions, strong adhesion occurs on the tips of plastically deformed asperities, but the faying surfaces are only supported by a small number of asperities, thus only a few isolated adhesive junctions are formed and normally too small to be observed by naked eyes. At this stage,

no adhesive layers can be observed. Therefore a so-called slipping zone is experimentally observed.

Adhesive junctions growth. As the increase of contact pressure, the number of plastically deformed asperities is increased, to support the increased contact pressure. In some regions with a higher asperity density, adhesive junctions growth takes place due to the plastic deformation and some of the adhesive junctions may coalesce to each other locally. Consequently, the workpiece material or intermetallic wear debris could adhere to the bearing surface of the die, due to the strong adhesive bonding. At this stage, an in-continuous tribo-layer might be visible on the die land, and the so-called transition zone between the slipping and sticking zone can be observed.

Coalescence of adhesive junctions. At the die entrance, where a high contact pressure is achieved, the real contact area is maximized, thus the number of adhesive junctions is significantly increased and they are close to each other, thus tend to coalesce with each other. Moreover, a great amount of workpiece material may transfer from the extrudates to the bearing surface of the die, due to the strong adhesive bonding. Therefore there exists a great chance for the adhesive junctions within a large area to coalesce with each other and thus the adhesive junctions can be observed by naked eyes. At this stage, a continuous tribo-layer, *i.e.* the so-called adhesive zones, can be observed on the bearing surface. However, after extrusion, the inlet of the bearing is heavily worn and a continuous tribo-layer may not be observed. This is probably due to the high rate of material renewal at the inlet of the bearing channel [2].

In this research, the strong adhesive friction generated from pure metal contact is modelled, and the strength of adhesive junctions is considered to be determined by two factors, namely, the rate of atomic interaction and the strength of adhesive joints (Equation 6). The interaction rate at atomic level increases with increasing temperature, which can be modeled by using an Arrhenius type equation [40] (Equation 7). The bonding strength decreases with increasing temperature, due to the decrease of the strength of adhesive joints with increasing temperatures, and the bonding strength drops to zero at the melting temperature of AA7475 (Equation 6). The friction stresses obtained from short sliding distance ball-on-disc tests, details found in [24], were used to determine the constants of the model, by fitting the outputs of the model with the stress-temperature curve obtained from ball-on-disc tests. Table 1 lists the determined material constants. As can be seen from Figure 4, a good agreement between the model and experimental results was obtained.

$$f\left(T\right)=\tau_0 D\left(1-\frac{T}{T_m}\right)^n \tag{6}$$

$$D=D_0\cdot\exp\left(-\frac{Q}{RT}\right) \tag{7}$$

where $f\left(T\right)$ is temperature dependant bonding strength or friction stress in a unit area;

τ_0 is the mean adhesive strength at room temperature (300 K) in a unit area;

D is the inter-diffusion coefficient at elevated temperatures;

T is the mean contact temperature (K);

T_m is the melting temperature of the workpiece material (K);

Q is the activation energy;

R is the universal gas constant;

D_0 and n are constants;

Table 1 Material constants of the ASFM for hot AA7475 and H11 steel

τ_0 (MPa)	T_m (K)	Q (J/mol)	R (J/K/mol)	D_0	n
378	811	2400	8.314	3.62	0.7

In this model, the bonding strength is determined by the combined effects of atomic interaction and the strength of adhesive joints, with the assumption that pure metal contact is taking place. At low temperature conditions ($T < 0.5T_m$ approximately), the interdiffusion rate increases with the increasing temperature. At this stage, the increase of temperature does not affect material strength significantly. Therefore the increase of inter-diffusion rate plays a dominant role under the low temperature circumstances, thus an increasing adhesive strength is predicted. The maximum value of adhesive strength is achieved at about 423 K ($0.5T_m$ approximately). At high temperatures ($0.5T_m < T \leq T_m$), the bonding strength decreases with increasing temperature, because the drop of the strength of adhesive joints plays a dominant role, although the atoms are highly activated and atomic interactions are more intensive. Therefore a decreased adhesive strength with the increasing temperature can be observed, which is consistent with other research results [35, 41].

5. Verification of the friction model

5.1. Experiment and FE simulation details

The double action extrusion (DAE) tests [17, 42], highlighting the friction in the bearing channel of the extrusion dies, were used to verify the proposed friction model. Figure 5 (a) shows the principle of the DAE, which was conducted on a Gleeble 3800 material thermo-mechanical simulator and Figure 5 (b) shows the experimental setup. In the tests, the combination of 2 and 6 mm bearing dies was employed to maximize the effect of friction in the bearing channels [18]. It has been found that the DAE is highly sensitive to the friction in the bearing regions, in terms of extrudate lengths and steady-state extrusion load. Figure 5 (c) shows the typical test results of DAE and the length differences were caused by the different friction forces generated from the two different extrusion dies, with different bearing lengths used. Figure 5 (d) shows the typical extrusion forces of DAE tests at different testing temperatures. As can be seen from Figure 5 (d), the extrusion forces decreased with increasing temperature, mainly due to the decreasing strength of the workpiece material with rising temperature. The extrusion forces at these temperatures showed a similar trend, *i.e.* a small plateau at the very early stage, followed by a sharp increase in extrusion force and then a gentle decrease as the process proceeded further. The small plateau corresponds to the initiation of extrusion toward both of the die (upsetting) and the sharp force increase corresponds to breakthrough. In DAE, there is no friction between the billet and container and therefore the extrusion force in the steady state reflects the dynamic balance of the deformation force of the workpiece material and the friction forces in the two dies which are governed by temperature and influenced by the temperature evolution during DAE.

DEFORM 3D version 6.1 was used to simulate the DAE process. Figure 6 shows the FEM model of the DAE. All the objects in the model were meshed with tetrahedral elements. The flow stress data of AA7475 aluminium alloy were determined from hot compression tests on a Gleeble 3800 material thermomechanical simulator, under a wide range of strain rate (0.01-180 s^{-1}), with the data at high strain rates corrected for deformational heating [43]. The ASFM were implemented into DEFORM 3D V6.1 via user defined subroutine. In DEFORM, to avoid the overestimation of friction stress, the value of the friction stress calculated from the a friction model is compared with the shear flow stress of the deformed material at each iteration step and automatically changed to the shear flow stress, if the calculated friction stress is larger than the shear flow stress.

5.2. Friction model verification by DAE tests

Figures 7-9 show the comparisons in the lengths of the extrudates between the DAE experiments and FEM simulations. In these figures, the FEM predictions of the extrudate lengths with the use of ASFM are superimposed onto the experimental data. At different temperatures, the extrudates from the 2 mm bearing are longer than those from the 6 mm bearing. The length difference of the extrudates increases with increasing ram displacement. At the initial stage of the DAE process, the workpiece is extruded at the same extrusion speed in both of the dies. As the ram displacement increases, the friction force increases at the same rate in the two dies due to the increasing contact area. When the extrudate lengths are greater than 2 mm, the contact area in the 2 mm bearing cannot

be further increased. Thus a constant friction force is achieved in the 2 mm bearing. In the 6 mm bearing, however, the contact area is further increased due to the increase of the extrudate length, thus the friction force increases and the material flow in the 6 mm bearing is restricted, consequently the extrusion speed slows down. In the meanwhile, the rate-dependant property of the billet material becomes explicit. In the severe deformation zone of the 2 mm bearing, the material is enhanced due to the higher extrusion speed and becomes more difficult to be deformed. In the severe deformation zone of the 6 mm bearing, however, the low extrusion speed results in lower material strength, thus the material becomes easier to be extruded. As such, a dynamic balance is maintained throughout the DAE process: the friction between the extrudates and bearing surfaces increases the length difference of the extrudates; on the other hand, the effect of rate-dependent material behaviour decreases the length difference. As can be seen from the figures, at these three extrusion temperatures, the implementation of the ASFM has led to highly accurate predictions, in terms of the extrudate lengths, suggesting that the ASFM is able to represent the friction conditions at the extrudate/bearing interface.

Figure 10 shows the FEM predicted and experimentally obtained steady-state extrusion forces at different extrusion temperatures. The extrusion force decreases with increasing temperature due to the material softening at higher temperatures. It can be seen that predictions from the ASFM show the same trend as the experimental results in terms of the temperature effect on the extrusion force. The predictions from the ASFM achieved a very good agreement between the FE predictions and experimental results.

6. Conclusions

In this study, a physically based friction model (ASFM) was developed and implemented into the FE simulation of hot aluminium extrusion process. Good agreements between the FE simulations and experiments were achieved, in terms of extrudate length and steady state extrusion force, indicating that ball-on-disc tests can represent the friction conditions in the bearing channel of the hot aluminium extrusion dies. The tribological conditions of hot aluminium extrusion process cannot be reflected by using one single friction testing technique, and a combination of different friction testing techniques should be used. For the bearing channel of the hot aluminium extrusion dies, the short sliding distance ball-on-disc test is recommended, with the disc made from the workpiece material and ball made from the die material. Strong adhesive friction occurs between the hot aluminium and steel and the nature of friction in the bearing channel can be summarized as a pressure dependant process, *i.e.* formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

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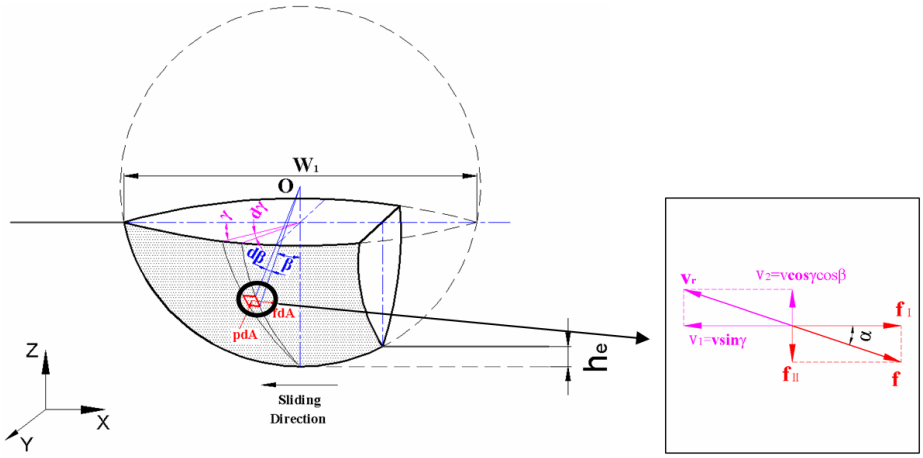
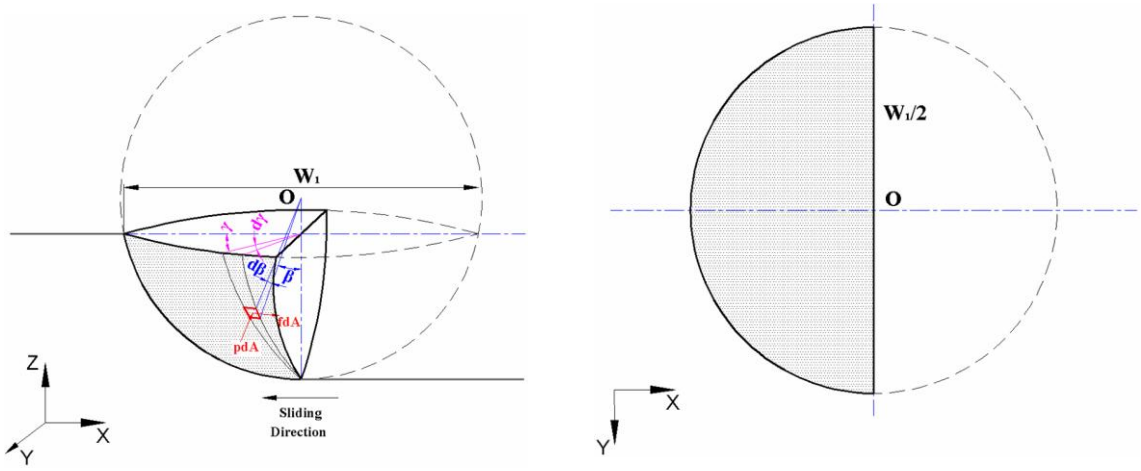
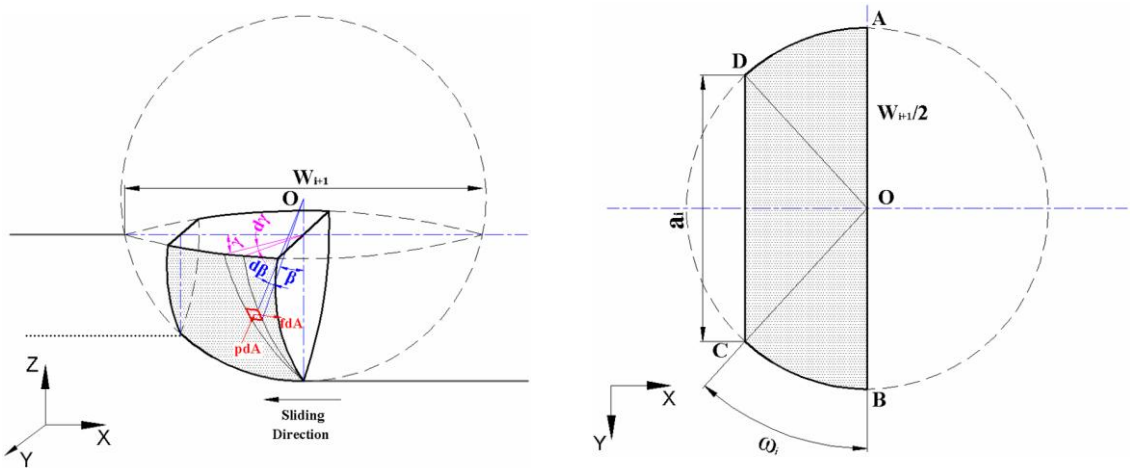


Figure 1 Close-up view of the friction force and velocity on an elemental area



(a) (b)

Figure 2 Schematic drawing of the contact interface in the first lap of wear during ball-on-disc testing



(a) (b)

Figure 3 Schematic drawing of the contact interface in an arbitrary $(i+1)th$ lap of wear during ball-on-disc testing

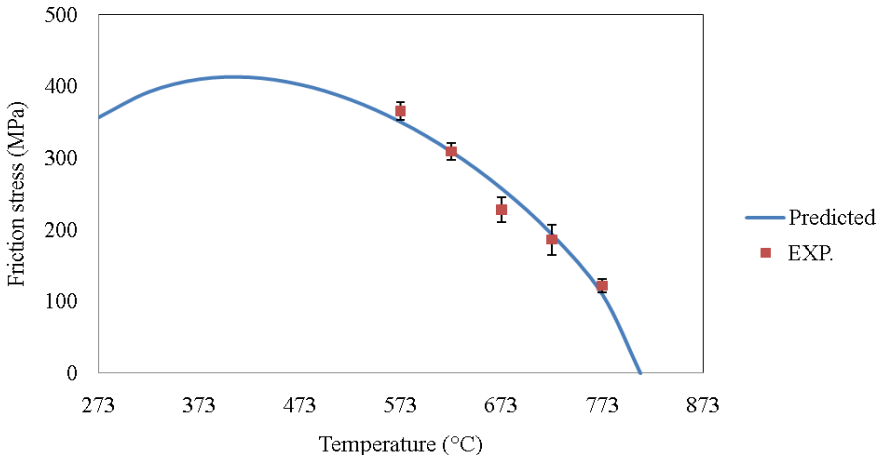
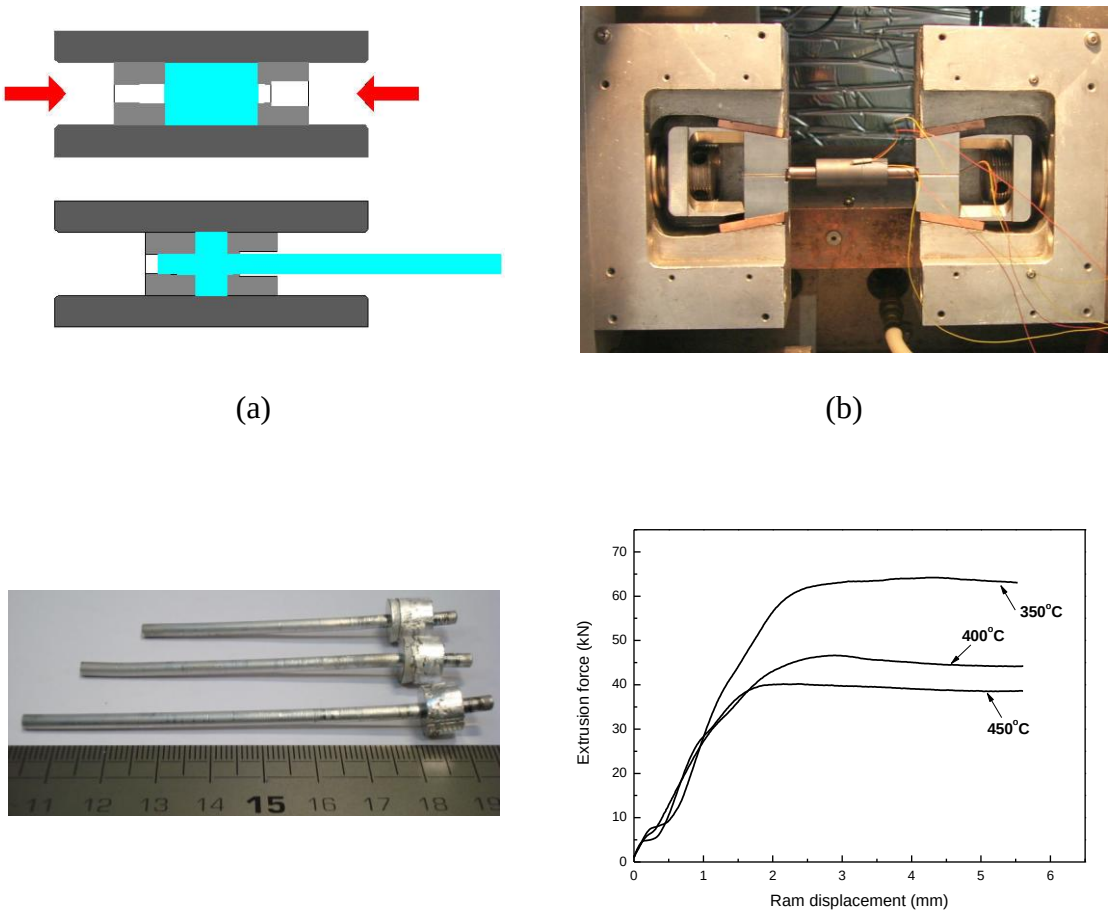


Figure 4 Evolution of friction stress between AA7475 and H11 steel at different temperatures



(a) (b)

(c) (d)

Figure 5 The (a) principle, (b) experimental setup and (c and d) typical test results of DAE

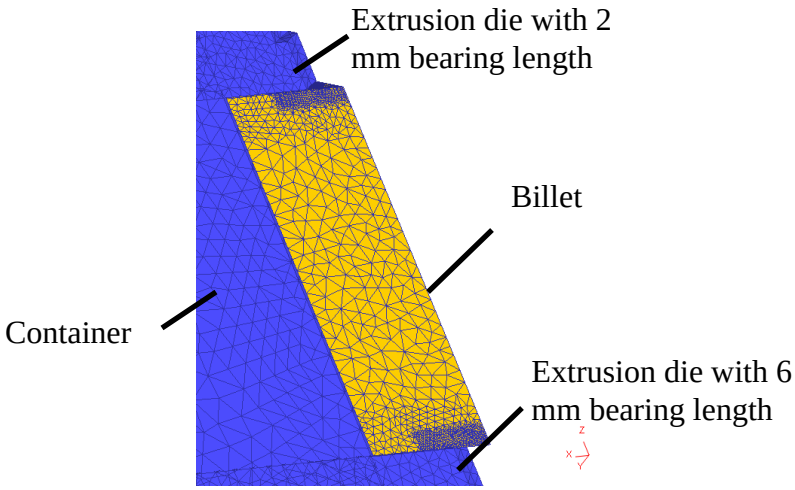


Figure 6 FE model for the DAE

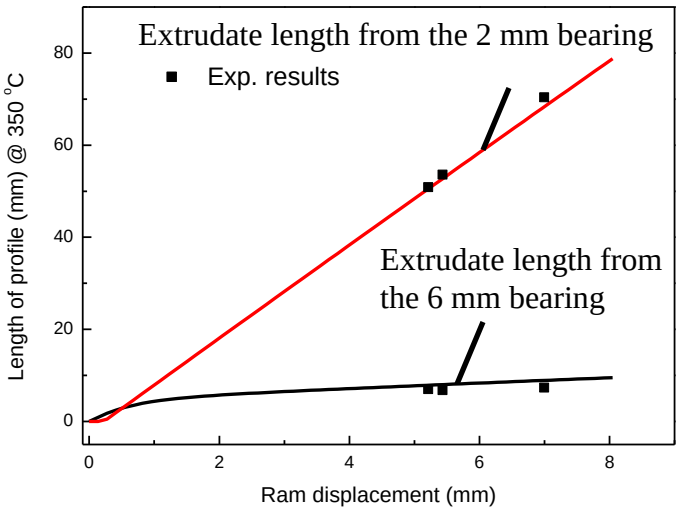


Figure 7 Comparison in the extrudate lengths from DAE at 350°C between the experiments and FEM simulations.

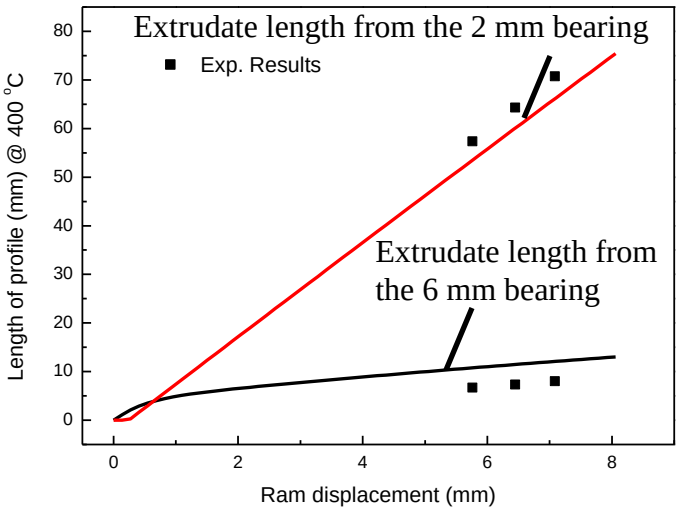


Figure 8 Comparison in the extrudate lengths from DAE at 400°C between the experiments and FEM simulations.

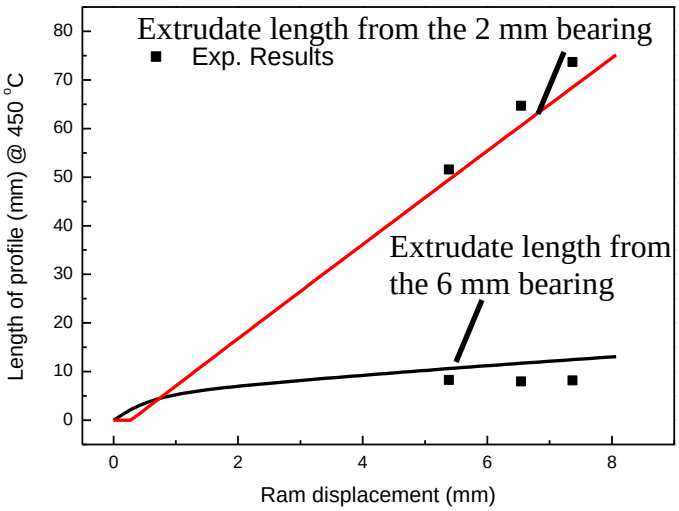


Figure 9 Comparison in the extrudate lengths from DAE at 450°C between the experiments and FEM simulations.

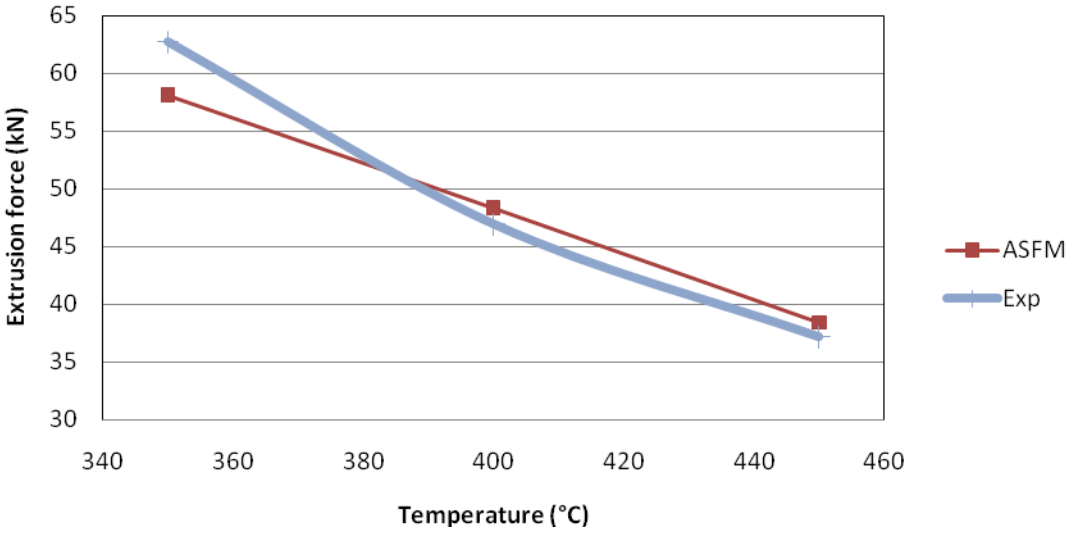


Figure 10 Steady state extrusion forces at different extrusion temperatures

Identification of a friction model for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

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Abstract

A physically-based friction model is developed based on the ball-on-disc test results. The model is verified by using double action extrusion tests. Good agreements between the FE predictions and experiments have been obtained, in terms of the extrudate length and steady-state extrusion load, indicating that ball-on-disc test is an effect way of characterizing the friction for the bearing channel of hot extrusion dies. The nature of friction in the bearing channel can be summarized as a pressure dependant process: formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

Keywords: FE Simulation; Friction model; Hot aluminium extrusion; Bearing channel

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1. Introduction

Extrusion is a process in which a cast billet of solid metal is converted into a continuous length of generally uniform cross-section by forcing it to flow through a shaped die opening. Generally, the extrusion process is a hot working operation, in which the metal billet is heated to a proper temperature, at which a relatively high ductility and low flow stress can be achieved. FE simulation of the extrusion processes is widely used in both scientific research and industrial practice. The selection of friction models and the assignment of friction coefficients or factors for the FE simulations of extrusion processes remain an essential issue, because the accuracy of the simulation results is strongly affected by the flow stress of workpiece material (thermo-viscoplastic behavior at elevated temperatures) and the assignment of boundary conditions, *e.g.* friction boundary conditions. The uncertainty of flow stress is low when the constitutive equations determined from thermo-mechanical testing are implemented. However, unreliable FE simulation results could be obtained if the friction boundary conditions are not assigned appropriately.

In the past years, efforts have been made to study the tribological phenomenon of the extrusion process and some friction testing techniques have been developed, which can be classified as three different categories, namely, field tests; simulative tests (or physical simulation tests) and tribological tests.

In general, field test is to estimate the friction coefficient or factor by using extrusion friction tests. Based on the material flow response to the friction force, some novel extrusion friction tests have been developed, including double backward extrusion [1], combined forward rod-backward can extrusion [2] and combined forward conical / straight can-backward straight can extrusion [3]. These tests were designed with highlighted friction sensitivity indicated by extrudate lengths, and the lubricants can be evaluated and the global friction coefficient or factor on the workpiece/tooling interface can be determined quantitatively with the aid of FE simulations. On the other hand, the friction coefficients/factors over the container wall can be estimated based on the friction effects on the extrusion load [4, 5]. Table 1 shows a summary of the friction test results obtained from extrusion friction tests. For the friction at extrudate/bearing interface, extrusion friction test [6-8] was used to characterize the friction in this region. A transition from full sticking to sliding was experimentally observed and the friction stress was therefore determined from the lengths of sticking and sliding zones [6, 7, 9].

Table 1 friction test results obtained from extrusion friction tests

Extrusion test	Work piece material	Tool material	Billet temp. (°C)	Die temp. (°C)	Lub(s)	Friction coef./factor
1992 Buschhausen *et al.* [1]	AISI 1006		25	25	Lub	m=0.08-0.2
1997 Nakamura *et al.* [2]	6061	High speed steel	-	-	Ca-Al	$\mu \approx 0.3$-0.4
					VG26	$\mu \approx 0.5$
					MoS_2	$\mu \approx 0.5$-0.6
1998 Nakamura *et al.* [3]	6061	High speed steel, cemented carbide	-	-	VG2	μ_d = 0.017-0.05 μ_{LP} = 0.37-0.42
					VG26	μ_d = 0.005-0.048 μ_{LP} = 0.15-0.19
					VG1000	μ_d = 0.001-0.039 μ_{LP} = 0.15-0.28
					MoS_2	μ_d = 0.088-0.105 μ_{LP} = 0.07-0.18
2002 Bakhshi-Jooybari [4]	CP Al	H13	25	25	No Lub.	m=0.84
	Steel		900	900	Graphite	-
2003 Flitta *et al.* [5]	AA2024 Al-Cu ally	-	300-450	250-400	No Lub.	m=0.654-0.92

Field tests are normally time consuming, expensive and difficult to control. In most of the field tests, the local contact conditions vary significantly throughout the whole operating cycle. Therefore, there is a need for simplified friction testing techniques, in which more stable contact conditions can be achieved. As such, simulative friction tests have been proposed and conducted. The block on cylinder tests [10, 11] were developed to simulate the contact between the workpiece and extrusion die, and the wear mechanisms in the bearing channel region were studied. The results revealed that adhesive wear and

abrasive wear were dominant wear patterns of the extrusion dies. In the meanwhile, high values of friction coefficients ($1<\mu<1.5$) were observed and this was attributed to a high degree of aluminium to aluminium contact [11]. Most recently, a novel simulative friction test method highlighting the friction in the bearing channel of the die, double action extrusion (DAE), was developed [12]. In the DAE, an aluminium billet was pressed against two extrusion dies with different bearing lengths and two indirect extrusions took place simultaneously. The lengths of the extrudates were found to be highly friction sensitive, because the friction force for the extrudate to flow through the die with a longer bearing length was greater than that through the die with a shorter bearing length. As such, friction between the extrudate and bearing channel of the extrusion dies can be characterized, with the aid of FE simulation [12] or theoretical analysis [13]. The results obtained from the DAE tests indicate that full sticking friction occurred at the extrudate/die interface when a 15' choke angle was applied in the extrusion dies [12, 13].

In the field tests or simulative tests, it is difficult to study the effects of individual factor, such as temperature, sliding speed or contact pressure *etc.*, on the friction. As such, tribological test is probably a sensible technique to reveal the mechanisms of friction under hot aluminium extrusion conditions. Tribological tests (pin/ball-on-disc tests) have been employed previously to identify the friction coefficients for metal cutting process [14-17]. Recently, the first attempt has been made to simulate the interactions at bearing surface by using ball/pin-on-disc tests [18]. The steady-state friction was found to be greater than 1.0 when the testing temperature was higher than 150°C and the magnitude

of friction increased with increasing temperature. The presence of a continuous transfer layer was thought to be responsible for the high magnitude of the frictional force.

Although more efforts have been made previously to simulate the extrudate/bearing interactions by using tribological tests [19, 20], the fundamental understanding of the friction phenomenon in the bearing channel of hot aluminium extrusion dies is still insufficient, and the tribological test results have not been implemented into the FE simulations of hot aluminium extrusion yet. The aim of this research is to understand the fundamental of friction phenomenon in the bearing channel of hot extrusion die from a tribological point of view. Moreover, based on the ball-on-disc test results, a physically-based friction model has been developed and implemented into the simulation of hot aluminium extrusion process.

2. Selection of friction testing techniques for the friction characterization of hot aluminium extrusion processes

During a friction test, the large variety of contact conditions, such as temperature, contact pressure, sliding distance, sliding velocity and oxidation scale should be considered very carefully [21], because these factors may influence the friction coefficients considerably. In general, it is very unlikely to emulate all the contact conditions or reflect all the tribological conditions by using one single friction testing technique, because one friction testing technique is only able to reflect one specific or a few tribological conditions, *i.e.* the tribological conditions of a particular region of the workpiece / tooling interface. Therefore, for the friction characterization of extrusion processes, a combination of

different testing methods should be used, for instance, the combination of extrusion friction tests (to determine the friction at billet / container interface) and short sliding distance ball-on-disc tests (to determine the friction in the bearing channel region).

Extrusion friction tests were developed to estimate the global friction coefficient at the billet/container interface. During the tests, high contact pressure and intensive surface enlargement can be achieved [2, 3, 5, 22, 23]. Most recent research results have shown that different contact conditions in the extrusion friction tests can be achieved by adjusting the extrusion ratio[23]: low contact pressure and surface enlargement can be achieved when low extrusion ratio is used, thus high level of friction sensitivity can be achieved. If a high extrusion ratio is used, high contact pressure and surface enlargement are obtained, which resemble the real contact condition of forging or extrusion processes, but sacrifice the fiction sensitivity. The combination of extrusion friction tests and FEM simulations is an effective way to estimate global friction at the billet and container interface.

Ball/pin-on-disc test is a widely used laboratory testing technique for the quantitative study of tribological behavior of materials. During ball-on-disc tests, high contact pressure can be achieved in a small contact area between the ball and the rotating disc. If a soft material is sliding over a harder one, severe plastic deformation may occur in the soft material, which could lead to the removal of oxide layers and the contact of pure metals. In the meanwhile, the contact pressure may drop with the increasing sliding distance. Therefore, ball-on-disc tests are favorable to the friction characterization of the

regions, in which local contact pressure is high and new surface generation is severe, such as the bearing channel of hot aluminium extrusion dies. During hot aluminium extrusion, fresh aluminium is extruded from the container, and in the die bearing, a pure metal contact takes place. It is well known that the presence of chemical stable surface oxides or scale prevents the strong atomic interactions [24]. Therefore, in order to reproduce the friction conditions in the bearing channel, it is vital to choose a friction testing technique being able to remove the surface oxides. Short sliding distance ball-on-disc test is one of the best friction testing techniques over the other ones, because during the ball-on-disc tests, severe plastic deformation occurs at the ball / disc interface [14, 15, 18], especially during the run-in period. Therefore, it is highly suitable for the study of friction between fresh metals, which emulates the contact condition in the bearing channel or welding chamber of the extrusion dies. However, the friction test results obtained from ball-on-disc tests cannot be translated into friction boundary conditions for the FE simulations of extrusion processes directly. Therefore, the selection of testing parameters, such as pin and disc materials, sliding distance and size of the ball has to be considered carefully. Furthermore, friction data processing has to be conducted with the aid of FEM simulation or theoretical analysis.

The selection of the pin and disc materials affects ball-on-disc test results. If the pin is made from a soft material, and the disc is made from a hard one, severe plastic deformation and wear would occur on the tip of the pin, which leads to a significant enlargement of the contact area. After the run-in period, a steep decrease of contact pressure occurs and the contact pressure during the steady-state sliding is close to or

lower than the yield strength of the soft material. On the other hand, if the disc is made from a soft material, while the pin is made from a hard one, plastic deformation tends to occur in the disc, but the material flow is most likely constrained by the remainder disc material, which is much larger than the size of the wear track. Hence a relatively high hydrostatic pressure which is greater than the strength of the disc material could be imposed onto the spherical pin head. Therefore, different materials combinations would result in different contact pressures, and the selection of pin and disc mating materials need to be considered carefully prior to testing, especially when the strengths of the pin and disc materials are different. In the meanwhile, the selection of ball size and sliding distance is of great importance. In general, the contact pressure decreases with increasing ball size [25] and increasing sliding distance [26].

When a hard pin is sliding over a soft disc, the apparent friction coefficient obtained from the test is normally composed of plowing and shearing (adhesive) friction [15, 16, 27]. The plowing friction is caused by the plastic deformation of the disc material in front of the pin, which depends on the size of the ball, sliding distance and the material strength. Consequently, the test results cannot be transferred into a metal forming operation directly, because the existence of plowing friction leads to an overestimation of the friction between the mating materials. The plowing and shear friction have to be discriminated by means of FEM simulations [15, 16] or theoretical analysis [19, 28], and only the shear component of apparent friction representing the real friction between the two mating materials should be used in the FE simulations of metal forming operations as boundary conditions [15, 16]. However, when the material combination of soft pin and

hard disc is used, the friction coefficients obtained from the tests are mainly attributed to the shearing (adhesive) friction. Therefore, with the knowledge of contact pressure evolution, the results can be transferred into the FE simulations as friction boundary conditions. To simulate the tribological conditions in the bearing channel of the hot aluminium extrusion die, short sliding distance ball-on-disc test is recommended, with the disc made from the workpiece material and ball made from the die material.

3. Determination of friction coefficient for the bearing channel of hot aluminium extrusion dies by using ball-on-disc tests

A CSM® high-temperature tribometer with a ball-on-disc configuration was used for the friction characterization. To emulate the extrusion process, the disc was made from AA7475 aluminium alloy, which was the same as the billet material used in the extrusion tests. The hardened H11 steel was selected as the mating material, which was the same material as that of extrusion dies. The tests were carried out under a constant normal load of 6 N at 350, 400, 450 and 500°C [19]. In order to achieve a high contact pressure between the mating materials, short sliding distance (1, 5 and 10 laps of sliding) ball-on-disc tests were employed to represent the friction condition in the bearing channel of hot aluminium extrusion process. Figure 1 shows the evolution of the friction coefficient over a sliding distance of 10 laps at different temperatures. It is of interest to note that friction coefficient increases with the sliding distance. At 500 °C, in particular, the friction coefficient increases even by 50%. The increase of the friction coefficient with sliding distance, leads to the uncertainty as to the exact value to be put into FE simulation. It is therefore necessary to have a model with which the friction coefficient and sliding

distance are correlated with each other. A previously developed model being able to characterize the evolution of contact interface during high-temperature ball-on-disc tests was used to determine the mean friction stresses at different temperatures [19]. The details of this model is shown below:

Figure 2 shows the forces acting on an elemental area during ball-on-disc testing, which are given in Equation (1).

$$\begin{cases} dF_x = \left(pr^2 \sin^2\beta\cos\gamma + fr^2 \sin\beta\sqrt{\cos^2\gamma\cos^2\beta + \sin^2\gamma} \right) d\gamma d\beta \\ dF_z = \left(pr^2 \cos\beta\sin\beta - fr^2 \dfrac{\cos\gamma\sin^2\beta\cos\beta}{\sqrt{\cos^2\gamma\cos^2\beta + \sin^2\gamma}} \right) d\gamma d\beta \end{cases} \quad (1)$$

First lap of wear

The aluminium disc was assumed to behave as a viscoplastic material at elevated temperatures and the elastic recovery of the disc at the rare part of the ball was omitted. Figure 3 schematically shows the contact interface during the 1st lap of wear. Equation (2) can be used to calculate the tangential and normal forces acting on the ball surface.

$$\begin{cases} F_x = 2\int_0^{\xi_1}\int_0^{\pi/2} dF_x \\ F_z = 2\int_0^{\xi_1}\int_0^{\pi/2} dF_z \end{cases} \quad (2)$$

where ξ_1 is the upper integral limit of angle β (see Figure 3a where W_1 is the width of the wear track after the first lap of wear).

Arbitrary $(i+1)$*th lap of wear*

The contact interface of an arbitrary lap of wear is schematically shown in Figure 4. The tangential and normal forces acting on the ball can be calculated by Equation (3).

$$\begin{cases} F_x = 2\int_0^{f_i(\gamma)} \int_0^{\pi/2-\omega_i} dF_x + 2\int_0^{\xi_i} \int_{\pi/2-\omega_i}^{\pi/2} dF_x \\ F_z = 2\int_0^{f_i(\gamma)} \int_0^{\pi/2-\omega_i} dF_z + 2\int_0^{\xi_i} \int_{\pi/2-\omega_i}^{\pi/2} dF_z \end{cases} \tag{3}$$

As shown in Figure 4b, in the area COD, $f_i(\gamma)$ is the upper integral limit of β, and in the areas AOD and COB, ξ_i is the upper integral limit of angle β. ω_i is the angle for locating the position of the front contact boundary during the $(i+1)th$ lap of wear. The shear friction stresses at different temperatures were determined by using Equations 1-3. Figure 5 shows the evolutions of the calculated shear friction stress at different temperatures and over a sliding distance of 10 laps. It is interesting to see that the shear friction stress starts from a relatively low value, and then becomes stable at different temperatures, while the friction coefficient increases considerably (Figure 1). The low shear friction stress at the initial stage may be due to the oxide layer on the disc and ball surfaces, which tends to lower the adhesion between aluminium and steel [29, 30]. After the initial stage of sliding, the oxide layer may be broken up and metal-to-metal contact occurs, leading to the increases in friction stress. In addition, the severe plastic deformation on the surface material may generate a considerable work-hardening effect [31, 32], which may also lead to the rise of shear friction stress.

4. A physically-based adhesive strength friction model (ASFM) for the bearing channel of hot aluminium extrusion die

According to the classic theory of tribology, the friction force mainly stems from ploughing (due to hard asperities and trapped wear debris) and adhesive (due to atomic or chemical interactions) forces [31-33]. At elevated temperatures, the adhesive friction plays a dominant role, due to the strong atomic or chemical interactions. The adhesive friction becomes more pronounced under high contact pressures [11, 34-36]. This is mainly caused by the following reasons: at elevated temperatures, the atoms in both materials in contact are highly active, which aids the interdiffusion at the surface layers of the materials and a strong chemical bonding tends to be formed. The mating materials and surface oxides are relatively soft and easy to be deformed or penetrated, which thus leads to the contact of pure metals. In addition, the high contact pressure (several times greater than the flow stress of the workpiece material) further aids the severe plastic deformation of the asperities or oxidation scale, and brings the faying material highly close to each other to a distance of atomic level. Therefore, in the bearing channel of hot aluminum extrusion, the strong chemical or diffusion bonding is the dominant friction mechanism, which has been verified experimentally before [11, 34-36]. Also, the strong interactions between hot Al and steel have been observed in the forge welding process [37-39]. From a micro-scale point of view, the influence of the contact pressure is to change the real contact area, *i.e.* the number of asperities in contact. Therefore, the nature of different friction modes within the bearing channel could be summarized as:

Formation of isolated adhesive junctions → Adhesive junctions growth → Coalescence

of adhesive junctions.

Formation of isolated adhesive junctions. At low contact pressure conditions, full sticking occurs on the tips of plastically deformed asperities, but the faying surfaces are only supported by a small number of asperities [40, 41], thus only a few isolated adhesive junctions are formed and normally too small to be observed by the naked eye. At this stage, no adhesive layers can be observed in the bearing channel of the extrusion dies. Therefore a so-called slipping zone can be observed experimentally, as shown in Figure 6 (b) and (d) [11].

Adhesive junctions growth. As the increase of contact pressure, the number of plastically deformed asperities is increased [40, 41], to support the increased contact pressure. In some regions with a higher asperity density, adhesive junctions growth takes place due to the plastic deformation and some of the adhesive junctions may coalesce to each other locally to form contact patches [40, 41]. Consequently, some of the work piece material or intermetallic wear debris may transfer from the extrudates to the bearing surface of the die, due to the strong adhesive bonding [42-44]. It is worth noting that, during hot aluminium extrusion, the temperature of the extrusion die is normally lower than that of the billets, and thus the strength of the adhesive junctions is enhanced once they are formed and adhere onto the extrusion die, as the temperature drops. Therefore, the size of the adhesive junctions might "grow" bigger and bigger, with the aggregation of wear debris, i.e. the "lump growth" occurs [42, 45], which might be one of the reasons for the generation of extrusion surface defects, such as die line and pick-up. At this stage, an in-

continuous tribo-layer might be visible on the die land, and the so-called transition zone between the slipping and sticking zone may be observed, as shown in Figure 6 (b) and (c) [11]. According to [6], the transition zone is normally observed when extruding with low die temperatures, and this region is composed of a sportlike aluminium deposit.

Coalescence of adhesive junctions. At the die entrance, where a high contact pressure is achieved, the real contact area is maximized, thus the number of adhesive junctions is significantly increased and they are close to each other, thus tend to coalesce with each other. Moreover, a great amount of workpiece material may transfer from the extrudates to the bearing surface of the die, due to the strong adhesive bonding. Therefore there exists a great chance for the adhesive junctions within a large area to coalesce with each other and thus the adhesive junctions can be observed by the naked eye. At this stage, a continuous tribo-layer, *i.e.* the so-called adhesive zones, can be observed on the bearing surface. However, after extrusion, the inlet of the bearing is heavily worn and a continuous tribo-layer may not be observed, as shown in Figure 6 (a) and (b) [11]. This is probably due to the high rate of material renewal at the inlet of the bearing channel [34].

In this research, the strong adhesive friction generated from pure metal contact is modelled, and the strength of adhesive junctions is considered to be determined by two factors, namely, the rate of atomic interaction and the strength of adhesive joints (Equation 6). The interaction rate at atomic level increases with increasing temperature, which can be modeled by using an Arrhenius type equation [46] (Equation 7). The bonding strength decreases with increasing temperature, due to the decreasing strength of

adhesive joints with increasing temperatures, and the bonding strength drops to zero at the melting temperature of AA7475 (Equation 6). The friction stresses obtained from short sliding distance ball-on-disc tests shown in Figure 5, were used to determine the constants of the model. Table 2 lists the determined material constants. As can be seen from Figure 7, a good agreement between the model and experimental results was obtained.

$$f(T) = f_0 D\left(1 - \frac{T}{T_m}\right)^{\eta} \tag{6}$$

$$D = D_0 \cdot \exp\left(-\frac{Q_D}{RT}\right) \tag{7}$$

where $f(T)$ is temperature dependant bonding strength or friction stress in a unit area;

f_0 is the mean adhesive strength at room temperature (300 K) in a unit area;

D is the inter-diffusion coefficient at elevated temperatures;

T is the mean contact temperature;

T_m is the melting temperature of the workpiece material;

Q_D is the activation energy;

R is the universal gas constant;

D_0 and η are constants;

Table 2 Material constants of the ASFM for hot AA7475 and H11 steel

$f_0 (MPa)$	$T_m\ (K)$	$Q_D (J/mol)$	$R (J/K/mol)$	D_0	η
378	811	2400	8.314	3.62	0.7

In this model, the bonding strength is determined by the combined effects of atomic interaction and the strength of adhesive joints, with the assumption that pure metal contact is taking place. At high temperatures ($0.5T_m < T \le T_m$), the bonding strength decreases with increasing temperature, because the decreased strength of adhesive joints plays a dominant role, although the atoms are highly active and atomic interactions are more intensive at elevated temperatures. Therefore a decreased adhesive strength with the increasing temperature can be observed, which is consistent with other research results [31, 47].

5. Verification of the friction model

5.1. Experiment and FE simulation details

The double action extrusion (DAE) tests [17, 18], highlighting the friction in the bearing channel of the extrusion dies, were used to verify the proposed friction model. Figure 8 (a) shows the principle of DAE, which was conducted on a Gleeble 3800 material thermo-mechanical simulator and Figure 8 (b) shows the experimental setup. In the DAE tests, a combination of 2 and 6 mm bearing dies with a choke angle of 15’ was employed to maximize the effect of friction in the bearing channels [48]. It has been found that the DAE is highly sensitive to the friction in the bearing regions, in terms of extrudate

lengths and steady-state extrusion load. Figure 8 (c) shows the typical test results of DAE and the length differences were caused by the different friction forces generated from the two different extrusion dies, with different bearing lengths used. Figure 8 (d) shows the typical extrusion forces of DAE tests at different testing temperatures. As can be seen from Figure 8 (d), the extrusion forces decreased with increasing temperature, mainly due to the decreased strength of the workpiece material with rising temperature. The extrusion forces at these temperatures showed a similar trend, *i.e.* a small plateau at the very early stage, followed by a sharp increase in extrusion force and then a gentle decrease as the process proceeded further. The small plateau corresponds to the initiation of extrusion toward both of the die (upsetting) and the sharp force increase corresponds to breakthrough. In DAE, there is no friction between the billet and container and therefore the extrusion force in the steady state reflects a dynamic balance between the deformation force of the workpiece material and the friction forces in the two dies which are governed by temperature.

DEFORM 3D version 6.1 was used to simulate the DAE process. Figure 9 shows the FEM model of the DAE. All the objects in the model were meshed with tetrahedral elements. The flow stress data of AA7475 aluminium alloy were determined from hot compression tests on a Gleeble 3800 material thermomechanical simulator, under a wide range of strain rate (0.01-180 s^{-1}), with the data at high strain rates corrected for deformational heating [49]. The ASFM were implemented into DEFORM 3D V6.1 via user defined subroutine. In DEFORM, to avoid the overestimation of friction stress, the friction stress calculated from a friction model is compared with the shear flow stress of

the deformed material at each iteration step and automatically changed to the shear flow stress, if the calculated friction stress is greater than the shear flow stress.

5.2. Friction model verification by DAE tests

Figures 10-12 show the comparisons in the lengths of the extrudates between the DAE experiments and FEM simulations. In these figures, the FEM predictions of the extrudate lengths with the use of ASFM are superimposed onto the experimental data. At different temperatures, the extrudates from the 2 mm bearing are longer than those from the 6 mm bearing. The length difference of the extrudates increases with increasing ram displacement. At the initial stage of the DAE, the workpiece is extruded at the same extrusion speed in both of the dies. As the ram displacement increases, the friction force increases at the same rate in the two dies due to the increasing contact area. When the extrudate lengths are greater than 2 mm, the contact area in the 2 mm bearing cannot be further increased. Thus a constant friction force is achieved in the 2 mm bearing. In the 6 mm bearing, however, the contact area is further increased due to the increase of the extrudate length, thus the friction force increases and the material flow in the 6 mm bearing is restricted, consequently the extrusion speed slows down. In the meanwhile, the rate-dependant property of the billet material becomes explicit. In the severe deformation zone of the 2 mm bearing, the material is enhanced due to the higher extrusion speed and becomes more difficult to be deformed. In the severe deformation zone of the 6 mm bearing, however, the low extrusion speed results in lower material strength, thus the material becomes easier to be extruded. As such, a dynamic balance is maintained

throughout the DAE process: the friction between extrudates and bearing surfaces increases the length difference of the extrudates; on the other hand, the effect of rate-dependent material behaviour decreases the length difference. As can be seen from the figures, at these three extrusion temperatures, the implementation of the ASFM has led to highly accurate predictions, in terms of the extrudate lengths, suggesting that the ASFM is able to represent the friction conditions at the extrudate/bearing interface.

Figure 13 shows the FEM predicted and experimentally obtained steady-state extrusion forces at different extrusion temperatures. The extrusion force decreases with increasing temperature due to the material softening at higher temperatures. It can be seen that predictions from the ASFM show the same trend as the experimental results in terms of the temperature effect on the extrusion force. The predictions from the ASFM achieved a very good agreement with experimental results.

6. Conclusions

In this study, a physically based friction model (ASFM) was developed and implemented into the FE simulation of hot aluminium extrusion process. Good agreements between the FE simulations and experiments were achieved, in terms of extrudate length and steady state extrusion force, indicating that ball-on-disc tests can represent the friction conditions in the bearing channel of the hot aluminium extrusion dies. The tribological conditions of hot aluminium extrusion process cannot be reflected by using one single friction testing technique, and a combination of different friction testing techniques

should be used. For the bearing channel of the hot aluminium extrusion dies, the short sliding distance ball-on-disc test is recommended, with the disc made from the workpiece material and ball made from the die material. Strong adhesive friction occurs between the hot aluminium and steel and the nature of friction in the bearing channel can be summarized as a pressure dependant process, *i.e.* formation of isolated adhesive junctions, adhesive junctions growth and coalescence of adhesive junctions.

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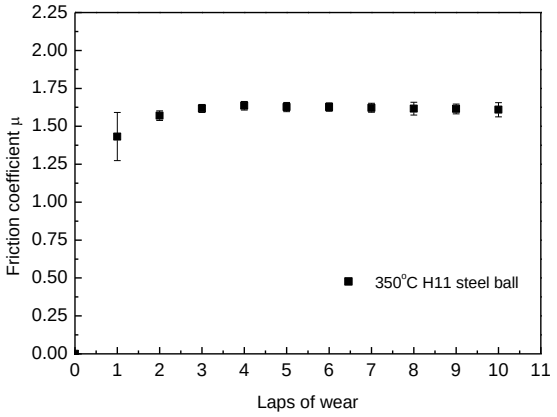
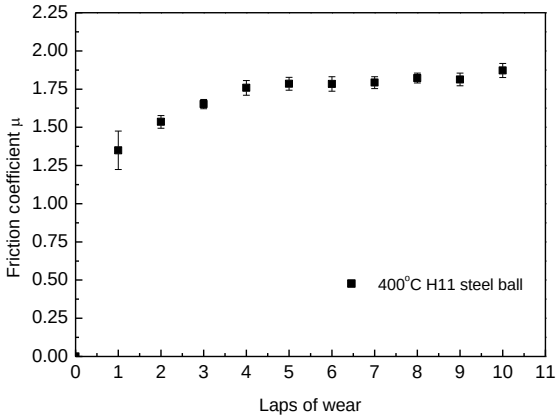


(a)



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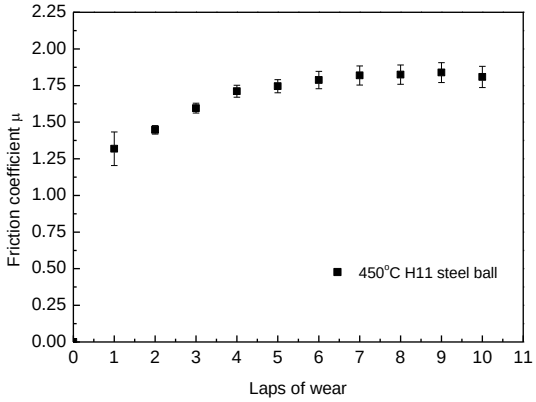

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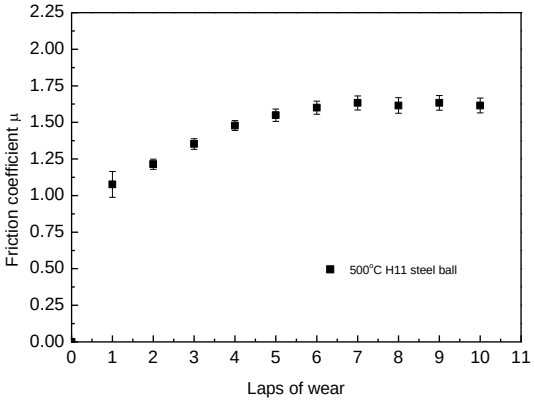


(d)

Figure 1 Evolution of the friction coefficient with increasing sliding distance at different temperatures.

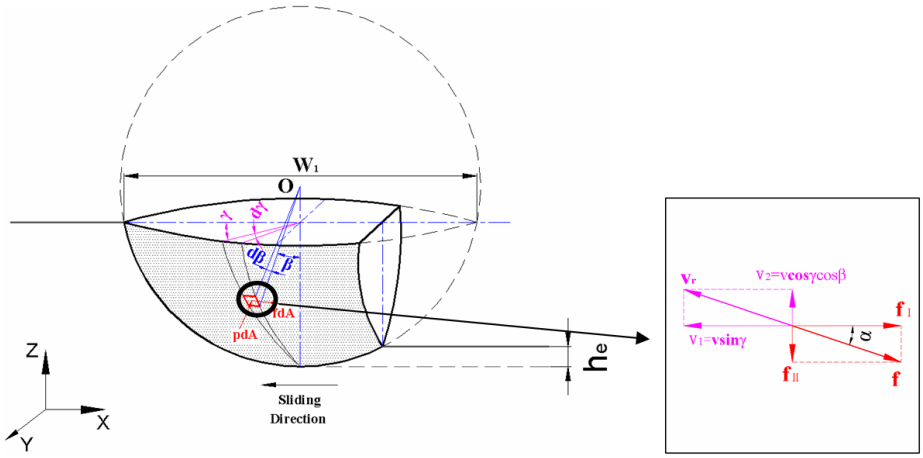
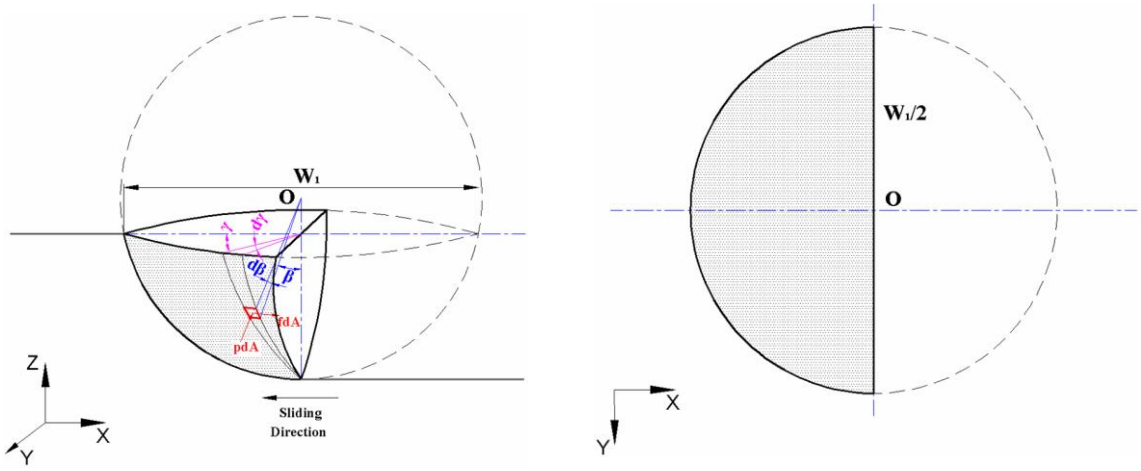
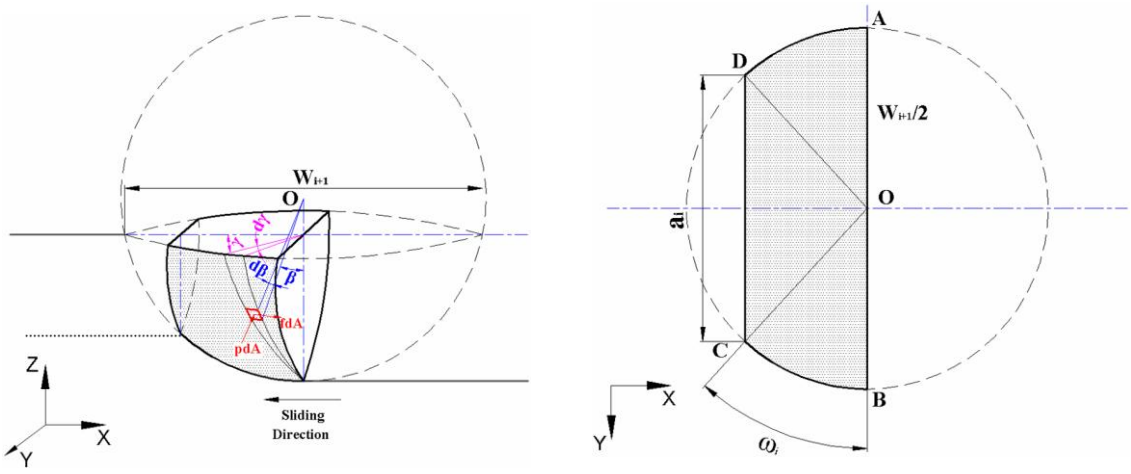


Figure 2 Close-up view of the friction force and velocity on an elemental area



(a) (b)

Figure 3 Schematic drawing of the contact interface in the first lap of wear during ball-on-disc testing



(a) (b)

Figure 4 Schematic drawing of the contact interface in an arbitrary $(i+1)th$ lap of wear during ball-on-disc testing

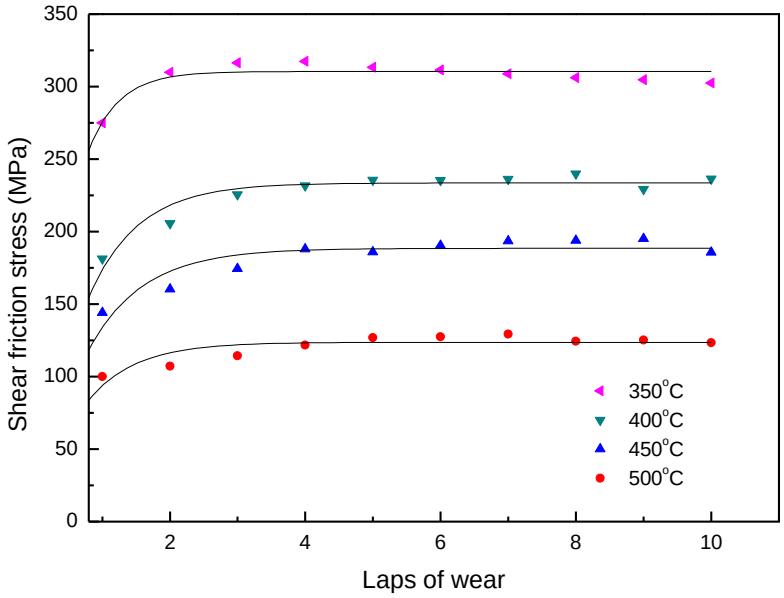


Figure 5 Evolution of the shear friction stress with sliding distance.

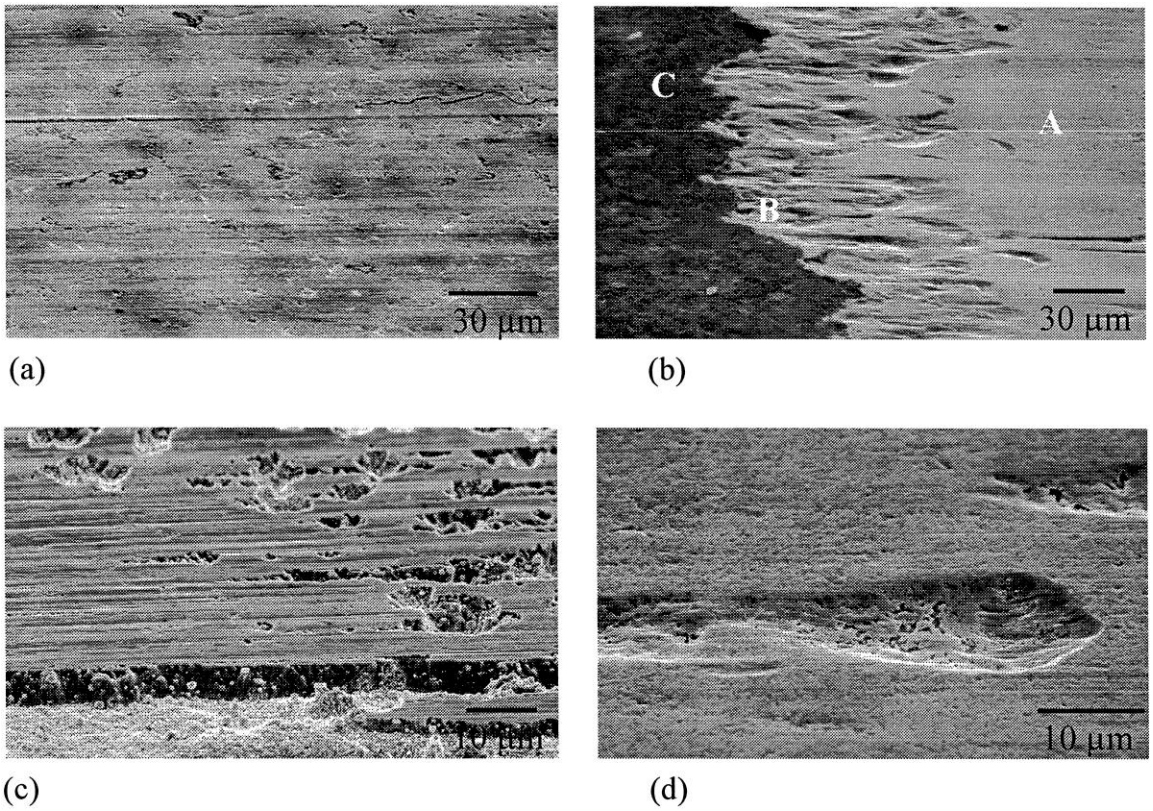


Figure 6 (a) Exposed steel substrate in the sticking zone at A in (b). (b) A transition zone, at B in (b), observed between slipping zone at C in (b), and sticking zone at A in (b). (c) Partly disrupted compound layer in the transition zone at B in (b). (d) Isolated local wear pit in the slipping zone observed at C in (b) [11]

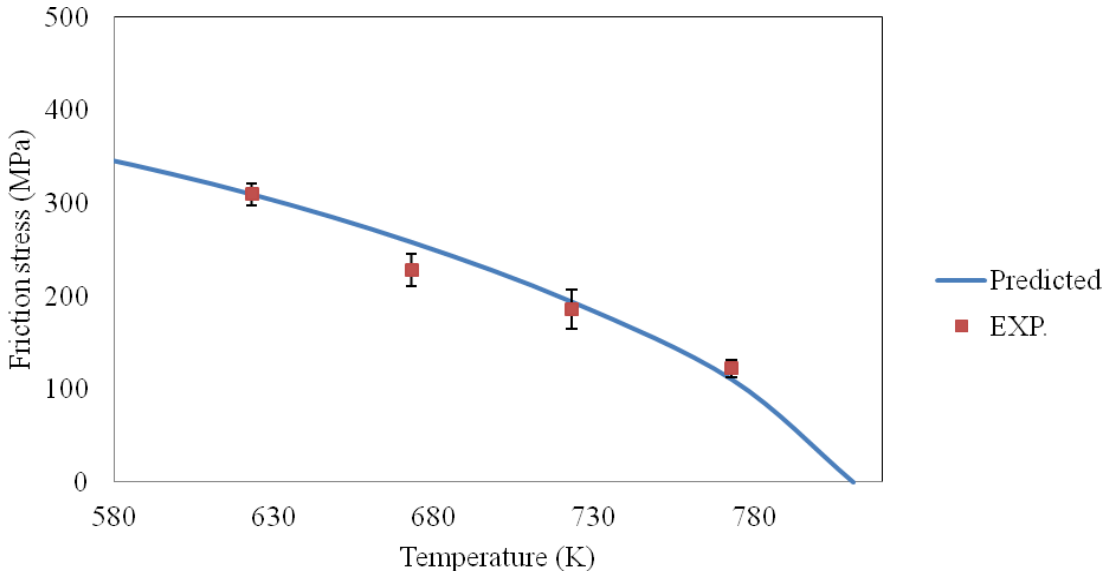
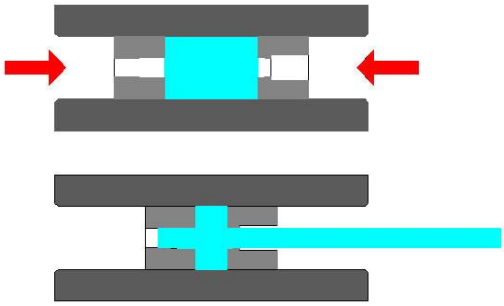
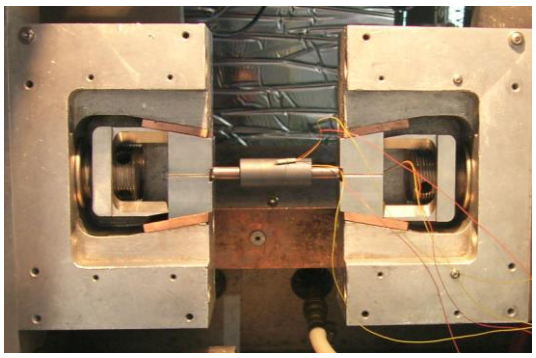


Figure 7 Evolution of friction stress between AA7475 and H11 steel at different temperatures

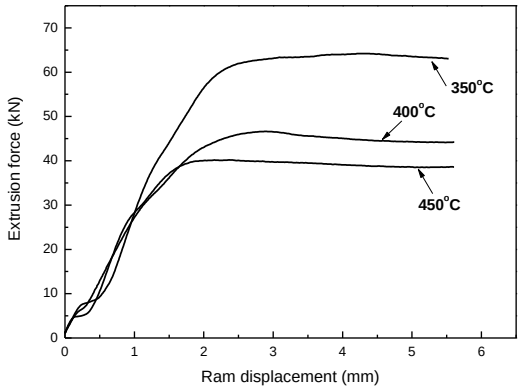


(a)



(b)

(c)



(d)

Figure 8 The (a) principle, (b) experimental setup and (c and d) typical test results of DAE

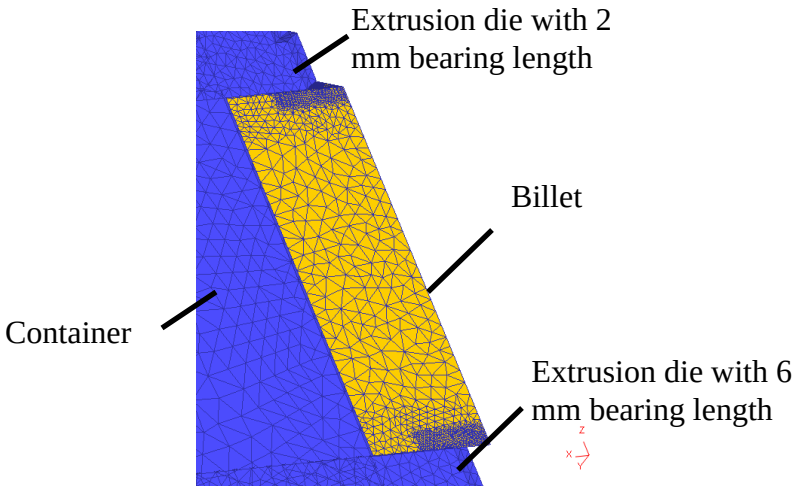


Figure 9 FE model for the DAE

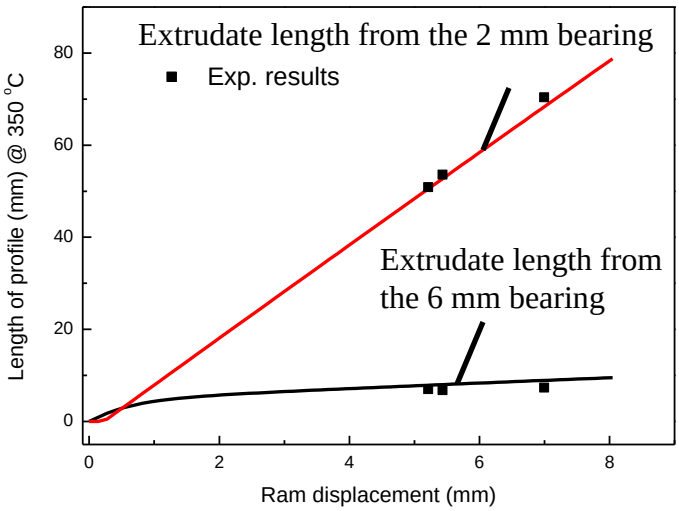


Figure 10 Comparison in the extrudate lengths from DAE at 350°C between the experiments and FEM simulations.

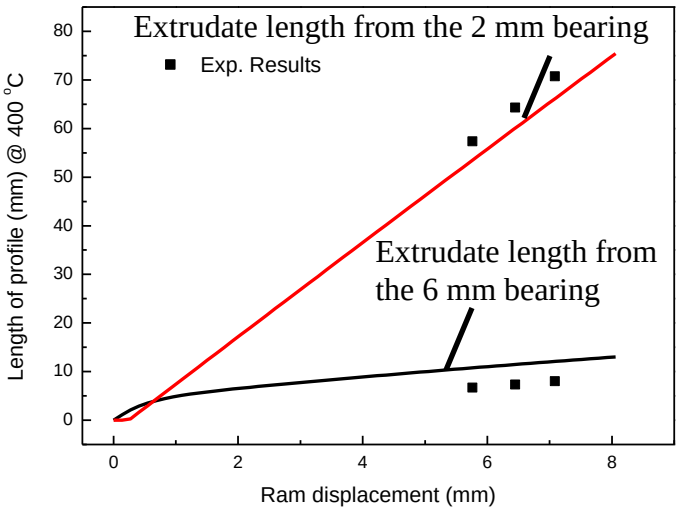


Figure 11 Comparison in the extrudate lengths from DAE at 400°C between the experiments and FEM simulations.

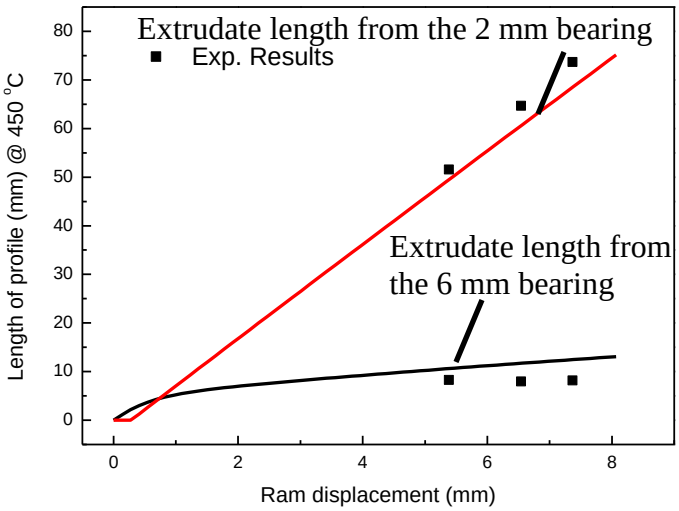


Figure 12 Comparison in the extrudate lengths from DAE at 450°C between the experiments and FEM simulations.

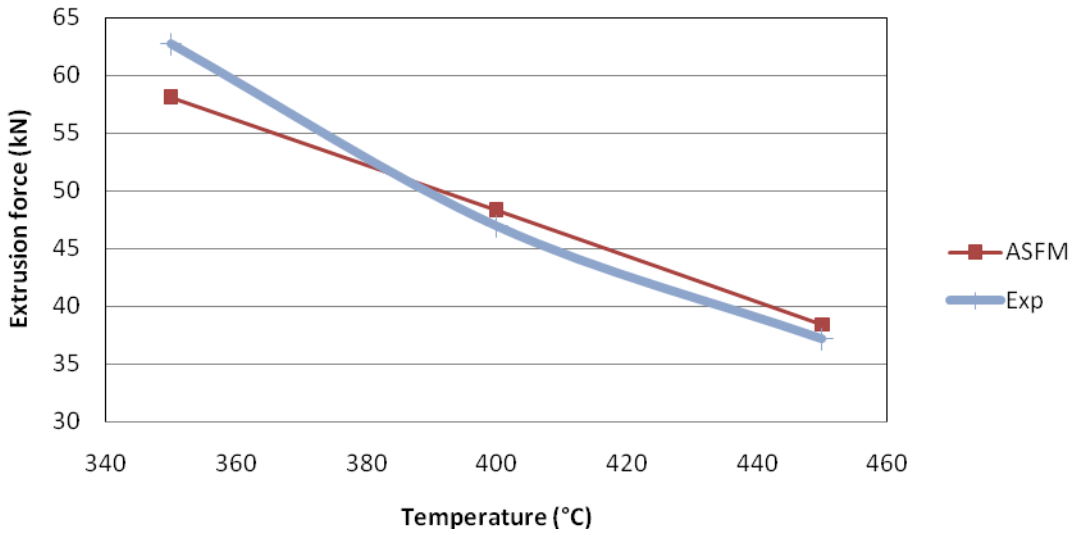


Figure 13 Steady state extrusion forces at different extrusion temperatures