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A STUDY ON HOT WORKING AND FRICTIONAL BEHAVIOUR OF 6082 ALUMINIUM ALLOY DURING HOT FORMING USING PRESSURE TESTS AND FINITE ELEMENT SIMULATION

Summary

Numerous variables affect the process of metal forming in which friction is the most important variable. Friction has effect on the material flow and the force required for metal forming. It is necessary to have the exact amount of the coefficient of friction in order to determine the amount and effect of the friction. In this paper, the ring compression test is used to determine the shear friction coefficient in hot working processes and the pressure test of cylindrical specimens is utilized to specify the hot working behaviour of 6082 aluminium alloy. The variation of the internal diameter of the ring during deformation is dependent of the shear friction coefficient, so it can be a criterion for determining this coefficient. Graphite, Teflon and Mica sheets are chosen as lubricants. Friction calibration curves are plotted using the finite element simulation to compare these results with the results obtained from the tests. Shear coefficients are obtained for every lubrication case. The results demonstrate that the best lubrication case of the hot working of 6082 aluminium alloy is achieved when the shear friction coefficient of m=0.32 is used whereas the value of m=0.69 is obtained in the case when no lubricant is used.

Key words: friction, hot working, ring pressure test, 6082 aluminium alloy

1. Introduction

The aim of accurate metal forming is to produce parts close to final dimensions without any defect, with the least waste of material and at lowest tool costs. To achieve this aim, it is essential to have a correct understanding of material properties, the process parameters and the behaviour between the workpiece and the die, i.e. friction [1]. Friction plays a major role in the whole process of forming and its role must be taken into account during the design process. The pattern of material flow and the effects exerted in the produced parts are strongly controlled under the effect of frictional conditions. Correct determination of the friction coefficient and choosing a proper test method to understand the friction phenomenon in the contact area of the workpiece and the die under different lubrication conditions are important. Among all common methods to measure the friction coefficient, the ring compression test is the most frequently used one. This method was first used by Kunogi [2] and was later developed and presented by Male and Cockcroft [3]. This method uses dimensional variations of the test specimen to achieve the friction coefficient. The internal diameter of the ring varies in the test of ring compression. Generally, it can be said that if the internal diameter of the specimen increases during deformation, friction is low and if the internal diameter decreases during deformation, friction is high [2]. This is shown in Fig (1) [3].

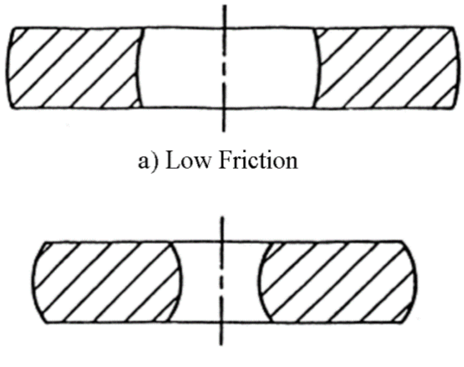


Fig. 1 Different friction conditions: a. low friction (good lubrication) b. high friction (bad lubrication)

Using this relation, the curves demonstrating the relationship between the percentage of the internal diameter of specimens and the percentage of their height decrease are shown for different values of friction. Fig (2) represents a sample curve of this kind.

After Male and Cockcroft published their paper about the friction coefficient, lots of studies were made by other researchers. In 1965, Male [5] showed that the friction coefficient μ varies with temperature change. It is shown that with an increase in temperature μ may lead to adhesive friction or may decrease due to the ring material. Male also performed a study in 1966 to find the difference in friction coefficients of metals during compression deformation at room temperature. His results showed that the friction coefficient tends to increase with an increase in the deformation rate for different materials.

Robinsion et al. [1] studied the ring compression test using experiments and finite element simulation and presented calibration curves for Plasticine in different lubrication conditions. Felder et al. [6] performed the ring compression test on steel at the temperature of 1,250 degrees centigrade. The results demonstrated that the speed of shaping tools has an important effect on friction and revealed that friction decreases with an increase in speed. Sofuoglu et al. [7] achieved friction calibration curves using finite element simulation and physical modelling and showed that material parameters and test conditions affect greatly these curves in both cases. Male et al. [8] performed a study in order to see which mode of friction

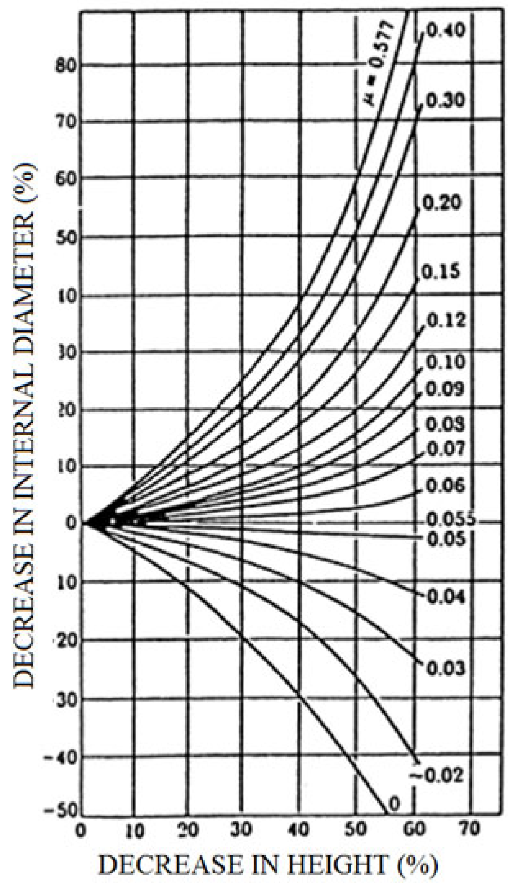


Fig. 2 Curves of friction calibration theory for a ring with the ratio of 6:3:2 [4]

presents a more realistic description of friction conditions during the shaping process. He demonstrated that m as a numeric index to define friction condition in the offsetting process is more realistic than μ. It was also determined that the ring compression test is an accurate method to determine the real stress-strain curve in the shaping operation. Shariari et al. [9] determined the shear friction coefficient in hot shaping of the superalloy Nimonic 115 with different lubricants using physical observations and finite element simulations. Zhu et al. [10] determined the shear friction coefficient of the titanium alloy Ti-6Al-4V in the hot shaping process by means of the ring compression test during a physical experiment and finite element simulation. In this study, the heat transfer coefficient of lubricants is considered as a parameter in plotting friction calibration curves. Also, the process of experimental and finite element modelling is presented to find the calibration curves of the 6082 aluminium alloy using different lubricants. The results of the ring compression test are analyzed by using experimental and finite element methods for considering the effect of different lubricants on the calibration curves.

2. Friction Models

There are numerous theoretical methods for determining calibration curves of the ring compression test. These methods are based on slab analysis, upper bound method and finite element method.

It should be noted that there are various theoretical models to study friction, three of which are here explained briefly.

2.1 Coulomb Friction Model

The Coulomb friction model, based on the Amonton law, is a friction model which is usually used in computer software. It is expressed as follows:

$$\tau = \mu \cdot p \tag{1}$$

where τ is the shear friction coefficient, μ is the friction coefficient at the common surface of the workpiece and the die and p is the applied normal force. This law is valid for the elastic mode as well as in the case of a shaping process with low pressure [11, 12].

2.2 Shear Friction Model

This model is used in the case of high pressure existing at the common surface of the workpiece and the die and is as follows [12]:

$$\tau = \mathrm{m} \cdot k \tag{2}$$

Where m is the shear friction which ranges from m=0, for zero friction surface, to m=1, for adhesive friction, and k is the shear yield limit.

Based on Avitzur [13], the mean Coulomb friction coefficient, μ, can be used to measure m as in equation (3):

$$k = \frac{\sigma_0}{\sqrt{3}} \tag{3}$$

$$\mu = \frac{\mathrm{m}}{\sqrt{3}}\left(\frac{\sigma_0}{P_{\text{ave}}}\right) \tag{4}$$

where σ_0 is the yield limit, P_{ave} is the mean pressure at the surface, k is the shear yield limit and m is the shear friction.

3.2 General Friction Model

This model is a combination of the previous models and is presented as follows:

$$\tau = \mathrm{f} \propto k \tag{5}$$

The friction coefficient μ or the shear friction factor (m and f) are considered as dimensionless numbers for homology in the frictional conditions. Using analytical methods, various sets of calibration curves are achieved to determine m or f for a special lubricant. The shape of these curves is affected by the primary geometry of the ring used in the analysis. In this study, the hot offsetting of the 6082 aluminium alloy is accomplished with high pressure at the common surface. Therefore, the constant friction model is considered as friction model at the contact surface. The major aim in this study is to find a proper lubricant and friction conditions for hot shaping with the 6082 aluminium alloy.

3. Experiments

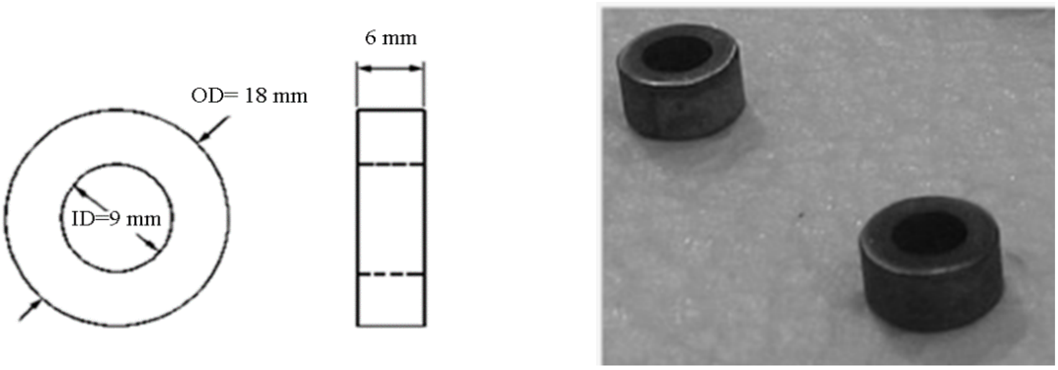
3.1 Used Materials and Preparing Specimens

The material that is used in the study is 6082 aluminium alloy. In recent years, this alloy is mostly used due to superior final properties, good weldability, soldering and machining capability, resistance to corrosion and good shapeability. The chemical composition of the used specimens of the 6082 aluminium alloy is presented in Table (1).

Table 1 Chemical composition of 6082 aluminium alloy specimens

Al	Zn	Cr	Mg	Ti	Mn	Cu	Fe	Si	Element
97.3	0.05	0.01	1.0	0.02	0.06	0.06	0.3	1.1	Percentage

The specimens for the hot pressure test were made by machining bars made of the 6082 aluminium alloy. The bars were drilled with the ratio of 6:3:2, which mean that the outer diameter was 18 mm, the inner diameter 9 mm and the height 6 mm. The dimensions of the specimens provided for the test of ring compression are shown in Fig (3).



a. Plot of ring compression specimens

b. Ring specimens for pressure test

Fig. 3 Ring compression test specimens

3.2 Test Procedure

In this study, a Roell/type 250 kN Zwick computer-controlled, servo-screw device is utilized to perform the hot pressure test of the ring. This device can be used for the simulation of an industrial process in both thermal and mechanical cases in a wide range of hot deformation conditions. During the ring pressure test, the speed of the lower die varies with press ram displacement; therefore, there will be a variable strain rate during deformation. The

Fig. 4 Pressure test device and the furnace

press ram speed in equation (6) is chosen so as to have a constant mean strain rate of $0.5s^{-1}$ during deformation. Thus, the hot pressure test on the ring is performed at the strain rate of $0.5s^{-1}$ and at the constant temperature of 450 degrees centigrade. The specimens' deformation is isothermal. As it is shown in Fig (4), the furnace includes completely the die and the specimens and its temperature is kept constant. This process is shown in Fig (5).

The test is done with three kinds of lubricants:

1) Teflon
2) Mica sheets
3) Graphite

$$\dot{\varepsilon} = \frac{V \cdot \varepsilon}{2 \cdot \Delta h} \tag{6}$$

1- Heating the specimens
2- Keeping the specimens at this temperature
3- Cooling to the test temperature
4- Test
5- Quenched rapidly after test

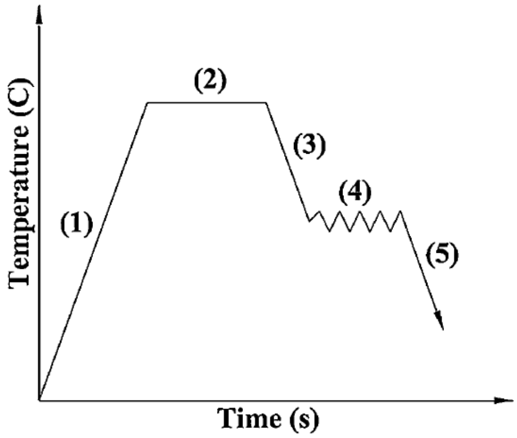


Fig. 5 Diagram of hot pressure test

The lubricant covers the whole surface of the specimens, except for the Mica lubricant, which covers only the surface that is in contact with the die. The ring test with 12 specimens was carried out with different height decreases (22%, 36% and 63%).

3.2.1 Material Properties

During deformation of the workpiece, strain, strain rate and temperature have great influence on the material flow and behaviour, which can be explained as follows:

$$\sigma = \sigma\left(\varepsilon, \dot{\varepsilon}, T\right) \tag{7}$$

To achieve mechanical properties of the 6082 aluminium alloy compression tests have been performed. Pressure tests were performed on cylinders of 10 mm in diameter and 15 mm in height. In this test, the specimen was compressed to the strain of 0.75. Temperature rate of hot forging was considered 350 to 500 degrees centigrade with a temperature interval of 50 degrees centigrade and the strain rates of 0.005, 0.05 and 0.5 (s^{-1}) for each temperature. Temperature range and strain rates were chosen regarding the range that will be encountered during forging. Each of the tests was repeated 2 to 3 times to ensure the accuracy and repeatability. Fig (6) demonstrates the cylinder pressure test.

Fig. 6 Cylinder pressure test specimen

Fig (7) shows the real strain-stress curve for the specimens at four temperatures of 350, 400, 450 and 500 degrees centigrade.

3.3 Measurement of Specimens Dimensions

Accuracy of the measurement of specimen dimensions before and after the test has a great impact on test results. The height and the inner diameter of the specimens were measured by using a micrometer. Due to the existing friction, the state of bulging occurs in the specimens. To measure the inner diameter of the specimens more accurately, the specimens were cut out from the centre and the inner diameter was measured for high, middle and low heights. The average of the high, middle and low heights is averaged again and the inner diameter is achieved.

4. Finite Element Simulation

The principle of the FEM is 'divide and conquer'. First, one must divide the problem into little subproblems that are easy to formulate and after the entire problem has been divided and formulated, the subproblems must all be carefully combined and then solved. The problem is divided through a process called meshing. There is a grid that has been superimposed on the figure of the work-piece. This grid is the mesh that represents the body being deformed. Each rectangle represents a portion of material and is called an element and the intersection of any grid lines is called a node. The element corresponds to a region of the material and the node corresponds to a discrete point in space. The solution to the equations are velocities at each node, which are shown as vector arrows. In addition, there are boundary conditions that should be specified in order to provide a unique solution to the problem. After all the equations for the elements have been written out, they must be combined into a single set of simultaneous equations. At the end, by using the Newton-Raphson iteration method, the updated velocity can be solved by solving a simultaneous set of equations.

The general FEM solution process is given as follows [14]:

a) Input geometry & processing conditions.
b) Generate the initial guess of the velocity field single step.
c) Calculate the element behaviour based on the velocity field & other variables (strain, temp, etc).
d) Calculate the force boundary conditions based on the velocity field.
e) Assemble and solve the matrix equation.
f) Calculate the error.
g) If the error is too large, apply a correction to the velocity field and go to "c". Otherwise, continue to step "i".
h) Update the geometry.
i) Calculate the temperature change for this step.
j) Calculate the new press velocity if necessary.
k) If stopping criteria has been reached, END. Otherwise, go to "c" and repeat the process.

Friction calibration curves are achieved through the use of finite element simulation. The information of the used materials is shown in Fig (7) as a function of temperature. This analysis is done by using the DEFORM 3D finite element software to measure dimension variations of the ring's inner diameter due to the height decrease under different friction conditions.

DEFORM is an engineering software that enables designers to analyze metal forming and other forming process on the computer. Process simulation using DEFORM has been instrumental in cost, quality and delivery improvements at leading companies for two decades. DEFORM has proven itself to be extremely effective in a wide range of research and industrial applications.

A comparison study between the finite element simulation and the test is possible for the ring pressure test. The shear friction coefficient m at the contact area of the workpiece and the die is achieved from stress tensors using the constant friction law.

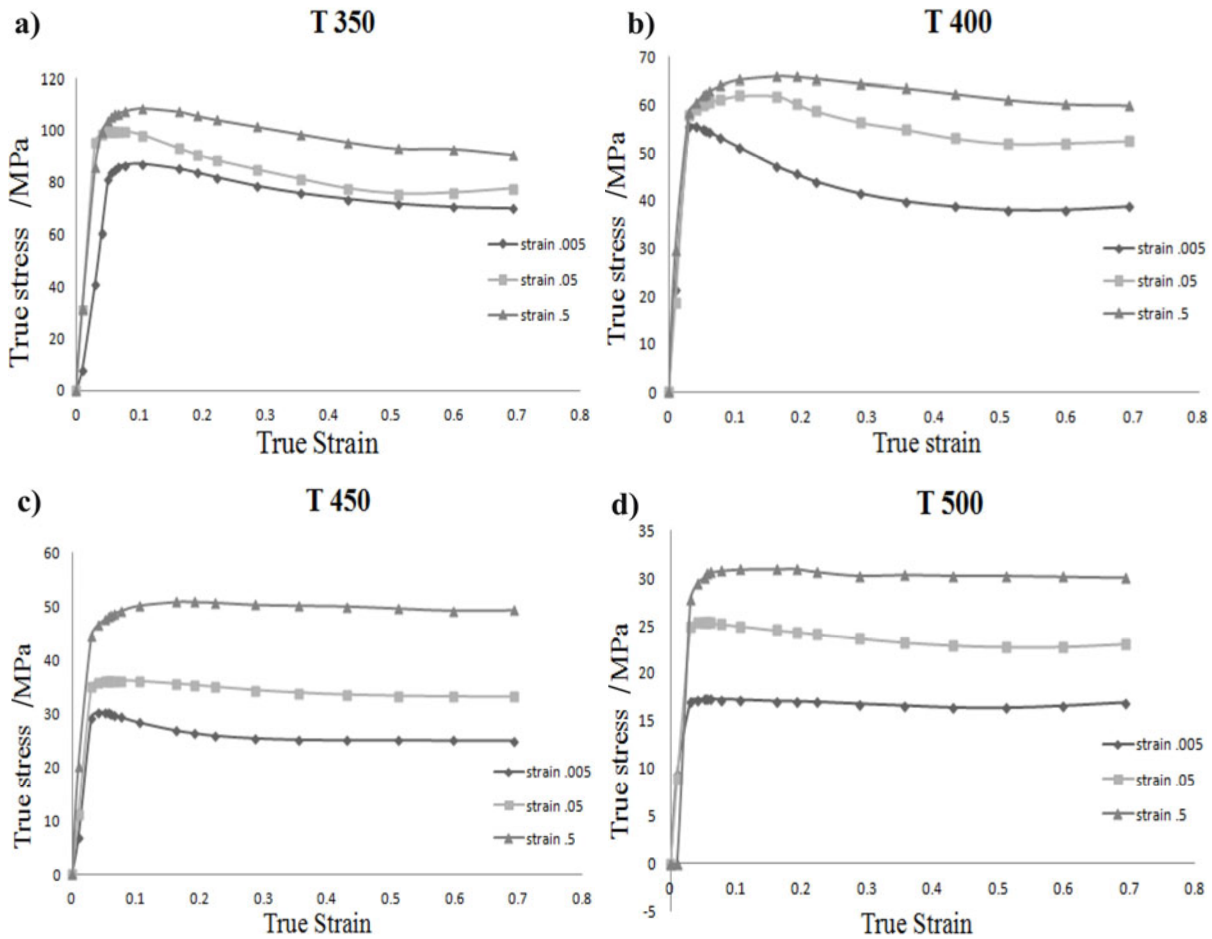
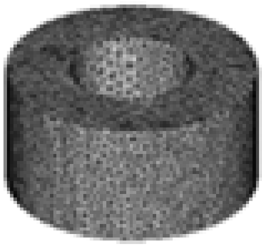


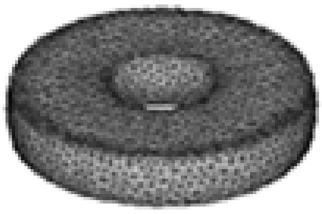
Fig. 7 Stress-strain curve at a) 350 to d) 500 degrees of centigrade

In the finite element modelling, the high and the low dies are chosen solid. Finite element simulations were done with 9 shear friction coefficients from m=0 to m=1 and the calibration curves were plotted using the simulation results. To obtain the shear friction coefficient of the lubricants, the dimension variations of the experimental and the simulation results must be compared to specify the simulation curve nearest to the experimental curve to determine the existing friction factor of each lubricant.

Fig (8) shows the deformation process in the ring compression simulation. During simulations, the specimens are divided into 29255 elements and 7183 nodes.



a. ring without deformation



b. deformed ring

Fig. 8 Finite element simulation of the ring compression test

5. Discussion

The rings deformed during the test are demonstrated for every lubricant in Fig (9).

a. Dry

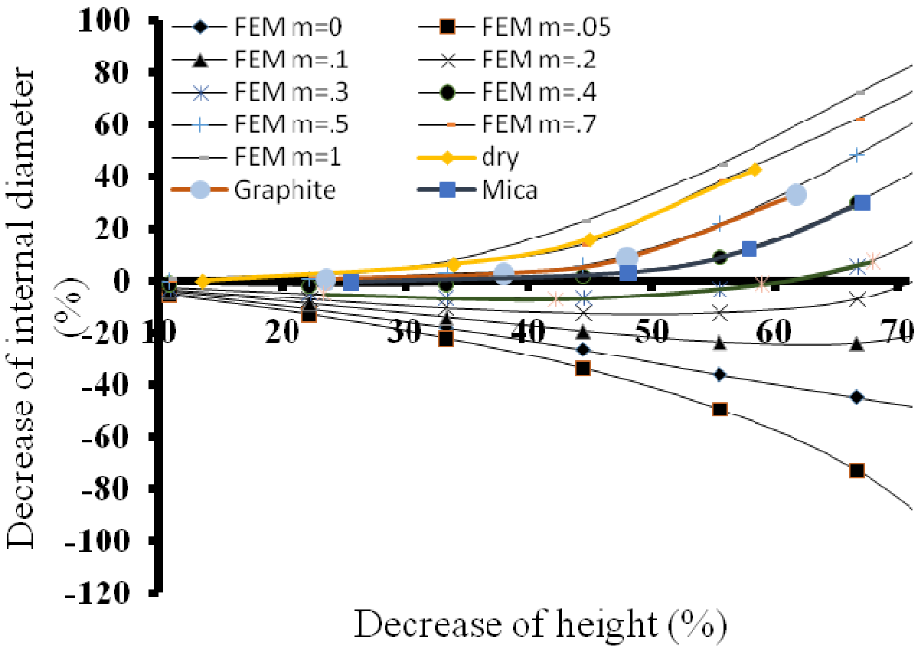
b. Graphite

c. Mica sheet

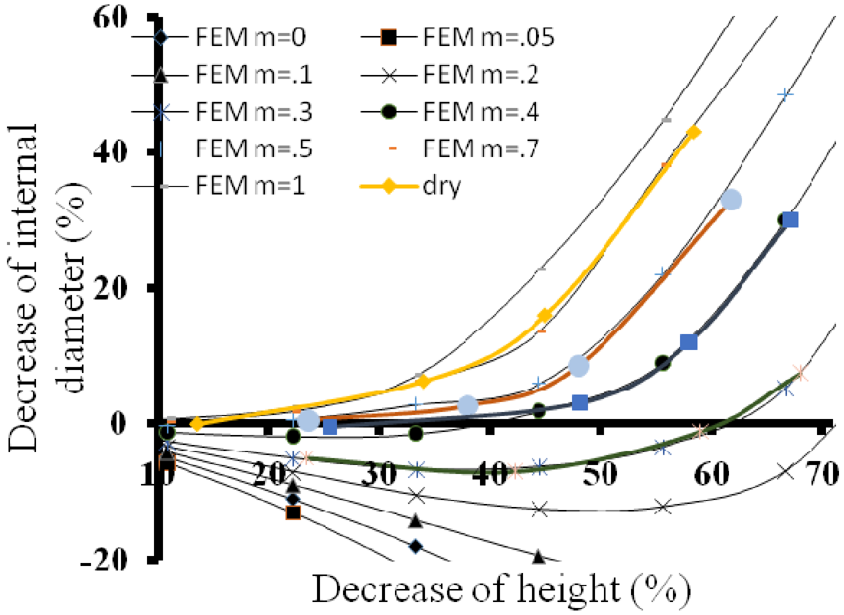
d. Teflon

Fig. 9 Compressed specimens lubricated with various lubricants

Fig (10.a) and Fig (10.b) show the calibration curves achieved through the use of the finite element simulation and the experimental ring pressure test with different lubricants. It is clear from the tests of the hot pressure ring that different lubricants application produces various geometric dimensions in the ring. For instance, the inner diameter increase is caused by using lubricants with low shear friction such as Teflon while the inner diameter decrease results from the use of lubricants such as Graphite which have high shear friction.



a. Friction calibration curve



b. Enlarged calibration curve

Fig. 10 Friction calibration curve

The analysis of the calibration curves gives the shear coefficient of m=0.32 for Teflon and a higher shear coefficient of m=0.4 for Mica. Graphite has the lowest ability of lubrication due to having the highest shear friction of m=0.48 among lubricants. The state of dry material (without a lubricant) has the shear friction coefficient of m=0.69. Therefore, Teflon used in the ring compression test of the 6082 aluminium alloy has the best lubrication ability at the temperature of 450 degrees centigrade. The mean of m for different lubrication cases is shown in Table (2).

Table 2 Shear friction coefficient mean for different lubricants

	Teflon	Mika Sheet	Graphite	Dry
Shear friction coefficient	0.32	0.40	0.48	0.69

6. Conclusion

The hot working behaviour and friction conditions are analyzed in the hot forging process of the 6082 aluminium alloy. Graphite, Teflon and Mica sheets were used as lubricants in this test. Some tests were performed without a lubricant for result comparison. The hot working behaviour was studied at four temperatures and real stress-strain curves were plotted for this alloy. Calibration curves were achieved by using the finite element simulation and then experimental results were incorporated. The shear friction coefficient was obtained for every deformation and lubricant. The results show that the best lubricant for the hot forging of this alloy is Teflon with the shear friction coefficient of m=0.32. Hot forging without a lubricant has a shear friction coefficient of m=0.69 for the alloy.

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