Evaluation of friction coefficient by experiment and FEM for medium carbon alloy steel in hot forging process

Md. Israr Equbal[1], P. Talukdar[2], R.K. Ohdar[3], Irfan Samad Wani[4]

[1]Equbal M. I. Department of Forge Technology, National Institute of Foundry and Forge Technology, Ranchi, India -834003
Email: israr_equbal@yahoo.co.in
[2]Talukdar P. Department of Forge Technology, National Institute of Foundry and Forge Technology, Ranchi, India -834003
Email: pinaki.t@rediffmail.com
[3]Ohdar R. K., Department of Forge Technology, National Institute of Foundry and Forge Technology, Ranchi, India -834003
Email: rkohdar@yahoo.com
[4]Wani I.S., Department of Material Science and Engineering, National Institute of Foundry and Forge Technology, Ranchi, India -834003
Email: irfan.s.wani@gmail.com

Abstract: The friction at die–workpiece interface is an important parameter in metal forming processes that influence on metal flow behavior, filling of metal in die, quality of surface fineness with contact time the surface quality etc. In this study, the lubrication behavior of DF 150 (Graphite, Water-Based) Die Lubricant has been evaluated. A series of ring compression tests were carried out to obtain friction coefficients for different composition of DF 150 in the ratio 1:20, 1:30, and 1:40 with water. The geometry of the ring compression test specimen has been prepared with respect to established international standard. It has observed that the increase in the ratio of water to the lubricant increases the frictional coefficient between the die and the specimen or workpiece. A Finite Element simulation has been adapted to validate the results after evaluation through material deformation, geometric configuration curves. The result of simulation has agreed excellently with experimentally evaluated results.

Keywords: *Friction, Ring compression, Finite element, Simulation.*

1 INTRODUCTION

It is well known that friction at the interface of die/workpiece plays an important role in the overall integrity of metal forming processes. Friction affect the deformation load, product surface quality, internal structure of the product, as well as die wear characteristics. During metalworking operations lubrication is introduced between two sliding solids by adding a gaseous, liquid, or solid lubricant in order to reduce friction and wear, and to carry away heat and debris generated during the sliding process. Lubrication processes can take many different forms, depending on the gross geometry of the contacting bodies, the roughness and texture of the sliding surfaces, the contacting load, the pressure and temperature, the rolling and sliding speeds, the environmental conditions, the physical and chemical properties of the lubricant, the material composition, and the properties of the near-surface layer [1]. To date, several methods have been developed for quantitative evaluation of friction in metal forming processes. The most accepted one for quantitative characterization of friction is to define a coefficient of friction (μ) at the die/workpiece interface, specifically, the Coulomb law of friction. Among the methods to measure the coefficient of friction, the ring compression test has gained wide acceptance in the last two decades. It was originated by Kunogi (1956) and later improved and presented in a usable way by Male and Cockcroft (1964). The methodology consists of a simple forging operation carried on a flat ring shaped specimen. When a flat ring specimen is plastically compressed between two flat platens, increasing friction results in an inward flow of the material, while decreasing friction results in an outward flow of the material as schematically shown in Fig.1. For a given percentage of height reduction during compression tests, the corresponding measurement of the internal diameter of the test specimen provides a quantitative knowledge of the magnitude of the prevailing friction coefficient at the die/workpiece interface. If the specimen's internal diameter increases during the deformation, friction is low; if the specimen's internal diameter decreases during the deformation, the friction is high. This method has a particular advantage when applied to the study of friction at elevated temperatures. At high strain rates, there is no need to measure the force required to deform and no yield strength values are needed.

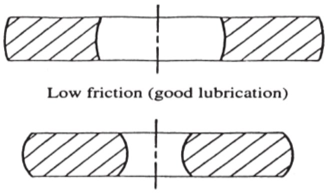


Fig.1 Effect of friction magnitude on metal flow during the ring compression test

The effects of variations in composition of DF-150 lubricant on change in internal diameter and friction coefficients are investigated as the emphasis of this paper. Meanwhile, the hot ring-compression test of AISI 1035 steel with the lubricant compositions of 1:20, 1:30 and 1:40 are conducted at the deformation temperature of 1200±50^{o}C and height reductions of 20%, 30%, 40% and 50%. Finally, the change in inner diameter of AISI 1035 alloy under above mentioned lubricant conditions are determined.

2. EXPERIMENTAL PROCEDURE

The chemical composition of as-received bars is given in Table 1. To carry out the ring compression test, the standard ring specimen has been prepared in the ratio of OD: ID: HT: 6:3:2. The ring specimens are all machined from the 100X100 RCS bar and turned to 54 mm external diameter, 27 mm internal diameter and 18 mm height, as shown in Fig. 2.

Table 1 Chemical Composition of the AISI 1035 alloy used in the present investigation (wt. %)

AISI	C	Mn	Si	S	P
1035	0.3-0.4	0.5-0.8	0.15-0.35	0.02-0.03	0.035

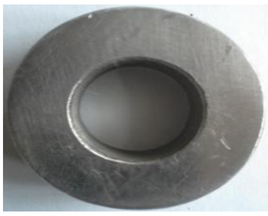


Fig.2 A sample ring specimen

DF 150 is a clean, environmentally compatible forging lubricant designed to work effectively on Forging Industries. This synthetic, organic polymer emulsion contains smoke and pollution free graphite. Petroleum oil is not used which reduces waste water treatment costs and wax is also not used eliminates buildup in the die cavity and on surrounding die and machine surfaces. The advantages of DF-150 lubricant are low porosity levels, high die temperature applications, superb surface finishes, low wastewater treatment costs, cleaner dies with no buildup and high temperature wetting to improve cycle time. The rings are compressed on the pair of dies of 150 ton hydraulic press with the compression load being kept in the range 2500±500 psi. A schematic arrangement of the press with specimen is shown in Fig. 3. During compression maximum ram speed of the press is used to maintain same strain rate. Lubricants of variable composition which has to be tested are applied on top and bottom dies with the help of spraying action. The tests have been done by using stoppers with different thickness with different reductions. We use 14.4 mm, 12.6 mm, 10.8 mm and 9 mm thickness of stoppers for 20%, 30%, 40% and 50% reduction respectively. The specimens were heated in an open hearth furnace. The tests have been carried out at constant billet temperature of 1200±50^{0}C and die temperature of 200±50^{0}C. When the compression was finished the inner diameter of the ring was measured before the specimen was removed from the platens. An average value was taken from three measurements from three arbitrary angles across the centre of the ring.

Fig.3 Schematic arrangement of the machine with specimen

3. 3D FINITE ELEMENT MODELING

The actual FEM-based analysis is carried out using FEM software package DEFORM^{TM} 3D v 6.1. It provides different methods of defining the flow stress, in which the method of tabular data format most highly recommended due to its ability to follow the true behavior of a material, where all material data were given as function of temperature, strain rate and strain [2]. FE simulations also provided detailed information on the ring deformation so that a comparative study between FE simulations and actual experiments of the ring compression tests may be possible. The same material properties were used as for the analysis of the ring compression of the specimens. In FE modeling, the top and bottom dies were represented as rigid, a total of 168457 coupled thermo-mechanical tetrahedron elements were selected to discretize the ring, with refined mesh in the inside and outside layers of the ring, where severe deformation usually occurred. 0.18 mm was used as the increment size for each step during loading to save computational time and decrease the number of remeshing so as to obtain a balance between accuracy and efficiency in computation. Two contact pairs are defined between the ring and the upper die as well as lower die, respectively. Fig. 4 shows the finite element model of the specimen.

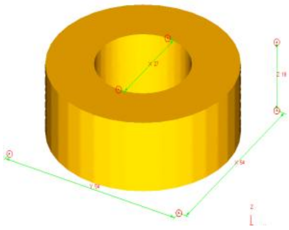


Fig.4 FE model of the ring compression test

4. RESULTS AND DISCUSSION

As per the experiment conducted, the decrease in hole diameter as a function of the amount of deformation has been determined for the specimens when compressed under the said three conditions (1:20, 1:30, 1:40). On a ring test, a ring, with outer and inner radius, is compressed. Because the inner radius is more sensitive to the friction, the inner diameter of the ring increases in the same manner as a solid section when the friction factor is low, whilst the inner diameter of the ring would decrease when the friction coefficient exceeds a critical value, as seen in Fig. 5, which shows the deformed rings for different lubricating conditions (1:20, 1:30, 1:40) at different high reductions (20%, 30%, 40% and 50%) from the experiments. Such dimensional changes of ring specimens can also be confirmed by the FE simulations. The measurements of the inner diameter and height of the specimens after hot compression tests are given in Table 2 and the calibration curve are plotted in Fig. 6.

(a)

(b)

(c)

Fig. 5: Macrographs of samples deformed at 20%, 30%, 40% and 50% height reduction (a) 1:20 (b) 1:30 and (c) 1:40 ratio.

Table 2 Results of the ring compression test

Lubricant	Δh (%)	ΔD(%) (mean)	Friction coefficient(μ)	Average (μ)
1:20	20	14.48	0.439	0.515
	30	22.18	0.428	
	40	41.07	0.635	
	50	60.37	0.558	
1:30	20	15.22	0.490	0.563
	30	21.06	0.386	
	40	42.17	0.679	
	50	66.06	0.695	
1:40	20	13.00	0.356	0.574
	30	21.44	0.400	
	40	49.48	0.712	
	50	70.96	0.827	

For each specimen, under these conditions, the coefficient of friction is calculated from the empirical relationship given by Male and Cockroft [3].

$$\mu = 0.055 \exp X \left(\frac{\Delta D}{\exp(0.044X\ \Delta h + 1.06)}\right)$$

(1)

Where μ is the coefficient of friction, ΔD the percentage decrease in internal diameter of the specimen and Δh is the percentage reduction in height due to compression.

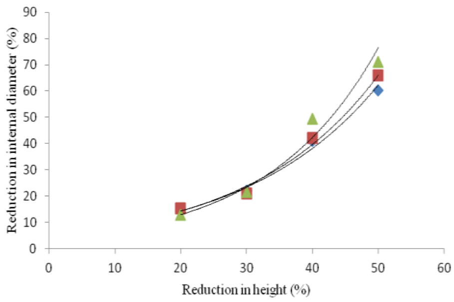


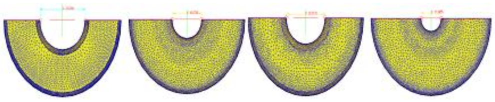
Fig. 6 Experimental friction calibration curves in terms of μ

Table 2 above gives the experimental values of friction coefficient and percentage change in internal diameter. whereas Table 3 gives the FEM simulated values of change in internal diameter of the ring specimen taking experimental value for coefficient of friction (μ) as input reference in FEM simulation.

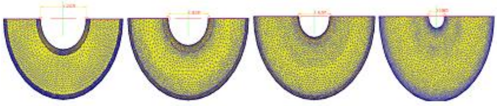
Table 3 Results of the Finite element simulations

Lubricant	Δh (%)	ΔD(mean) simulation	ΔD (mean) experimental	% ΔD change
1:20	20	22.68	23.09	1.77
	30	20.37	21.01	3.05
	40	16.07	15.91	-1.00
	50	11.30	10.70	-5.61

1:30	20	22.62	22.89	1.18
	30	20.62	21.31	3.24
	40	16.30	15.61	-4.42
	50	9.74	9.16	-6.33
1:40	20	22.93	23.49	2.38
	30	20.35	21.44	5.08
	40	16.17	15.4	-5
	50	8.23	7.93	-3.78



(a)



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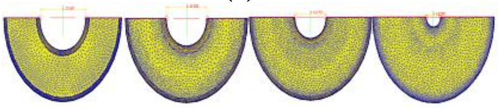

(c)

Fig.7 FEM samples deformed at 20%, 30%, 40% and 50% height reduction (a) 1:20 (b) 1:30 and (c) 1:40 ratio

The parameters and variables that affect the interfacial friction coefficient involve the material, the surface condition, the temperature, the strain rate, the geometry of the specimen and so on. The present investigation is focused on the effects of different compositions of DF-150 water based lubricant, on the friction coefficient at same condition. As mentioned above, the calibration curve used in the present study is derived assuming that the ring retains its right cylindrical shape during deformation. The present results, a compilation of which is given in Table 2, are plotted in Fig. 6. The current results show that if we increase the ratio of water to the lubricant the value of coefficient of friction will increase. That's why for the composition 1:20 the value of coefficient of friction is low in comparison to 1:30 and 1:40. Finally in order to verify the validity of the evaluated friction coefficient, the simulations of ring-compression are carried out at the friction coefficient of 0.515, 0.545 and 0.574. Fig. 7 shows the geometry change simulated by FEM and Fig. 8 shows the stress distribution during deformation. As it has shown, the profile and dimensions of specimen from simulations are very close to that from experimental tests. To test the performance of FE model to inner diameter, the simulated values from FEM are compared to experimental values. It can be seen that the relative error obtained from 1:20 and 1:30 is found to vary from -5.61% to 3.05%, -6.33% to 3.24% whereas it is in the range from -5% to 5.08% for 1:40.

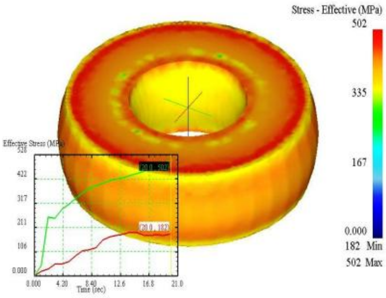

Fig.8 Stress distribution of ring after deformation

5. CONCLUSION

Ring compression tests were carried out on AISI 1035 alloy with DF 150 water based graphite lubricant applied to the two ends of the specimens. The performance of the DF 150 lubricant was analyzed. Based on experimental conditions, the FE simulations are carried out to compare and validate the results. The following conclusions have been made.

(i) The compression of flat ring-shaped specimen appears to be a very reliable method of detecting variations in friction during bulk plastic deformation. The ring test is sensitive to changes in friction at high values of friction as well as low values. This makes the test particularly suitable for studying hot working conditions, where the friction is usually rather high.

(ii) It is observed from the experimental results that 1:20 ratio has slightly lower value of friction coefficient in alloy steel sample under no varying conditions in comparison to 1:30 and 1:40 ratios.

(iii) The simulation results presented an excellent agreement with the experimental results. Thus the FE simulations and hot compression experiments provided a more effective means in the study of the friction at the die/workpiece interface.

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