Trans Indian Inst Met (2016) 69(5):1031–1041
DOI 10.1007/s12666-015-0617-6

TECHNICAL PAPER

Evaluation of Friction of Powder Metallurgical Al–4 wt% Cu Preforms by Employing Ring Compression Test and FEM in Hot Compression Test

Desalegn Wogaso Wolla[1] · M. Joseph Davidson[1] · Asit Kumar Khanra[2]

Received: 6 March 2015 / Accepted: 16 June 2015 / Published online: 8 January 2016

Abstract In this investigation, the interface friction behaviour of powder metallurgical (P/M) Al–4 wt% Cu preforms was evaluated by using ring compression tests and finite element (FE) simulations at elevated temperature. P/M Al–4 wt% Cu ring specimens of different initial relative densities, 84, 87 and 90 %, were hot compressed at temperature ranging from 300 to 500 °C under graphite lubricant and dry friction conditions. FE simulation was used to derive the calibration curves, analyze the densification behaviour and geometric changes and to evaluate the metal flow. Different interface heat transfer coefficients were used to generate friction calibration curves for graphite lubricant and dry friction conditions. The results revealed that increase in temperature or decrease in initial relative density increases the interface friction factor between tool and work piece. It was found that the influence of temperature was relatively less significant in dry friction than graphite lubricant condition. In addition, the effect of temperature, initial relative density and lubricating conditions on the densification behaviour, barreling phenomenon and metal flow was evaluated. FE simulations provided detailed and accurate results of the frictional behaviour at the tool-work piece interface, and hence employment of ring compression test with FE simulations is a reliable and feasible way to evaluate interface friction behaviour of P/M components in hot compression test.

Keywords Powder metallurgical preform · Calibration curve · Ring compression test · FE simulation · Heat transfer coefficient

1 Introduction

Pure aluminium and aluminium–copper alloys have got wide applications in major industrial areas such as automobile, aerospace, architecture and others due to their light weight, easy extrudability and high strength [1]. Particularly, aluminium–copper alloys have been intensively used for forgings, extrusions and liquefied gas storage tanks in civil transport and supersonic aircrafts. In recent years, parts have been extensively made through powder metallurgy (P/M) route owing to its rapid, economical and high volume production rate. In addition, it provides products with higher strength, wear resistance, close dimensional tolerances and design flexibility.

Friction occurs in all metal forming operations, and it plays a significant role in many bulk forming processes like forging, extrusion and rolling. In general, it has negative influences on the deformation load requirement, metal flow, product surface quality and formability of the metals. Especially, P/M components exhibit severe frictional conditions due to the presence of inherent porosity left after sintering [2]. Thus, an adequate control of friction between tool and work piece interfaces is required to get crack free products during bulk forming of P/M components.

✉ Desalegn Wogaso Wolla
desalegnnitw@gmail.com

M. Joseph Davidson
mjdavidson2001@yahoo.co.in

Asit Kumar Khanra
asit@nitw.ac.in

[1] Department of Mechanical Engineering, National Institute of Technology, Warangal, Warangal 506 004, Andhra Pradesh, India

[2] Department of Metallurgical and Materials Engineering, National Institute of Technology, Warangal, Warangal 506 004, Andhra Pradesh, India

The understanding of friction in hot metal forming processes is essential for economical production of components with desired geometry and internal structures. Therefore, the interface friction needs to be intensively investigated, controlled and understood during deformation at elevated temperature. Among the different methods developed for quantitative evaluation of friction factor, ring compression test is a widely accepted and well suitable way for forging applications over the last three decades. In addition, it is simple, inexpensive and reliable method. It was first introduced by Kunogi [3], and later improved and presented in a useful way by Male and Cockcroft [4]. Different researchers [5–7] applied ring compression test to evaluate the interface friction under different lubricating conditions. Recently, considerable efforts have been made in combining FE simulations and ring compression test to understand interface friction phenomenon. In our previous work [8], FE simulations were used to evaluate density variations, metal flow, geometric changes, and to determine the deformation load requirement and induced effective stress and strain for P/M Al–4 wt% Cu preforms during cold upsetting. Zhu et al. [9] determined the friction factor of Ti–6Al–4V titanium alloy in hot forging by means of ring compression test and FE simulation. The FE simulations were applied to derive the friction calibration curves and evaluate the effect of heat transfer coefficient (HTC) of the interface friction. Shahriari et al. [10] carried out evaluation of friction coefficient for nimonic 115 superalloy using experimental observations and 3D FEM simulations under various deformation temperature and lubricating conditions. They concluded that variation in temperature significantly affected the frictional behaviour at tool-work piece interface. Rudkins et al. [11] performed an experimental investigation on friction under hot forming conditions. They observed notable influence of temperature on the interface friction factor and concluded that ring compression test is a good simulative technique to explore friction behaviour in hot metal forming and rolling. Fereshteh-Saniee and Pezeshki [12] indicated that increase in working temperature or decrease in strain rate increases the interface friction in hot ring compression test of AZ80 magnesium alloy.

Nowadays, applications of modeling techniques in evaluating friction behaviour during bulk forming processes have been very popular due to their numerous advantages to the designers and manufacturers of engineering components. Several researchers [5, 7, 13] performed investigations on the measurement of friction using physical modeling, FE simulation and ring compression test, and they revealed that the combined use of physical modeling experiment and FE simulation provides a simple and effective methodology in exploring the frictional mechanisms during bulk metal forming processes.

During hot compression of aluminium alloys, graphite lubricant is normally used to reduce the interface friction between tool and work piece due to its high interlayer binding energy [14] and, hence it is chosen to lubricate tool-work piece interface in this investigation. The present investigation aims at evaluating the influence of deformation temperature, initial relative density and lubricating conditions on the frictional behaviour of P/M Al–4 wt% Cu preforms during deformation at elevated temperature. Effect of interface HTC on the friction calibration curves is evaluated for different frictional conditions. The friction factor for P/M Al–4 wt% Cu preforms for various initial relative densities is determined for temperature ranging from 300 to 500 °C under graphite lubricant and dry friction conditions. The hot ring compression test with FE simulations is expected to give accurate and detailed results of the interface friction behaviour for P/M preforms.

2 Experimental Procedures and Finite Element (FE) Simulations

2.1 Experimental Procedures

P/M processed Al–4 wt% Cu preforms were prepared from atomized pure aluminium and copper powders of each −325 µm mesh size. The purity level of aluminium powder is 99 % with a maximum of 0.53 % insoluble impurity limit while copper powder is 99 % pure, and it has a maximum of 0.5 and 0.03 % impurities of iron and heavy metal (Pb), respectively. The detail experimental procedure was presented in the previous work [8] and also highlighted in this investigation. Sintered Al–4 wt% Cu preforms of initial relative density of 84, 87 and 90 % were prepared using recommended compaction pressures. Zinc stearate was used for lubricating the die, punch and butt to reduce interface friction during powder compaction. The powder compacts were sintered in a tubular furnace to a sintering temperature of 550 ± 5 °C for a holding time of 45 min in argon gas flowing atmosphere. The preforms were allowed to cool to room temperature inside the furnace by switching off the power source of the furnace. Archimedes' principle was adopted to measure the density of the preforms with an accuracy of ±1 %.

The sintered preforms were machined to the standard ring compression specimen of size outer diameter:inner diameter:height ratio of 6:3:2 (20:10:6.67). Both upper and lower surfaces of the ring specimens were polished by emery paper to ensure the same surface roughness. Figure 1 shows the geometry of the ring specimen before and after compression under different frictional conditions in which $\boldsymbol{D_{bl}}$—bulged diameter of the ring, $\boldsymbol{D_{eh}}$—diameterial

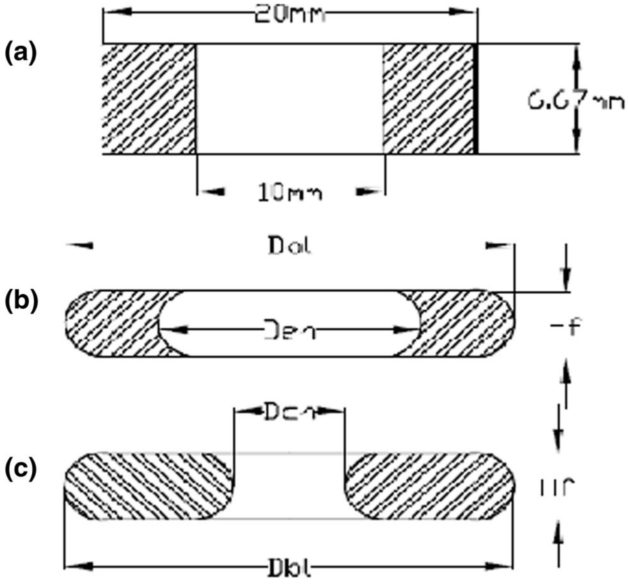


Fig. 1 Ring specimen geometry **a** before deformation, **b** after deformation under low frictional condition, **c** after deformation under high frictional condition

expansion of the hole, $\boldsymbol{D_{ch}}$—diameterial contraction of hole and $\boldsymbol{H_f}$—height after deformation.

The hot ring compression test was carried out between two flat open mirror polished dies of hydraulic press with 50 ton capacity which is mounted with an electrical resistance split muffle furnace. The test was conducted for successive load increments until fracture occurs. The furnace was closed during the testing and could be opened after the testing to facilitate specimen removal. The temperature of the specimen was monitored with the aid of thermocouple feedback-controlled AC current embedded on the furnace. The compression test was performed on preforms with various initial relative densities of 84, 87 and 90 % at deformation temperatures ranging from 300 to 500 °C using graphite dispersion in water and dry friction conditions. Constant strain rate of 0.2/s was considered for all the experimental conditions. For each experimental condition, six samples were prepared and hot compressed to different strain levels.

2.2 Finite Element (FE) Modeling

In order to evaluate the frictional behaviour of P/M Al–4 wt% Cu preforms, commercial FEM software, DEFORM 2D, was adopted. It was employed to derive the friction calibration curves and to evaluate the geometric changes, densification behaviour and metal flow. The FE simulation modeled the hot deformation behaviour of ring specimens by means of the constitutive equations developed to predict hot deformation behaviour of P/M Al–4 wt% Cu preforms for various initial relative densities and the details are given in Ref. [15]. The constitutive model was developed as a function of initial relative densities as given in Eq. (1).

$$\sigma = \frac{1}{\alpha}\ln\left\{\left(\frac{Z}{A}\right)^{\frac{1}{n}} + \left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1\right]^{\frac{1}{2}}\right\} \tag{1}$$

where σ is the flow stress (MPa), α, n, and A are material constants, as given in Eqs. (3)–(6), and Z is Zener–Hollomon parameter, temperature compensated strain rate, which is given as in Eq. (2).

$$Z = \dot{\epsilon}\exp\left(\frac{Q}{RT}\right) \tag{2}$$

where $\dot{\epsilon}$ is the strain rate (/s), R is the universal gas constant (8.31 J mol K^{-1}); T is the absolute temperature (K); Q is the activation energy required for hot deformation (kJ mol^{-1}) as given in Eq. (5).

$$n = 1190IRD^2 - 1877IRD + 762.6 \tag{3}$$

$$\alpha = -0.018IRD^2 + 0.027IRD - 0.004 \tag{4}$$

$$Q = 3026IRD^2 - 4672IRD + 1870 \tag{5}$$

$$lnA = 761.1IRD^2 - 1247IRD + 522.1 \tag{6}$$

IRD is initial relative density of the preforms.

An axisymmetric formulation of the ring specimen was considered during modeling and hence, only one half of the ring specimen was modeled by applying a constraint on the symmetry plane to save computation time. A quadrilateral nodded, 2000 elements with size ratio of 3, were selected to discretize the ring specimen. Among several friction models [5, 13] which have been utilized for quantitative evaluation of the interface friction between tool and work piece during bulk metal forming, constant friction model was considered due to its applicability for high interfacial pressures and inelastic constants. The FE simulations were conducted for different friction factors (m), 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 1. The processing temperature was set to 300, 400 and 500 °C while the temperature of surrounding environment was taken as room temperature. Figure 2 shows the FE modeling of the P/M Al–4 wt% Cu preforms ring specimen before and after deformation under different frictional conditions.

3 Results and Discussion

3.1 Experimental Results

The friction factor, m, was determined by plotting the change in the inner diameter (%) and change in height reduction (%) for different experimental conditions. The

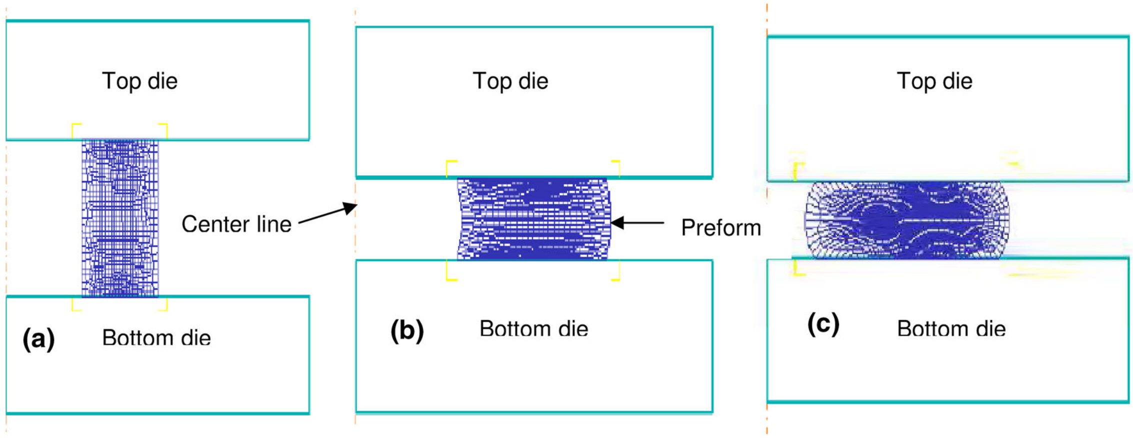


Fig. 2 Finite element method modeling of ring compression test **a** before deformation, **b** after deformation under low friction, **c** after deformation under high friction

material properties to establish the calibration curves were taken from the findings reported elsewhere [14]. Figure 3a, b depicts the photographs of few ring specimens hot compressed at various experimental conditions.

From Fig. 3, it is clearly observed that the interface surfaces of hot compressed ring specimens have different surface profiles, roughness and geometric changes for various friction conditions. Specimens hot compressed under dry friction condition shows increased ring hole contraction or 'barreling' while specimen deformed using graphite lubricant results in relatively lower 'barreling' effect irrespective of the initial relative density and deformation temperature. The 'barreling' phenomena increases with decrease in the initial relative density or increase in the deformation temperature.

The deformation load required to compress the ring specimens with different initial relative densities under various deformation temperatures and friction conditions was determined using FEM, and compared with the experimental results. Figure 4a–d presents comparison between experimental and FEM computed load requirement to deform sintered Al–4 wt% Cu preforms to 50 % height reduction under different experimental conditions. The deformation load requirement increases with increase in the frictional condition. The FE simulations are in a reasonable agreement with the experimental results.

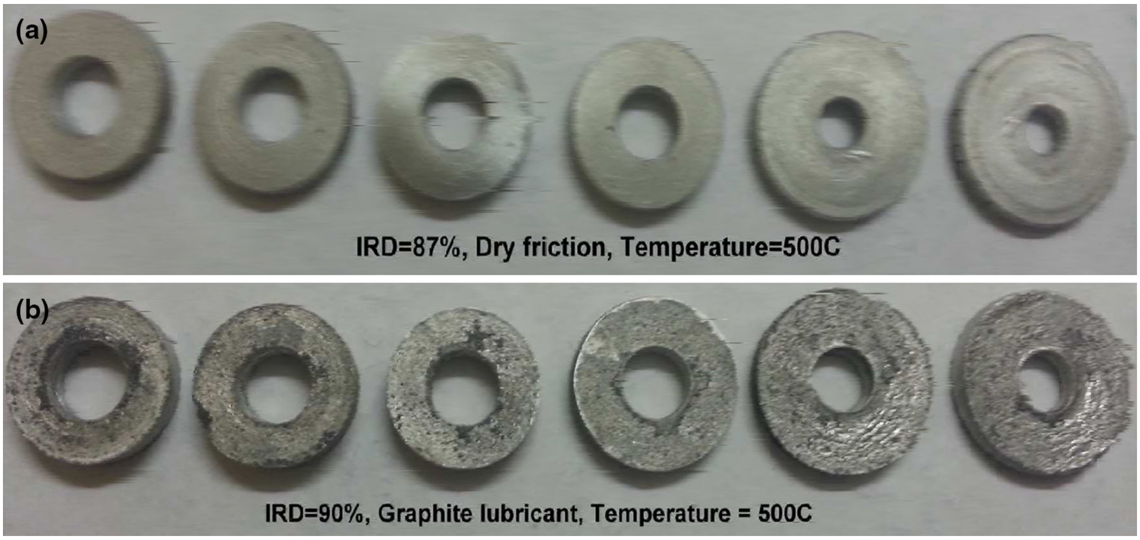


Fig. 3 Photographs of P/M Al–4 wt% Cu ring specimens **a** 87 % initial relative density compressed at 500 °C in dry friction condition, **b** 90 % initial relative density compressed at 500 °C under graphite lubricant

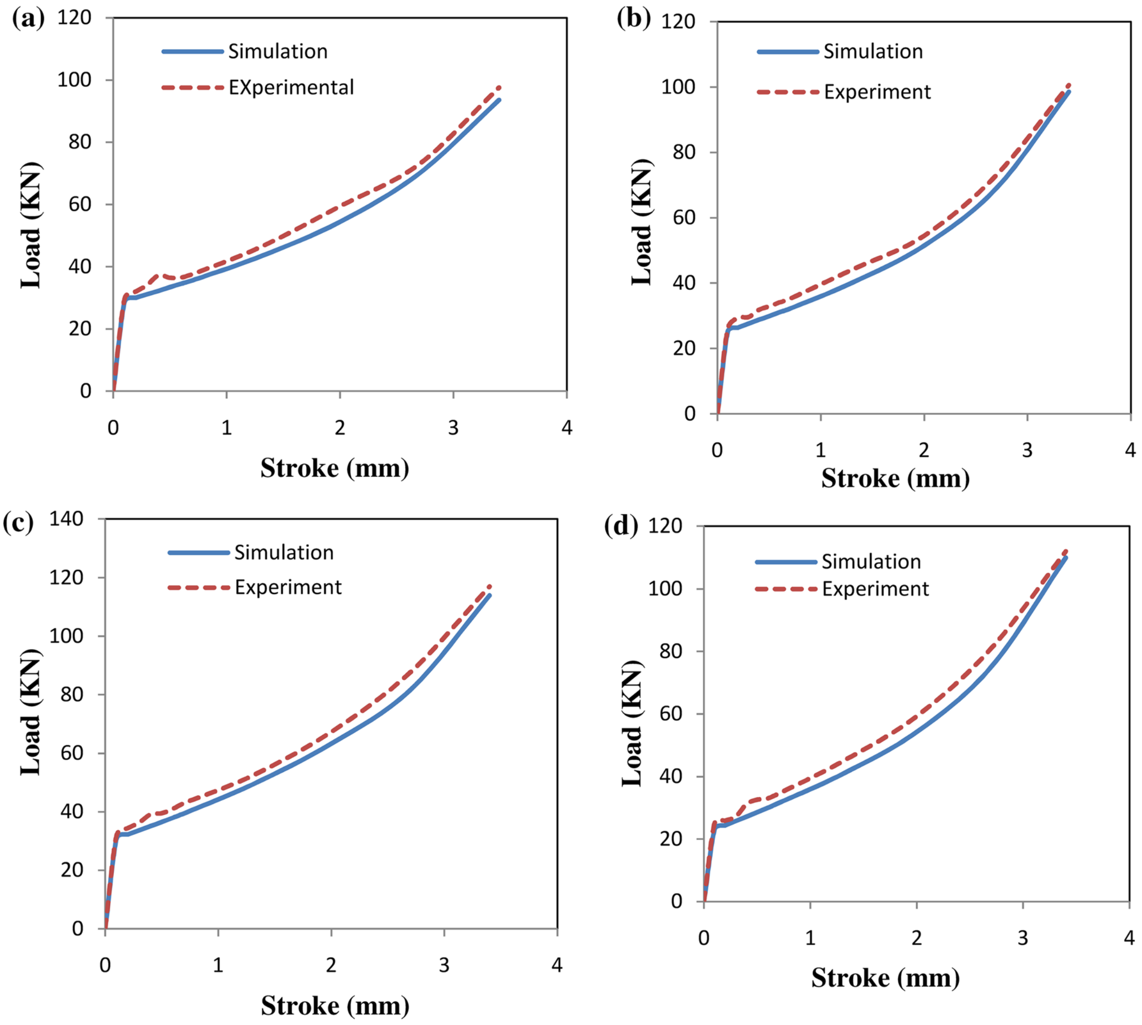


Fig. 4 Experimental and FE computed load–displacement curves of ring compression test of P/M Al–4 wt% Cu preforms with **a** 90 % initial relative density deformed at 300 °C under graphite lubricant, **b** 90 % initial relative density deformed at 500 °C under dry friction condition, **c** 84 % initial relative density deformed at 300 °C under graphite lubricant, **d** 84 % initial relative density deformed at 500 °C under dry friction condition

3.2 Effect of Interface Heat Transfer on the Friction Calibration Curves

There has been very little attention directed towards considering the effect of interface HTC during derivation of the friction calibration curves using FEM software. To determine the friction factor for P/M Al–4 wt% Cu preforms with reasonable accuracy, it is essential to evaluate the effect of interface HTC on the characteristics friction calibration curves. Interface HTC is an important parameter which quantifies the amount of heat transferred from the specimen to the deforming tool during metal forming. In the current work, interface HTC of values 1, 5, 10, 15, 10 and 25 N/(s/mm/°C) were chosen for FE simulations at different frictional conditions. To evaluate the effect of interface HTC on the friction calibration curves, a more appropriate way is to analyze the variation in the inner diameter rather than the interface HTC, due to its higher sensitivity to the interface friction than outer diameter. The FE simulations were conducted for three different friction factors, namely, m = 0.2, m = 0.4 and m = 0.6 at 50 % height reduction. Table 1 presents the variation in the inner diameter with interface HTC of P/M Al–4 wt% Cu preforms with 90 % initial relative density deformed at 500 °C to 50 % height reduction for various friction conditions.

The results indicate that an increase in the interface HTC decreases the inner diameter of the ring specimen. For example, an increase in HTC from 1 to 20 N/(s/mm/°C) results in decrease in inner diameter from 9.39 to 9.35 for friction factor of 0.2. This implies that friction calibration curves are obviously affected by variations in the interface HTC. The decrease rate in the inner diameter is different for various friction conditions with increase in interface HTC. For lower frictional conditions, the decrease of inner diameter with increase in the interface HTC is more as compared to higher friction condition. This suggests that the amount of interface heat transferred depends on the tool-work piece interface friction conditions. Decrease in the inner diameter due to increase in the interface HTC leads to more and faster flow of metals to the inner side of the ring specimen. Thus, an increase in HTC obviously leads to increase in interface friction, and not to be ignored during determination of friction factor

Table 1 Variation of inner diameter with interface HTC for the ring specimen with 90 % initial relative density deformed at 500 °C under various friction conditions

Interface heat transfer coefficient (N/(s/mm/°C)	Inner diameter after 50 % height reduction					
	m = 0.2	Change in inner diameter (%)	m = 0.4	Change in inner diameter (%)	m = 0.6	Change in inner diameter (%)
1	9.396	6.04	7.336	26.64	6.427	35.73
5	9.387	6.132	7.328	26.72	6.412	35.88
10	9.372	6.28	7.314	26.86	6.402	35.98
15	9.360	6.4	7.199	28.01	6.394	36.06
20	9.351	6.49	7.170	28.3	6.382	36.18
25	9.329	6.71	7.162	28.38	6.267	37.33

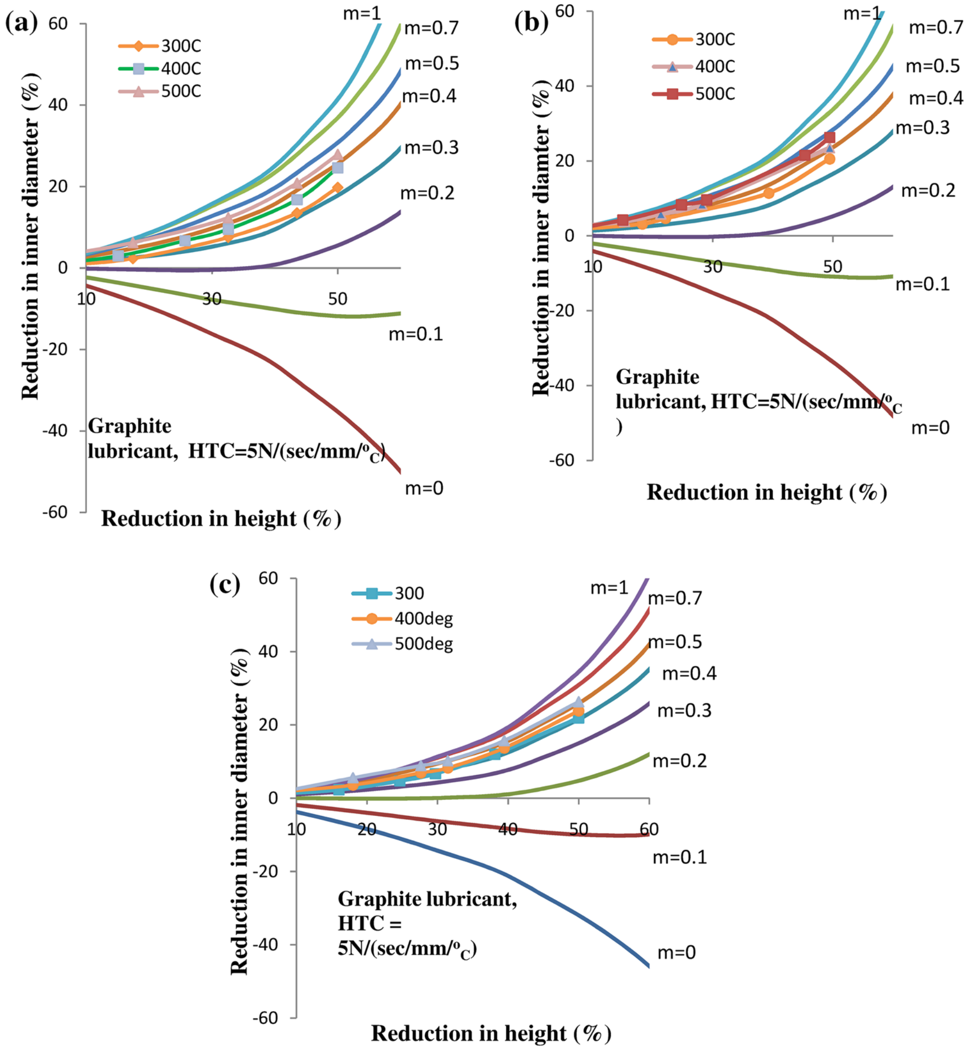


Fig. 5 Friction calibration curves of P/M Al–4 wt% Cu preforms hot deformed under various temperatures using graphite lubricant for preforms with initial relative density **a** 90 %, **b** 87 %, **c** 84 %

Table 2 Friction factor (m) and density in-homogeneity for different experimental conditions

Initial relative density (%)	Temperature (°C)	Friction condition		Density in-homogeneity	
		Dry friction	Graphite lubricant	Variation (%) in density for graphite lubricant	Variation (%) in density for dry friction
90	300	0.65	0.34	6.8	9.9
	400	0.67	0.39	7.5	10
	500	0.69	0.43	8	10.1
87	300	0.68	0.38	9.5	12.6
	400	0.7	0.42	10.1	12.7
	500	0.71	0.47	10.8	12.8
84	300	0.71	0.41	12	15.2
	400	0.73	0.46	12.8	15.3
	500	0.75	0.5	13.3	15.4

using hot ring compression test and FE simulation. Therefore, different interface HTCs were chosen based on DEFORM 2D information for various lubricating conditions, namely, graphite lubricant and dry friction conditions while determining the friction factors.

3.3 Determination of Friction Factor

The friction calibration curves are derived for P/M Al–4 wt% Cu preforms with various initial relative densities during hot compression test at different temperature under dry and graphite friction conditions. Figure 5a–c shows partial friction calibration curves derived for various experimental conditions using DEFORM 2D software. The friction factor (m) is determined for each experimental situation by fitting experimental results into friction calibration curves derived using FE simulations. Table 2 presents the friction factor and density variation for different experimental conditions.

It is clearly evident that increase in deformation temperature leads to the increase in the friction factor. The reason is at higher temperature, the flow stress of the metal decreases due to flow softening which results in more particle–tool interaction at the interface. The effect of temperature on friction factor is relatively less significant in dry friction condition than graphite lubricant, and the result agrees well with the previous findings [16, 17] in which it was revealed that deformation temperature does not have significant effect on the magnitude of friction factor during ring compression test in unlubricated condition. Figure 6a, b shows the variation in friction factor with deformation temperature for preforms with initial relative density of 84, 87 and 90 % in dry and graphite lubricating conditions, respectively.

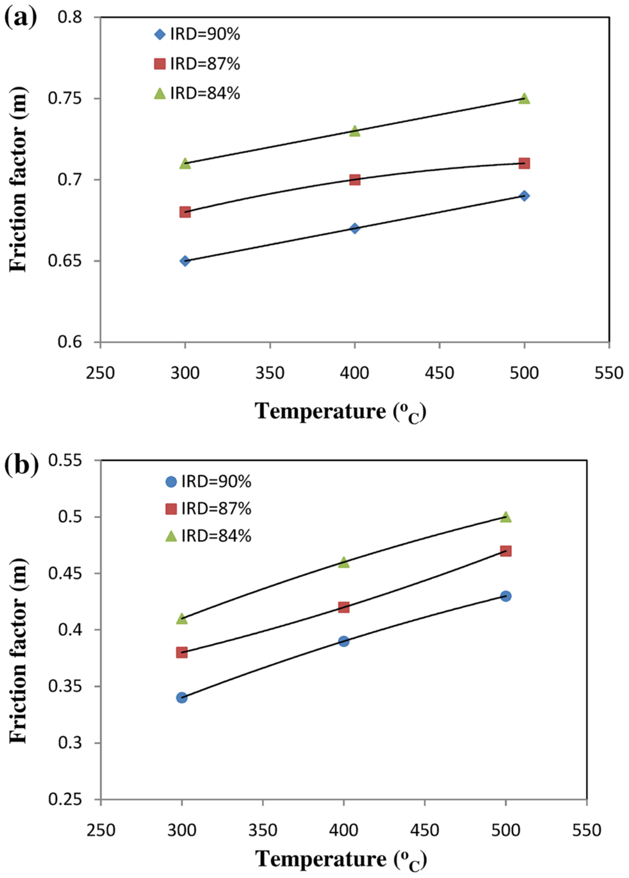


Fig. 6 Variation of friction factor (m) with deformation temperature for **a** dry friction condition, **b** graphite lubricating condition

The deformation temperature has a significant influence on the friction factor of preforms deformed under graphite lubricanting condition. An increase in temperature from 300 to 500 °C increases the friction factor from

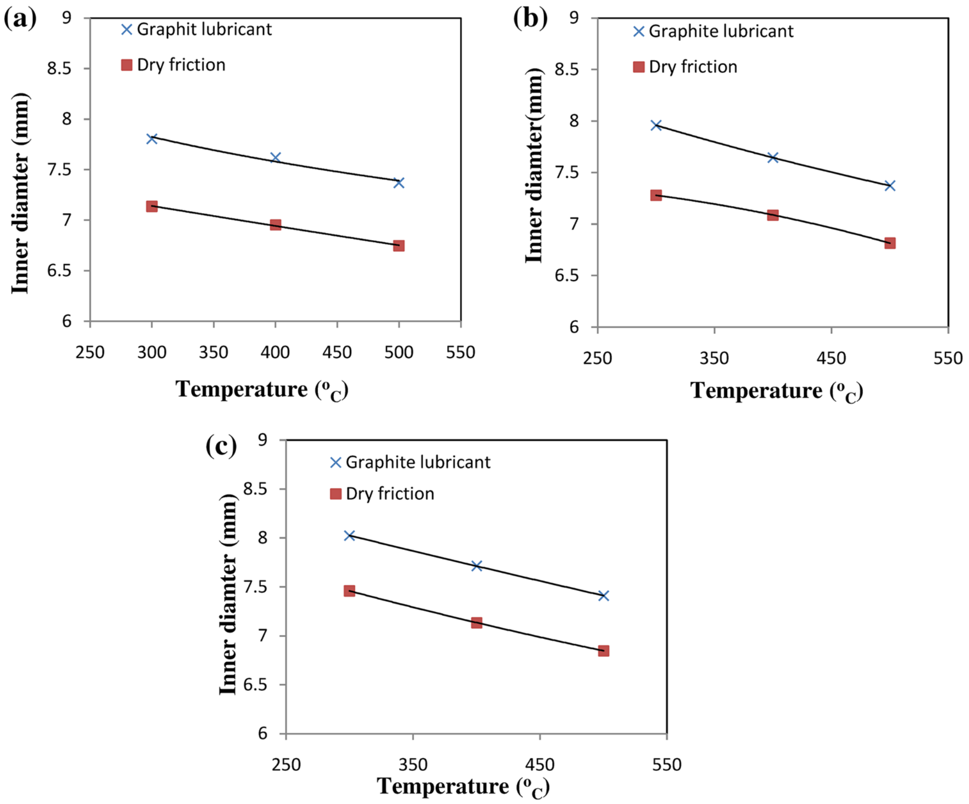
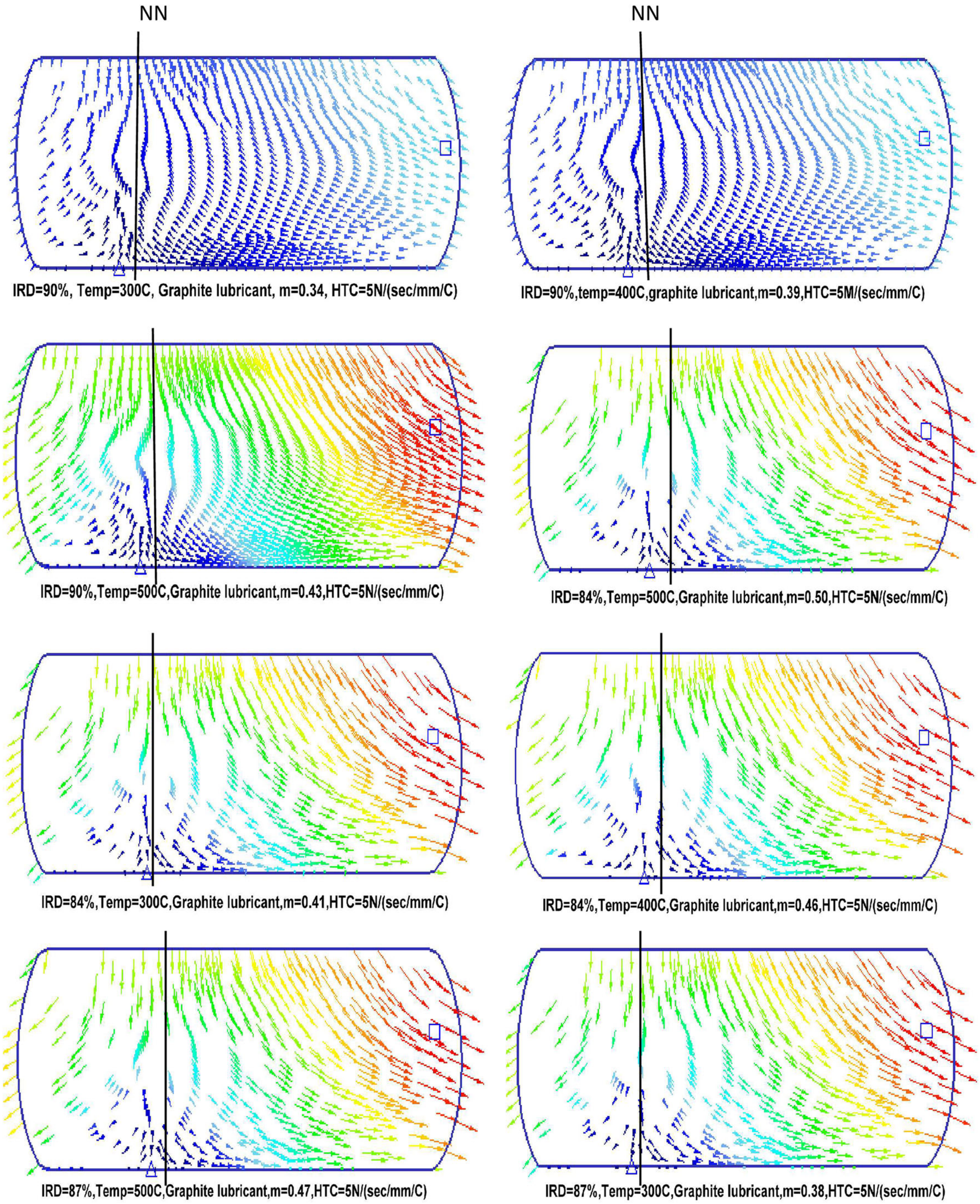


Fig. 7 Variation in the inner diameter with temperature at 50 % height reduction for **a** 84 % initial relative density, **b** 87 % initial relative density, **c** 90 % initial relative density

0.41 to 0.5 for preforms with initial relative density of 84 % deformed using graphite lubricant. The reason is increase in deformation temperature leads to loss in lubricating performance of graphite lubricant due to increase in the shear strength of graphite film and as a result, the friction factor increases, and the same was reported by Li et al. [18]. The use of graphite lubricant decreases the friction factor from 0.65 to 0.34 for preforms with initial relative density of 90 % deformed at 300 °C while it decreases from 0.75 to 0.5 for preforms with initial relative density 84 % deformed at 500 °C. The presence of more number of pores in case of the lower initial relative density preforms further severs the frictional condition. This is due to more work hardening phenomena at the initial stage of deformation which is the cumulative effect of both matrix work hardening and densification hardening. As a result, the material yielding is more at the tool-work piece interface which leads to higher friction condition. Thus, the case of graphite lubricant deformed at 300 °C for preforms with initial relative density of 90 % deformed at 300 °C provided the best lubricating condition with the minimum friction factor of 0.34. To further evaluate the effect of temperature, initial relative density and lubricating conditions on the frictional behaviour, the change in the inner diameter was investigated. Figure 7a–c shows the variation in the inner diameter with temperature at 50 % height reduction for different initial relative density and friction conditions.

The inner diameter of the ring specimen decreases from 7.81 to 7.36 mm with increase in the temperature from 300 to 500 °C for preforms with initial relative density of 84 % under graphite lubricant while it decreases from 7.14 to 6.74 under dry friction condition. The decrease of inner diameter with increase in temperature is higher for preforms with lower initial relative density. In addition, metal flow field analysis was carried out to evaluate the influence of temperature, initial relative density and lubricating conditions on the friction factor. Figures 8 and 9 present the metal flow fields of P/M Al–4 wt% Cu preforms for different deformation temperature and initial relative density under graphite lubricant and dry friction conditions, respectively.

The plane 'NN' represents neutral plane along which the velocity of metal flow is nearly zero. There is a continuous change in the volume of P/M preforms during deformation due to persistent pore closure phenomena. The increase in temperature increases the shift away of the neutral plane from axis of ring specimen. For example, for preforms with initial relative density of 90 % deformed under graphite



IRD=90%, Temp=300C, Graphite lubricant, m=0.34, HTC=5N/(sec/mm/C)

IRD=90%,temp=400C,graphite lubricant,m=0.39,HTC=5M/(sec/mm/C)

IRD=90%,Temp=500C,Graphite lubricant,m=0.43,HTC=5N/(sec/mm/C)

IRD=84%,Temp=500C,Graphite lubricant,m=0.50,HTC=5N/(sec/mm/C)

IRD=84%,Temp=300C,Graphite lubricant,m=0.41,HTC=5N/(sec/mm/C)

IRD=84%,Temp=400C,Graphite lubricant,m=0.46,HTC=5N/(sec/mm/C)

IRD=87%,Temp=500C,Graphite lubricant,m=0.47,HTC=5N/(sec/mm/C)

IRD=87%,Temp=300C,Graphite lubricant,m=0.38,HTC=5N/(sec/mm/C)

Fig. 8 Metal flow field of P/M Al–4 wt% Cu preforms of various initial relative density deformed at temperature ranging from 300 to 500 °C under graphite lubricant condition

lubricant, the neutral plane distance from the axis of the ring specimen increases from 6.16 to 6.35 mm for increase in deformation temperature from 300 to 500 °C. It clearly shows more metal flow towards the inside surface of the ring specimen with increase in temperature. On the other hand, the use of graphite lubricant reduces the shift away of neutral plane from the axis of ring specimen resulting in decreased barreling effect. Decrease in the initial relative density of the preforms leads to increase in the neutral plane distance from the axis of the ring. This explains well that pores in the powder metallurgical preforms sever the interface friction as the same is reported elsewhere [2, 8]. Figure 10a, b shows the variation in neutral plane distance from the ring axis with deformation temperature for

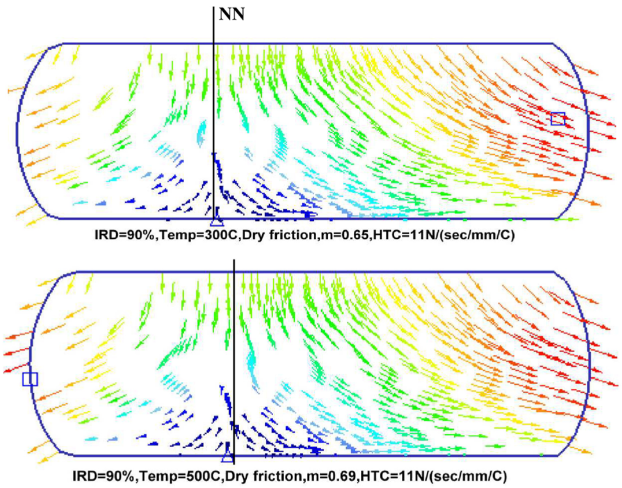


Fig. 9 The metal flow fields of P/M Al–4 wt% Cu preforms with 90 % initial relative density deformed at 300 and 500 °C under dry friction condition

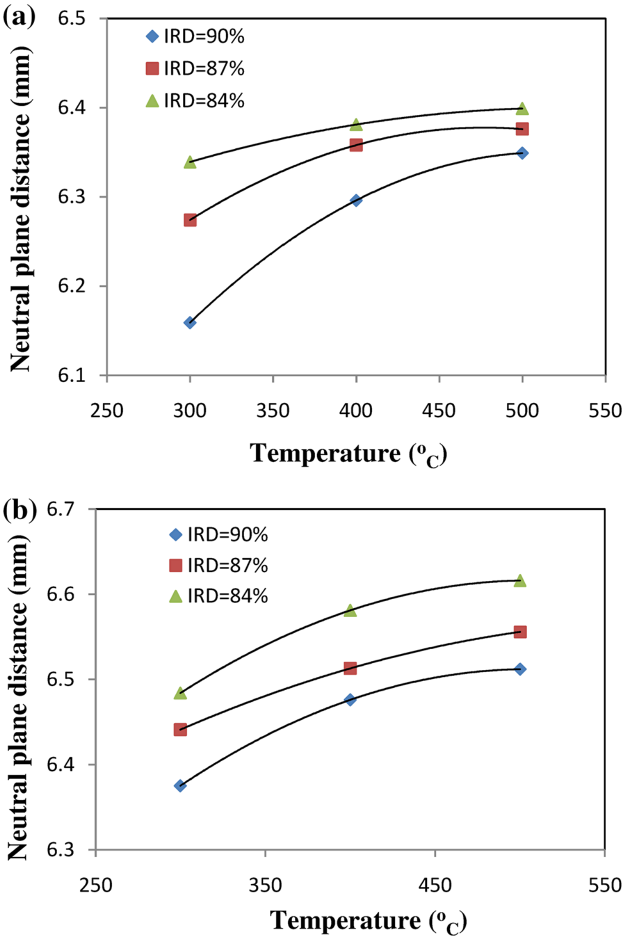


Fig. 10 Variation of neutral plane distance from the axis of ring specimen with deformation temperature for 50 % height reduction under **a** graphite lubricant, **b** dry friction condition

different initial relative density under graphite lubricant and dry friction conditions.

Uniformity in density gradient during densification for various experimental conditions was analyzed using FE simulations. The results show that higher interface friction condition leads to more in-homogeneity in densification and deformation. In the case of graphite lubricating condition, the density in-homogeneity is relatively decreased. As presented in Table 1, the non-uniformity in the density of the preforms during densification increases with decrease in initial relative density and increase in deformation temperature.

In order to verify the validity of determined friction factors, comparison between the geometric changes of ring specimen obtained using FE simulations and experiment was done. Table 3 demonstrates the comparison of geometric changes, i.e. outer diameter of the ring specimen, obtained by FEM simulations and experiment at 50 % height reduction.

It can be seen in Table 3 that the maximum absolute relative error found is 1.79 % for preforms deformed at 300 °C under graphite lubricating condition which is quite reasonable considering the complexity of deformation behaviour of P/M components. Thus, the determined friction factors are valid for different industrial applications of metal forming processes and researches.

4 Conclusions

In this research, the hot ring compression tests of P/M Al–4 wt% Cu preforms with FE simulations were carried out to determine the friction factor between the tool-work piece interfaces. A series of hot compression tests were performed on P/M A-4 wt% Cu ring specimens of various initial relative densities, 84, 87 and 90 %, for temperature ranging from 300 to 500 °C under graphite lubricant and dry friction conditions. The FE simulations were employed to derive the friction calibration curves, analyze densification behaviour and geometric changes and evaluate the metal flow. Based on the results of FE simulation, different interface HTCs were used to generate the friction calibration curves for graphite lubricant and dry friction conditions, respectively. The results showed that an increase in deformation temperature or decrease in initial relative density increased the friction factor irrespective of tool-work piece interface friction conditions. The effect of temperature on the friction behaviour of P/M Al–4 wt% Cu preforms was more significant in graphite lubricant condition than dry friction. The simulation results showed that the neutral plane distance from the

Table 3 Comparison between FEM simulation and experimental results of geometry changes P/M Al–4 wt% Cu preforms with initial relative density of 87 % at 50 % height reduction for various temperature and friction conditions

Height reduction (%)	Outer diameter of ring specimen after deformation (mm)																	
	Graphite lubricant									Dry friction								
	Temp = 300 °C, m = 0.38			Temp = 400 °C, m = 0.42			Temp = 500 °C, m = 0.47			Temp = 300 °C, m = 0.68			Temp = 400 °C, m = 0.7			Temp = 500 °C, m = 0.71		
	Exp.	FEM	Error (%)	Exp.	FEM	Error (%)	Exp.	FEM	Error (%)	Exp.	FEM	Error (%)	Exp.	FEM	Error (%)	Exp.	FEM	Error (%)
10	20.52	20.582	0.30	20.48	20.58	0.47	20.41	20.58	0.82	20.43	20.58	0.74	20.41	20.58	0.84	20.37	20.58	1.03
20	21.39	21.178	0.99	21.31	21.17	0.67	21.26	21.15	0.49	21.33	21.14	0.87	21.28	21.14	0.64	21.19	21.14	0.22
30	22.22	22.054	0.75	22.19	22.02	0.76	22.17	21.99	0.81	22.02	21.94	0.37	21.98	21.94	0.19	21.91	21.94	0.12
40	22.92	23.202	1.23	22.84	23.15	1.36	22.79	23.11	1.40	22.89	23.01	0.49	22.78	23	0.97	22.75	22.99	1.09
50	24.34	24.778	1.79	24.31	24.72	1.69	24.26	24.67	1.69	24.23	24.51	1.17	24.19	24.51	1.31	24.19	24.50	1.29

axis of the ring and in-homogeneity in density increased with increase in the friction factor. In general, the FE results were in excellent agreement with the experimental results, and hence, it proved to be a reliable and feasible way to employ hot ring compression test with FE simulations for quantitative evaluation of friction behaviour of P/M components.

Acknowledgments The authors would like to thank the technical staffs of National Institute of Technology, Warangal, India for helping to carry out the research work.

References

1. Mondolfo L F, *Aluminum Alloys: Structures and Properties*, Butterworths, London (1976) p 14.
2. Venugopal P, Venkatraman S, Vasudevan R, and Padmanabhan K A, *Mech Work Technol J* **16** (1988) 51.
3. Kunogi M, Reports of Scientific Research Institute, Tokyo **30** (1954) 63.
4. Male A T, and Cockcroft M G, *Inst Met J* **93** (1964/1965) 38.
5. Sofuoglu H, and Rasty J, *Tribol Int J* **32** (1999) 327.
6. Krause A, Weirauch R, Bräuer G, Stonis M, and Behrens B-A, *Prod Eng Res Dev* **9** (2015) 41.
7. Robinson T, Ou H, and Armstrong C G, *Mater Process Technol J* **153–154** (2004) 54.
8. Wogaso D, Davidson M J, and Khanra A K, *Mater Eng Perform J* **23** (2014) 3058.
9. Zhu Y, Zeng W, Ma X, Tai Q, Li Z, and Li X, *Tribol Int* **44** (2011) 2074.
10. Shahriari D, Amiri A, and Sadeghi M H, *Mater Eng Perform J* **19** (2010) 633.
11. Rudkins N T, Hartley P, Pillinger I, and Petty D, *Mater Process Technol J* **60** (1996) 349.
12. Fereshteh-Saniee F, and Pezeshki S M, *Mater Trans* **53** (2012) 201.
13. Sofuoglu H, Gedikli H, and Rasty J, *Eng Mater Technol J* **123** (2001) 338.
14. Schey J A, *Metal Deformation Process: Friction and Lubrication,* Marcel Dekker, New York (1970) p 46.
15. Wogaso D, Davidson M J, and Khanra K A, *Mater Des* **65** (2015) 83.
16. Vengopal S, Srinvan G, Venkadensen S, and Seetharaman V, *Mech Work Technol J* **19** (1989) 261.
17. Wang F, and Lenard J G, *Eng Mater Technol J* **114** (1992) 13.
18. Li L X, Peng D S, Liu J A, and Liu Z Q, *Mater Process Technol J* **112** (2001) 1.