Journal of Materials Processing Technology 224 (2015) 18–25

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

An alternative evaluation method for friction condition in cold forging by ring with boss compression test

Chengliang Hu[a], Hengan Ou[b,*], Zhen Zhao[a,*]

[a] Institute of Forming Technology & Equipment, Shanghai Jiaotong University, Shanghai 200030, China
[b] Department of Mechanical, Materials and Manufacture Engineering, University of Nottingham, Nottingham NG7 2RD, UK

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form 27 September 2014
Accepted 12 April 2015
Available online 22 April 2015

Keywords:
Friction
RCT
RCT-B
Calibration curves
Friction difference

ABSTRACT

Ring compression test (RCT) is a very popular method used to quantitatively evaluate friction conditions at the tool–workpiece interface by measuring the variations of the inner diameter of the ring in metal forming. There are many possibilities for measuring the inner diameter variations in RCT because of non-uniform deformation of the inner hole during the test. Such non-uniform deformation of the inner hole causes difficulties in precise measurement of the inner diameter and hence the accuracy of the derived friction coefficient. To avoid the disadvantage in dimension measurement of the conventional RCT, an alternative method for evaluating friction conditions in cold forging named ring with boss compression test (RCT-B) is proposed. By the introduction of the RCT-B concept, finite element simulation results under different friction conditions were obtained. Results showed that the shape of the outer boss remains stable during the compression deformation and allows the diameter of the outer boss to be measured more easily and accurately. The calibration curves of the RCT-B concept were constructed by using FE simulation, which cover the range of friction conditions in cold forging process. Finally, the RCT-B method was successfully applied to determine the friction factors of four different lubricating conditions in compression of aluminum rings. Furthermore, the phenomena with different lubricating conditions between the upper and lower die–workpiece interfaces were also studied using both simulation and experimental testing. The results show that it is possible to quantitatively assess the difference of friction conditions at the upper and lower die–workpiece interfaces by simply checking the inclined angle of the outer boss with the RCT-B method.

1. Introduction

1.1. Historical development

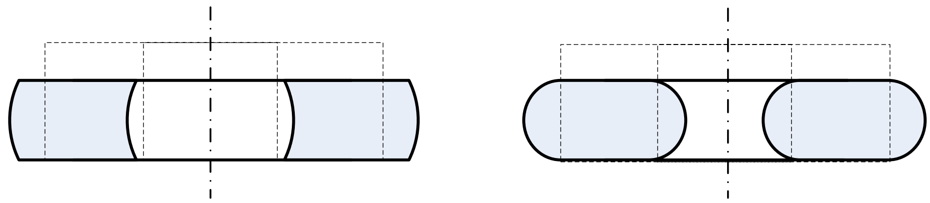
In metal forming processes, friction always takes place at the interface between the workpiece and the die or tool. Friction condition has a significant effect on the material flow. On one hand, because of high friction condition, underfilling of material into the die cavity occurs. On the other hand, severe local friction condition could be beneficial to the filling of the die cavity. Friction plays an important role in the finally required forming load, i.e., higher friction results in larger total forming load required for completing necessary deformation in a metal forming process. Friction also directly influences the surface quality of the formed parts and excessive friction leads to wear, pick-up or galling of the tool surface and hence reduces tool life. Therefore, friction is an important parameter in metal forming and should be precisely measured and carefully controlled for forming qualified products at low cost.

The ring compression test (RCT) has proven to be one of the most popular and commonly used methods for quantitative evaluation of friction conditions in bulk forming operations (Rao and Sivaram, 1993). The ring compression test was firstly used by Kunogi (1956) as a qualitative method of comparing lubricants for cold extrusion. In the test, a flat ring-shaped specimen is compressed to 50% reduction using flat tool. If the lubricant has a good lubrication property to ensure very low friction coefficient, the inner diameter (ID) expands during the deformation, and when the friction coefficient is high the ID shrinks, as shown in Fig. 1. It is quite easy to recognize the different friction conditions of different lubricants by observing the ID variation due to its sensitivity to friction.

To determine the friction coefficient for hot-working process, the RCT was further developed by introducing a set of

* Corresponding authors at: Institute of Forming Technology & Equipment, School of Materials Science and Engineering, Shanghai Jiaotong University, 1954 Huashan Road, Shanghai, 200030, China. Tel.: +86 2152580156/+44 115 846 7391; fax: +86 2162826575.
E-mail addresses: h.ou@nottingham.ac.uk (H. Ou), zzhao@sjtu.edu.cn, z_zhaoc@online.sh.cn (Z. Zhao).

http://dx.doi.org/10.1016/j.jmatprotec.2015.04.010



(a) (b)

Fig. 1. Ring compression test: (a) low friction; (b) high friction.

calibration curves by Male and Cockcroft (1964–1965). For the calibration work, the ring specimens of 6:3:2 were compressed under sticking and zero friction conditions. Analytical data from Schroeder and Webster (1949) which were extracted from the experimental results of compression of disc-shaped specimens were used in the intermediate friction conditions. By conducting the test using a range of materials with different deformation and lubricants at elevated temperatures, RCT appears to be a reliable method in detecting the variations of friction conditions during bulk plastic deformation.

Based on the assumption of uniform deformation as well as conformance of Mises rule and constant shear friction factor, the first satisfactory analysis of the compression of a flat ring was made by Avitzur (1964) through an optimum upper bound method and later verified by Hawkyard and Johnson (1967) using a stress analysis approach, and the current position of the neutral surface, which divides the regions of inward and outward flows of material, was determined. By dividing the whole deformation process into a series of small deformation increments, Male and Depierre (1970) provided a possible means for the calibration of different ring geometries by computer solution. However, the actual friction factor obtained by using the theory to analyze experimentally determined shape changes appears to produce a degree of overestimation.

To minimize the discrepancy between the theoretical and experimental results, the bulging effect caused by non-uniform deformation should be further considered. By using a simple parabolic curve with only one uncertain coefficient to represent the profile of the bulge, Liu (1972) theoretically calculated the stress and strain components at the outer equator based on a supposed velocity field described by a trigonometric function and presented a set of calibration curves for 6:3:2 ring geometry. By introducing a constant average value of stress at each step of relative small deformation, Lee and Altan (1972) computed another set of calibration curves in consideration of bulging. By adopting an assumed velocity field described by exponential function, Depierre and Gurney (1974) developed a reliable method for treating experimental results from RCT with and without bulge formation so as to obtain a quantitative evaluation of friction factor, in which a parabolic curve with two unknown coefficients were used to describe the bulge profile. Compared to the curves developed by Male and Depierre (1970), the calibration curves considering of bulging are closer to the experimental results.

To facilitate the application of RCT in industry, Abdul (1981) attempted to develop a calibration chart, which provides friction factor lines and height reduction lines against the graduated axis of ID change, without the consideration of the bulging effect. To consider the actual non-constant friction shear stress distributions during RCT, Wang (2001) proposed a new way to recreate calibration curves by using the non-constant friction stress expressed by a function of the *F*-coefficient, and the obtained calibration curves showed a good agreement with experimental data.

To simulate the state of low and high levels of normal pressure on the tool–workpiece interface of metal forming, two alternative ring compression tests with concave-shaped and convex-shaped cross-section in the ring geometries were put forward as a complementary approach of RCT. The corresponding calibration curves were obtained using FEM analysis and verified by the experimental results (Petersen et al., 1998; Tan et al., 1998).

1.2. Dimensional measurement of RCT

The popularity of RCT can be attributed to its practical convenience and the friction condition can be quantified by measuring the dimensional change of the inner diameter. The accuracy in the measurements of the specimen dimensions before and after testing has a significant effect on the accuracy of the results of friction. Originally aiming at the slightly non-circular shape upon deformation, an enlarged tracing of each specimen was made using a profile projector, the area of the central hole was found by means of a planimeter, and the mean diameter was calculated assuming that this was the area of a true circle, and the incurred error was found to be 1 in 250 (Male and Cockcroft, 1964–1965).

As recommended by Wang and Lenard (1992), the inner diameter was measured in two directions at right angles, on both the specimen ends and at the middle. The average was used to calculate the percentage change. The height reduction percentage was also calculated from the average of four measurements. In this case, only caliper was needed.

Measurements of the height and ID were made by utilizing a digital caliper (Petersen et al., 1998), whereas details of the geometrical profile of the deformed specimens were obtained on a toolmaker's microscope equipped with an *X*–*Y* micrometer table connected to a PC-based data-logging system. To allow detailed comparison with the computed changes in geometry for the complementary RCT, the external profile of selected specimens was digitized using an inductive probe.

Considering the soft property of the workpiece material 'Plasticine', after compression the ID was measured before the specimen was removed from the bottom platen to avoid any change of shape. An average value was taken from three measurements on the top surface from three arbitrary angles across the centre of the ring (Robinson et al., 2004).

As shown in Fig. 1, the ID at the flat faces differs from the ID at the specimen mid-line due to barreling. Hartley et al. (2007) proposed a method to measure the ID by placing a ball-bearing of known diameter onto the specimen so that it projects slightly into the inner hole, and this technique enables measurement of the ID at the flat specimen faces. From the dimensions depicted in Fig. 2, all of these can be measured accurately using a standard micrometer, the ID is simply calculated from

$$\mathrm{ID} = 2\sqrt{\frac{D^2}{4} - \left(\mathrm{OH} - h - \frac{D}{2}\right)^2} \quad (1)$$

As mentioned by Shahriari et al. (2010), a profile projector equipped with an *X*–*Y* micrometer table connected to a PC-based data-logging system and the same measurement technique with

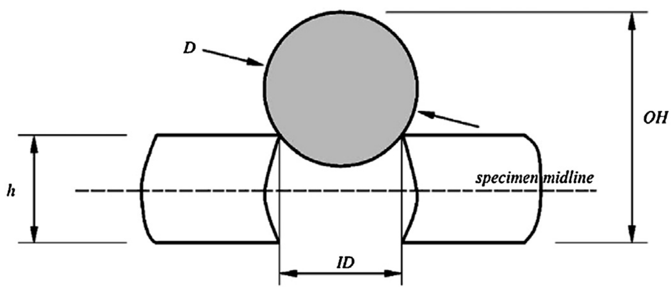


Fig. 2. Diagram illustrating the measurement technique with ball-bearing (Hartley et al., 2007).

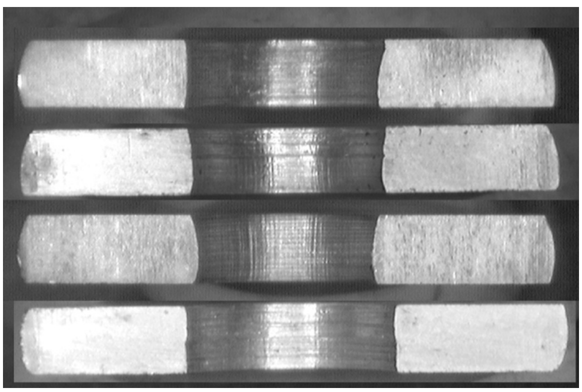


Fig. 3. Cross-section of different RCT specimen (Macaskill, 2012).

ball-bearing were both used to determine the friction coefficients for the Nimonic 115 hot forging process by RCT.

For the convex (high friction) profile, the smallest ID at the equator could be properly measured by using the profile projector and planimeter. For the concave (low friction) profile, the profile projector could not catch the largest ID at the equator. Although the measurement technique with ball-bearing may be used conveniently, the assumption of the deformed profile as a circular shape makes the technique not so precise. To obtain the average value, the measurement of the ID by using a caliper is an easy but not a precise way, because it is difficult to position the equator. To get more accurate value of the ID using a simple caliper, the specimen after deformation could be cut at a cross section through the axisymmetric z-axis, as shown in Fig. 3. However, it requires more time to complete the cutting.

In addition to the two typical deformed modes shown in Fig. 1, Abdul (1981) reported three other possible modes of inhomogeneous deformation during his experimental study at various levels of friction. Goetz et al. (1991) also found that the profile of the ID after deformation was not only concave or convex, but also straight or buckled. And in the practical experimental work, there are many possibilities for the deformed ID profile, as shown in Fig. 3. This indicates that the shape of the ID of the ring during test is not so uniform. Correspondingly, the shape of the outer diameter also becomes unsteady.

In the present work, to overcome the disadvantage in measurement of the inner diameter in conventional RCT, an alternative method to evaluate the friction condition namely ring with boss compression test (RCT-B) was proposed. In the following sections, the RCT-B concept is first discussed. In Section 3, finite element (FE) simulations are carried out for detailed evaluation of material deformations under different RCT-B friction conditions and the FE results are used to construct the calibration curves of the RCT-B. Section 4 summarizes the procedures for both the RCT-B and RCT experiments so as to validate the RCT-B method as compared to the conventional RCT approach. Detailed evaluation and discussion of the friction conditions obtained from both the RCT-B and RCT methods are given in Section 5. This is followed by the conclusions drawn from this research in Section 6.

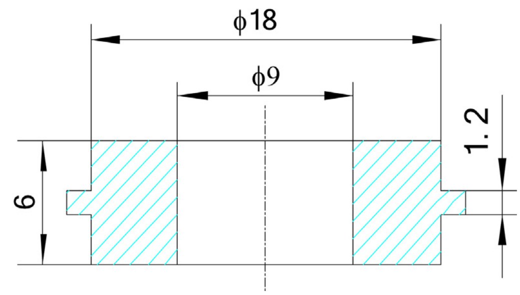


Fig. 4. The ring geometry of RCT-B.

2. The concept of ring with boss compression test (RCT-B)

To achieve a uniformly deformed shape, the ring with an outer boss is proposed for the compression test based on the following considerations: (1) The outer boss would not be deformed during the compression process because it does not contact with the dies; (2) The outer boss would be a rigid zone expanding with the outer diameter because it is not affected by the deformation of the ring.

The ring geometry 6:3:2 used by Male and Cockcroft (1964–1965) is commonly used for obtaining experimental calibration curves because of practical convenience (Rao and Sivaram, 1993). The proposed ring geometry with boss is designed based on this commonly used RCT geometry. As shown in Fig. 4, the ratio of outer diameter to inner diameter and to height is 6:3:2, and the height and width of the outer boss have the same value of 0.4. Based on the above considerations of material deformation of the RCT-B specimen under compression, it is assumed that the variations of the boss would be sufficiently sensitive to different friction conditions. Similar to the conventional RCT approach, it is necessary to construct a set of calibration curves for the measurement of friction conditions. FE method may be used to evaluate material deformation of the RCT-B specimen under different friction conditions and to construct the calibration curves of the proposed RCT-B method.

3. Finite element simulation

3.1. Analysis of deformation process

In this work, aluminum material Al6082 was selected as the material for the RCT-B. To obtain material properties tensile tests were carried out, and the true stress and strain curve was modeled using the simple power law $\sigma = K\varepsilon^n$. After regression analysis of experimental data, the flow stress constant K and the strain hardening exponent n were calculated to be $K = 191.88$ and $n = 0.181$, respectively. Thus the specific material model could be determined and adopted for the FE model.

2D axisymmetric model with shear friction law was used to simulate the RCT-B tests at room temperature. The simulation results of deformation process under different friction conditions are shown in Fig. 5. When the friction factor is 0.0, the material uniformly flows outward and the inner diameter keeps straight with height reduction. When the friction factor is 0.1, the material flows outward and a concave profile of ID is obtained. When the friction factor is 0.3, the material flows inward and a convex profile of ID is formed. All these phenomena on the ID deformation are quite similar to the conventional RCT. This suggests that the outer boss does not change the main deformation mode of the ring.

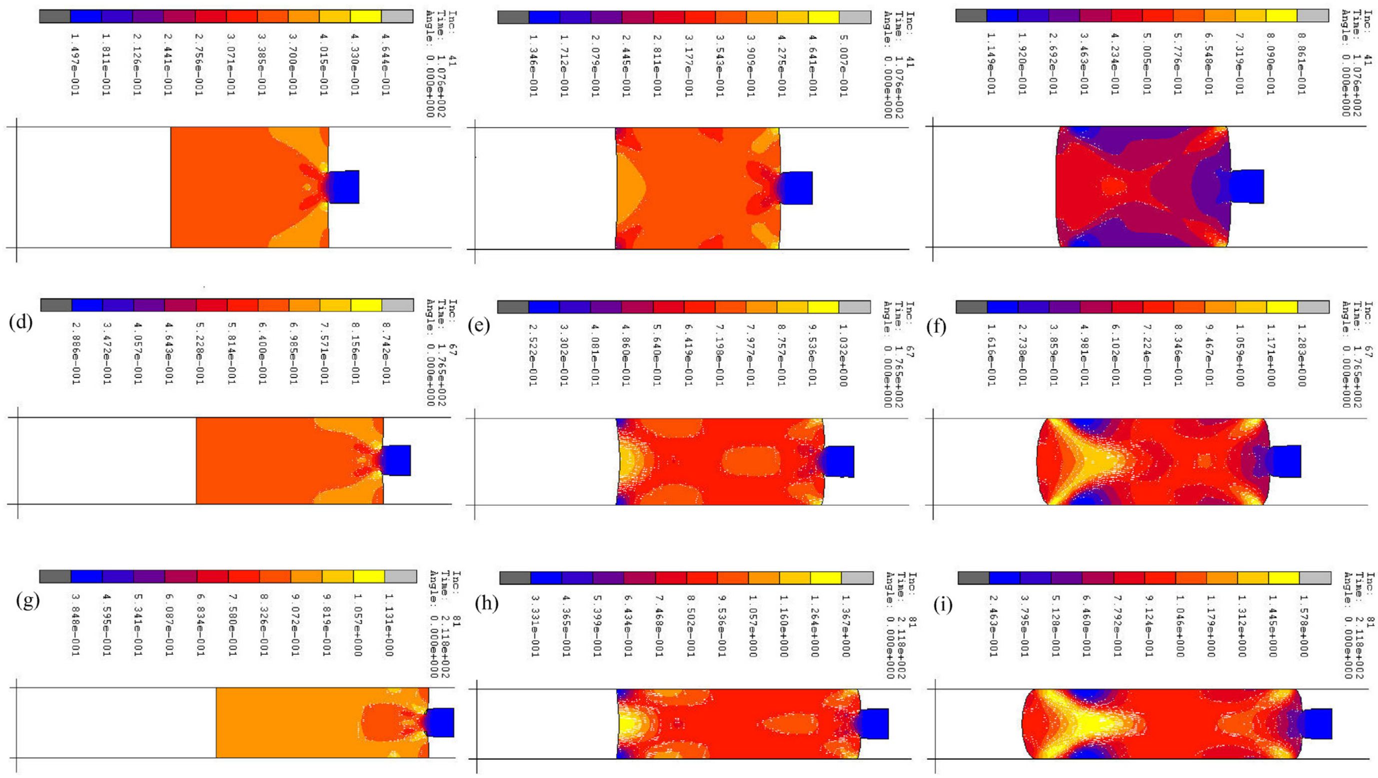


Fig. 5. Simulation results of deformation during RCT-B under different friction condition: (a) friction factor $m = 0.0$, height reduction $R_H = 30\%$; (b) $m = 0.1$, $R_H = 30\%$; (b) $m = 0.3$, $R_H = 30\%$; (e) $m = 0.0$, $R_H = 50\%$; (f) $m = 0.1$, $R_H = 50\%$; (g) $m = 0.3$, $R_H = 50\%$;(e) $m = 0.0$, $R_H = 60\%$; (f) $m = 0.1$, $R_H = 60\%$; (g) $m = 0.3$, $R_H = 60\%$.

What is more important is that there is almost no deformation at the outer boss of the ring, as shown in Fig. 5. The equivalent strain in that area is very small during the deformation process. Even at very high friction conditions such as $m = 0.7$ and $m = 1.0$, the shape of the outer boss still keeps unchanged as a rigid zone, as shown in Fig. 6. During the RCT-B test, the outer boss expands with the outer diameter and there is not any bulging or barreling effect at the outer boss. Therefore, the outer diameter of the specimen can be measured quite easily and precisely.

3.2. Construction of calibration curves

From the literature mentioned above, discrepancies exist between the reported calibration curves because of many factors that affect the final shape of the calibration curves. Goetz et al. (1991) examined the effects of strain rate, inner diameter profile and ring geometry upon ring curves using the rigid viscoplastic FE program ALPID and experimental data. Andersson et al. (1996) evaluated the effect of the heat-transfer coefficient in ring-compression tests using a commercially available FE program DEFORM, and the effect can be considered small as compared to the inaccuracies involved in the calibration curves. By investigating the effects of material properties, strain-rate sensitivity, and the barreling effect on the calibration curves by using FE simulation, Sofuoglu and Rasty (1999) concluded that the use of a generalized calibration curves regardless of the material type and test conditions must be avoided. It was recommended that specific calibration curves for a specific material be used to obtain reliable data of friction coefficients under the specific test conditions. For these reasons, the corresponding calibration curves for the new RCT-B concept and the conventional RCT are both constructed by FE method.

To obtain the calibration curves of the new RCT-B concept, the displacement of the node at the middle of the outer boss and one node at the top edge are extracted from the FE simulation results to quantify the deformation of the ring with boss specimen. The reduction in the outer diameter of the boss after deformation is calculated as $R_{OD} = (D_{B1} - D_{B0})/D_0$ and the reduction in height is calculated as $R_H = (H_0 - H_1)/H_0$, as shown in Fig. 7. Finally, the specific calibration curves can be created as shown in Fig. 8.

To make necessary comparisons, the calibration curves for the conventional RCT are created based on the reduction in the inner diameter at the middle of the specimen, as shown in Fig. 9.

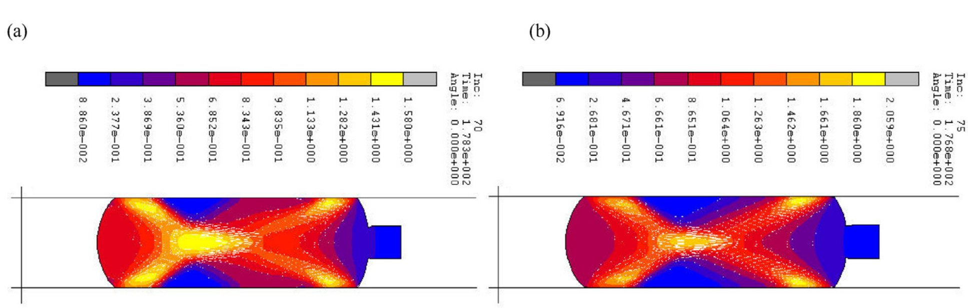


Fig. 6. Equivalent effective strain distribution of workpiece after 50% height reduction during the RCT-B at high level friction conditions: (a) friction factor $m = 0.7$; (b) $m = 1.0$.

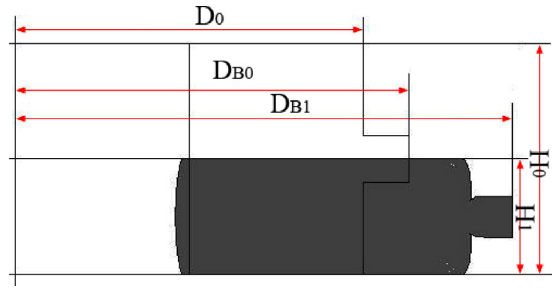


Fig. 7. Reduction in outer diameter.

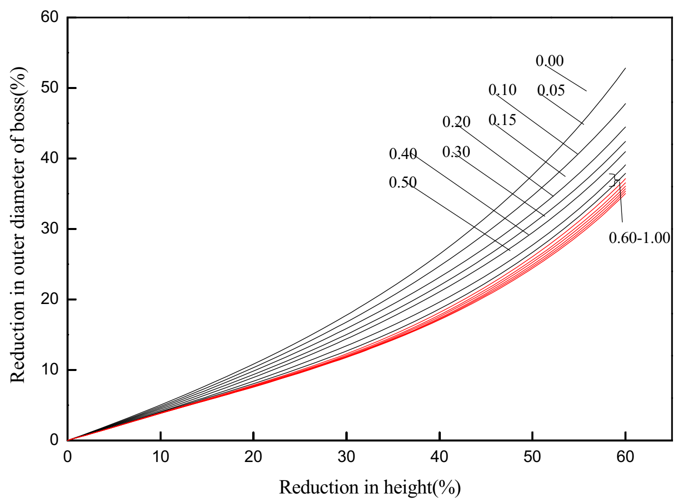


Fig. 8. Calibration curves for the RCT-B.

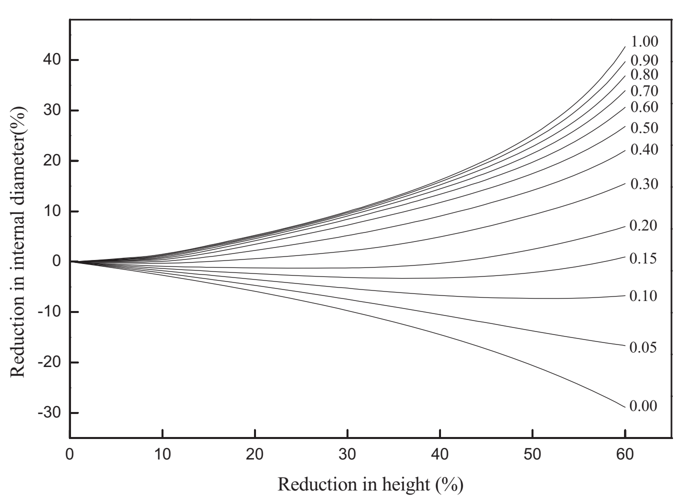


Fig. 9. Calibration curves of the RCT approach.

It is observed that of the change of the outer diameter of the boss in RCT-B is less sensitive than that of the inner diameter in the RCT, and when the friction factor is larger than 0.5 it would be difficult for the RCT-B to quantitatively determine the friction condition. However, in most cold forging processes the friction factor would be less than 0.5, so the RCT-B method could be used to measure the friction conditions.

For further study, FE simulations were carried out with different friction factors between the top and bottom die–workpiece interfaces. As shown in Fig. 10, because of the friction difference the outer boss of the ring can't keep horizontal after deformation, and the outer boss inclines to the bottom die with relatively larger friction factor. Compared the figures from the left to the right in Fig. 10, it can be found that greater friction differences result in larger inclined angle of the outer boss. When the friction difference is only 0.01, the inclined angle is very small and could be ignored, as shown in Fig. 10c and e). With the friction difference increased to 0.02, the inclined angle can be observed easily, as shown in Fig. 10d and f). As discussed above, the sensitivity to the interfacial friction of the RCT-B reduces when the friction factor becomes larger than 0.5. Therefore, the inclined angles under the same friction difference between the top and bottom surfaces at higher friction conditions (Fig. 10i–k) are obviously smaller than the results at lower friction conditions (Fig. 10a, b, g and h) as expected.

As shown in Fig. 10k, the friction factors at the top and bottom die–workpiece interfaces are supposed to be 0.70 and 0.75, respectively, and the inclined angle is small. However, when the reduction in height is increased from 60% to 65%, the inclined angle becomes larger. The inclined angle of the outer boss also increases with the increase of deformation during the RCT-B as shown in Fig. 10k and l.

Based on the above analysis, the RCT-B can be used to evaluate the lubrication performance (friction condition) by using different lubricants between the top and bottom die–workpiece interfaces in one simple test. According to the simulation results, if the friction difference is more than 0.02 at lower friction condition and is more than 0.05 at larger friction condition, it is possible to distinguish the difference by simply investigating the inclined angle of the outer boss of the ring.

4. Experimental works

The workpieces shown in Fig. 11 were machined from annealed Al6082 bar. For the ring workpieces with outer boss, the nominal dimensions of the outer diameter, inner diameter, height, as well as the height and width of the outer boss are 18.00 mm, 9.00 mm, 6.00 mm, 1.20 mm and 1.20 mm, as shown in Fig. 4. For the conventional ring workpiece, the nominal dimensions of the outer diameter, inner diameter and height are 18.00 mm, 9.00 mm and 6.00 mm, respectively.

Two cylindrical dies with 100.00 mm diameter were machined and hardened by heat treatment, and then the die surface rehardening was carried out by Tufftride process. The working surface of the die was treated by lapping and polishing processes and the mirror surface with a surface roughness of Ra 0.05 μm was achieved, as shown in Fig. 11c.

Three types of lubricating oils were adopted as the lubricant for the tests, and the main properties are shown in Table 1. During each test, the die working surfaces were cleaned up with alcohol at first, then a lubricating oil was brushed on them as even as possible, after that a workpiece was put in the middle and the compression test was performed.

All the tests were conducted on a 250 kN Instron 5985 material testing machine and the compression velocity was controlled at 1 mm/min by a Bluehill2 system. The dimensions of workpiece before and after compression were checked using a digital vernier caliper. During the RCT-B tests, the initial outer diameter of boss, outer diameter and height of each workpiece were measured, and the outer diameter of boss and the height were also measured after test, each dimension was obtained from the average of three measurements. During the conventional RCT tests, the initial inner diameter and height of each workpiece were measured, and the inner diameter and height were also measured according to the recommendation from Wang and Lenard (1992), each dimension was obtained from the average of four measurements.

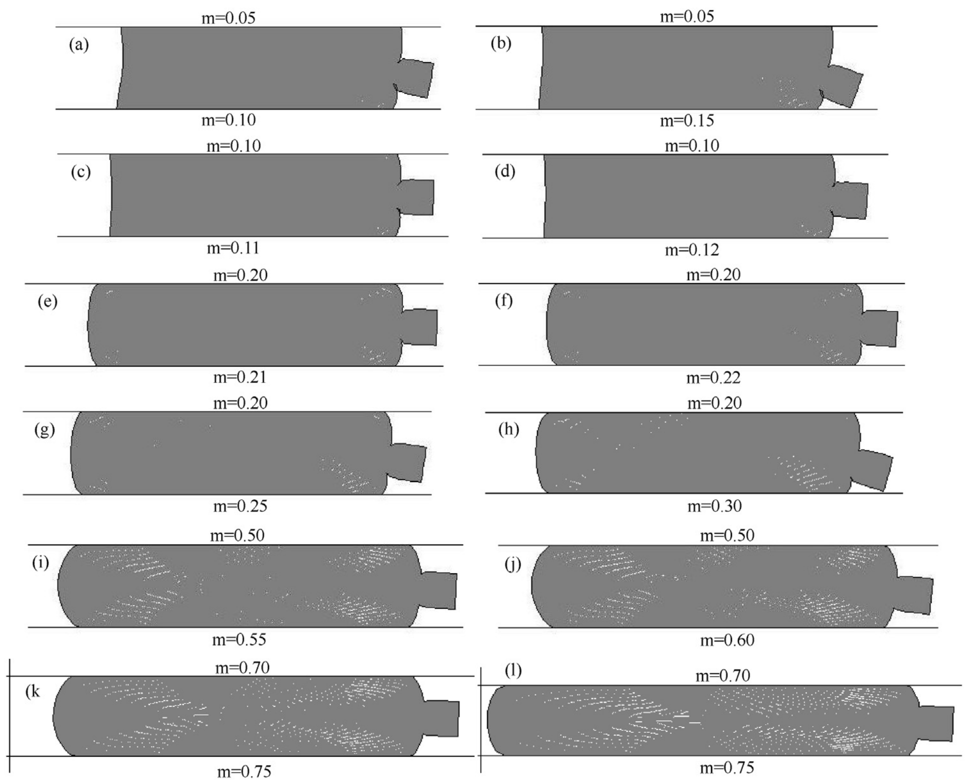
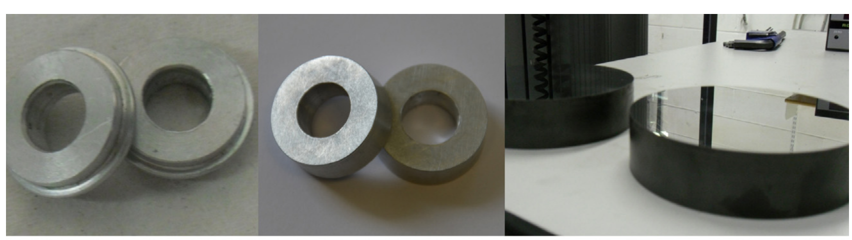


Fig. 10. Deformation results with different friction factor between the top and bottom die: (a) $R_H = 60\%$; (b) $R_H = 60\%$; (c) $R_H = 60\%$; (b) $R_H = 60\%$; (d) $R_H = 60\%$; (h) $R_H = 60\%$; (i) $R_H = 60\%$; (j) $R_H = 60\%$; (k) $R_H = 60\%$; (l) $R_H = 65\%$.



(a) Workpiece for RCT-B (b) Workpiece for RCT (c) Dies

Fig. 11. Workpieces and dies for experimental tests.

5. Results and discussion

5.1. Determination of friction factors

Fig. 12 shows the deformation condition of the ring workpieces with outer boss after compression at different height reductions. It can be observed that the workpieces after compression under the dry dies still kept in circular shape even when the reduction in height reached 58%. And as expected according to the simulation results discussed above, little deformation took place at the outer boss. This confirms that the shape of the outer boss remains undeformed during the test.

By calculation of the reduction of the outer diameter of boss and the reduction of height, the friction factors under four different lubricating conditions including the use of three lubricants and dry contact between the workpiece and dies were determined based on the calibration curves presented in Fig. 8. As observed in Fig. 13, the friction factors with lubricating oil A, B and C are 0.21, 0.20 and 0.22, respectively. The friction factor under dry contact condition is 0.24.

For the conventional RCT cases, the reduction of the inner diameter and the reduction of height were also calculated, and the corresponding data are shown in Fig. 14. From the calibration curves, the friction factors from the conventional RCT cases with

Table 1
Lubricating oils using in the test.

No.	Lubricating oil	Density@15 °C/kg/m^3	Kinematic viscosity @40 °C/mm^2/s	Kinematic viscosity @100 °C/mm^2/s	Viscosity index
A	Rando HD68	–	64.6	8.4	98
B	Magna BD68	880	68	8.7	99
C	Magna 100	890	100	11.1	97

(a) R_H =49.67% (b) R_H =50.17% (c) R_H =58.13%

Fig. 12. The ring workpiece with outer boss after compression under the dry dies.

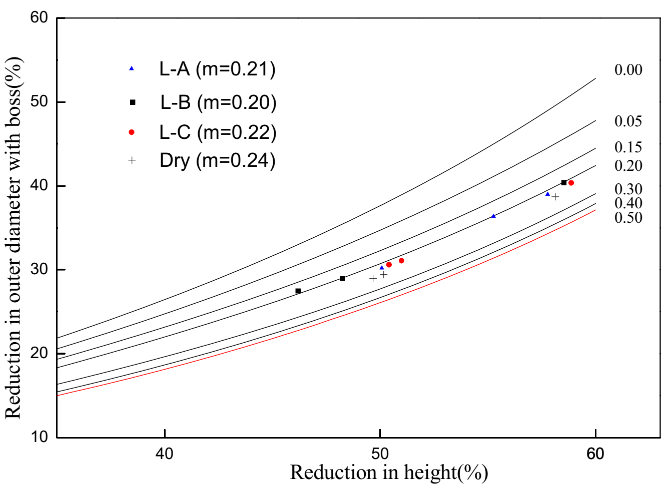


Fig. 13. Experimental data points on the calibration chart of the RCT-B tests.

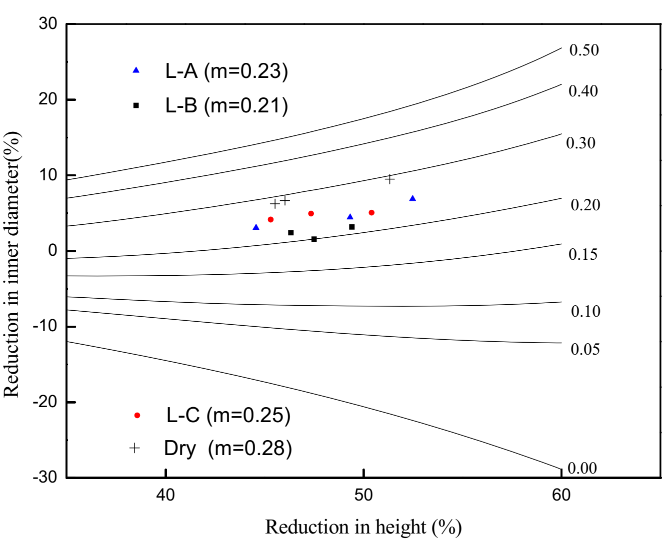


Fig. 14. Experimental data points on the calibration chart of the conventional RCT tests.

(a) R_H =45.53% (b) R_H =46.03% (c) R_H =51.32%

Fig. 15. The ring workpiece after compression under the dry dies.

lubricating oil A, B and C could be determined as 0.23, 0.21 and 0.25, respectively, and the friction factor at dry contact condition can be determined as 0.28.

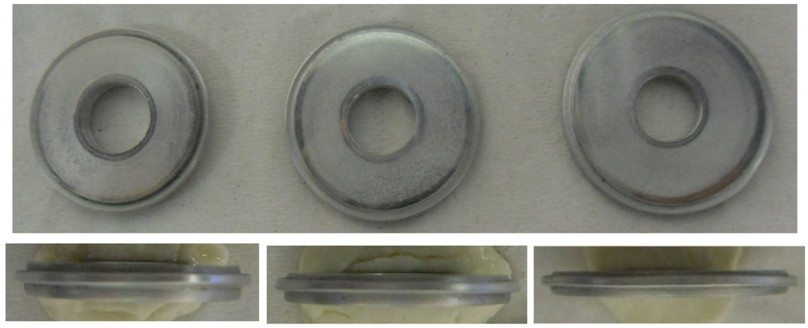
Comparing the test results obtained by both the RCT-B and RCT methods, the measurements of four different friction conditions from the RCT-B cases are in a good agreement with that from the conventional RCT method producing a maximum error less than 15% in the dry contact condition, as shown in Table 2. In general, the specific friction factor determined by the RCT method is larger than that from the RCT-B method. As shown in Fig. 15, the inner diameter of the conventional RCT ring is not circular and instead it becomes an oval shape especially at larger reduction of height. The minimum inner diameter due to the oval shape to a certain degree contributes to the relative larger reduction of inner diameter and hence larger friction factor value.

5.2. Evaluation of lubrication conditions

To evaluate the frictions under different lubricating conditions at the top and bottom surfaces between the workpiece and dies, only the lower die was brushed with the best lubricating oil Magna BD68 and followed by compressions of three workpieces with outer boss. As shown in Fig. 16, the workpieces remain in circular shape basically, and the outer boss is inclined to the upper die under dry condition, and the inclined angle of the outer boss increases with the reduction of height during the test. These experimental results are in good agreement with the simulation results as discussed in Section 4, which further proves that the difference in lubrication conditions can be recognized by checking the inclined angle of the outer boss of the ring.

Table 2
Friction factors determined by different tests.

No.	Lubricating oil	Friction factor *m* (RCT test)	Friction factor *m* (RCT-B test)	Error (%)
A	Rando HD68	0.23	0.21	8.7
B	Magna BD68	0.21	0.20	4.8
C	Magna 100	0.25	0.22	12.0
D	Dry condition	0.28	0.24	14.3



(a) R_H =44.28% (b) R_H =52.07% (c) R_H =58.80%

Fig. 16. The ring workpiece with outer boss after compression with different lubricating conditions between the upper and lower die–workpiece interfaces.

6. Conclusions

(1) An alternative quantitative evaluation method for the friction conditions in cold forging by ring with boss compression test was proposed in order to address the difficulties encountered in the measurement of the inner diameter in conventional ring compression test.
(2) For the RCT-B test, the proposed proportion of ring geometry of the outer diameter, inner diameter, height and the height o and width of the outer boss was designed to be 6:3:2:0.4:0.4. The compression processes of the ring with boss under different friction conditions were simulated and the results showed that the shape of the outer boss remains undeformed during the ring deformation. The undeformed outer boss was verified by the RCT-B experimental results to allow the outer diameter of boss to be measured easily and precisely, which enables more accurate measurement of friction conditions.
(3) The calibration curves of the new RCT-B concept and the conventional RCT methods are both constructed by FE simulations. Although the change of the outer diameter of boss in RCT-B is less sensitive than that of the inner diameter in the conventional RCT, it is still sufficient for accurate prediction of friction condition when the friction factor is less than 0.5. Therefore the RCT-B method can be used to measure the range of friction conditions in cold forging process.
(4) The RCT-B method was successfully applied to determine the friction factors of four different lubricating conditions with aluminum workpieces. The RCT-B measurement results were verified by conducting experimental tests using the conventional RCT method. The testing results from both the RCT-B and conventional RCT were in a good agreement in terms of the measured friction factors with a maximum error less than 15%.
(5) FE simulations with different friction factors between the top and bottom die–workpiece interfaces are carried out. The outer boss is inclined to the die surface of greater friction, and the inclined angle of the outer boss becomes larger with greater friction difference between the interfaces. The inclined angle tends to increase with the increase of deformation during the RCT-B as observed by RCT-B testing results. This observation leads to the conclusion that the difference of lubrication conditions can be quantitatively evaluated by simply investigating the inclined angle of the outer boss under ring compression conditions.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 51475294), FP7-Marie Curie Action IRSES MatProFuture project (No. 318968) and the Engineering and Physical Sciences Research Council (EPSRC, EP/L02084X/1). The useful discussion with Prof. Niels Bay from Technical University of Denmark on the tooling lapping and polishing during the 46th ICFG Plenary Meeting in Paris should be mentioned. The authors wish to thank the Mr. Tom Buss of the Faculty of Engineering at Nottingham for his support in experimental testing.

References

Abdul, N.A., 1981. Friction determination during bulk plastic deformation of metals. CIRP Ann.—Manuf. Technol. 30 (1), 143–146.
Andersson, K., Kivivuori, S., Korhonen, A.S., 1996. Effect of the heat-transfer coefficient in ring-compression tests. J. Mater. Process. Technol. 62 (1), 10–13.
Avitzur, B., 1964. Forging of hollow discs. Isr. J. Technol. 2 (3), 295–304.
Depierre, V., Gurney, F., 1974. A method for determination of constant and varying friction factors during ring compression tests. J. Lubr. Technol., Trans. ASME 96, 482–488.
Goetz, R.L., Jain, V.K., Morgan, J.T., Wierschke, M.W., 1991. Effects of material and processing conditions upon ring calibration curves. Wear 143 (1), 71–86.
Hartley, R.S., Cloete, T.J., Nurick, G.N., 2007. An experimental assessment of friction effects in the split Hopkinson pressure bar using the ring compression test. Int. J. Impact Eng. 34 (10), 1705–1728.
Hawkyard, J.B., Johnson, W., 1967. An analysis of the changes in geometry of a short hollow cylinder during axial compression. Int. J. Mech. Sci. 9 (4), 163–182.
Kunogi, M., 1956. A new method of cold extrusion. J. Sci. Res. Inst. (Tokyo) 50, 215–246.
Lee, C.H., Altan, T., 1972. Influence of flow stress and friction upon metal flow in upset forging of rings and cylinders. J. Eng. Ind., Trans. ASME 94, 775–782.
Liu, J.Y., 1972. An analysis of deformation characteristics and interfacial friction conditions in simple upsetting of rings. J. Eng. Ind., Trans. ASME 94, 1149–1156.
Macaskill, S., 2012. The effect of friction on the geometric deformation of aluminium for a ring compression test. In: Final Year Report. The University of Nottingham.
Male, A.T., Cockcroft, M.G., 1964–1965. A method for the determination of the coefficient of friction of metals under conditions of bulk plastic deformation. J. Inst. Met. 93, 38–46.
Male, A.T., Depierre, V., 1970. The validity of mathematical solutions for determining friction from the ring compression test. J. Lubr. Technol., Trans. ASME 92, 389–397.
Petersen, S.B., Martins, P.A.F., Bay, N., 1998. An alternative ring-test geometry for the evaluation of friction under low normal pressure. J. Mater. Process. Technol. 79 (1), 14–24.
Rao, K.P., Sivaram, K., 1993. A review of ring-compression testing and applicability of the calibration curves. J. Mater. Process. Technol. 37 (1), 295–318.
Robinson, T., Ou, H., Armstrong, C.G., 2004. Study on ring compression test using physical modelling and FE simulation. J. Mater. Process. Technol. 153, 54–59.
Schroeder, W., Webster, D.A., 1949. Press-forging thin sections: effect of friction, area and thickness on pressure required. J. Appl. Mech. 16, 289–294.
Shahriari, D., Amiri, A., Sadeghi, M.H., 2010. Study on hot ring compression test of Nimonic 115 superalloy using experimental observations and 3D FEM simulation. J. Mater. Eng. Perform. 19 (5), 633–642.
Sofuoglu, H., Rasty, J., 1999. On the measurement of friction coefficient utilizing the ring compression test. Tribol. Int. 32 (6), 327–335.
Tan, X., Martins, P.A.F., Bay, N., Zhang, W., 1998. Friction studies at different normal pressures with alternative ring-compression tests. J. Mater. Process. Technol. 80–91, 292–297.
Wang, F., Lenard, J.G., 1992. An experimental study of interfacial friction-hot ring compression. J. Eng. Mater. Technol. 114, 13–18.
Wang, J.P., 2001. A new evaluation to friction analysis for the ring test. Int. J. Mach. Tools Manuf. 41 (3), 311–324.