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# Flow Stresses in a Hollow Disc of Al 6063 Subjected to Various Interfacial Conditions

**Shrishail Kakkeri[1]*, Namdev Ashok Patil[1], Swati Singh[1] and S. K. Nisha[2]**

*[1]Department of Product Design, Dr. D. Y. Patil School of Design, Dr. D. Y. Patil Vidyapeeth, Pune – 411033, Maharashtra, India; shrishail.kakkeri@dpu.edu.in*

*[2]Sai Vidya Institute of Technology, Bangalore - 560064, Karnataka, India*

## Abstract

*Forging is an operation of deforming the material to the required shape. The forged part will have grain refinement and a good surface finish. Sometimes, especially in cold forming, the finishing operations may not require further machining. The amount of load applied, the rate of deformation, and the surface conditions between the die and workpiece decide the filling of the die without any defects in the deformed components. The flow strength or the flow stress of the material decides the plastic deformation of the material under specified operating conditions. Hence, the flow stress in the bulk deformation of materials has drawn the attention of researchers. Several techniques are made available to find the flow stresses experimentally. Due to simplicity, the Ring Compression Test (RTC) is a more commonly used method. This test utilises the dimensional change of the specimen during compression. Here, an attempt has been made to quantitively analyse the prevailing frictional conditions in the Al 6063 hollow disc using castor oil, grease and dry lubrication conditions. The dimensional changes in the ring were used to draw the friction calibration curves and the stress-strain curves. The friction calibration curves were used to find the friction coefficient. The stress-strain curves were used to form the flow stress equations depending on the prevailing interface conditions. The strength coefficient and the strain hardening coefficient relations were proposed to build empirical relations of flow stresses for various interfacial conditions.*

***Major Findings:*** *The paper shows, an estimation of friction coefficient and flow stresses in the materials by RCT. The test results indicated that the mathematical model formed for a material under defined process conditions data will be helpful for Finite Element (FE) simulation of the process.*

**Keywords:** *Bulk Deformation, Friction coefficient, Hollow Disc, Ring Compression Test (RCT)*

## 1.0 Introduction

It has been the oldest method of forming materials according to the required geometry by forming the material between the die with or without the application of heat. Most of the experimental works use the RCT to find the flow stress in the materials at higher strains[1]. Male *et. al*[2], Burgdorf[3] and Avitzur[4], proposed RTC for the quantitative analysis of frictional stresses and flow stress existing in bulk metal forming. They have obtained the flow stress in the ring compression by assuming the constant interfacial frictional conditions. Yhu *et. al.*,[5] have estimated the flow stress by conducting the RCT. Rao *et al.*,[6] have used calibration curves developed by Lee *et al.*,[7] to find the flow stress in Aluminum alloy specimens. Bremly and Abdul also have used RCT to evaluate the flow stress. They have used the mathematical analysis developed by Avitzur[4]. Nagpal *et al.*,[8] have studied the effect of strain rate and temperature by upper bound analysis of RCT. DePierre and Gurney[9] also

*Author for correspondence

utilised the RCT for flow stress evaluation of flow stress, with and without the effect of bulge formation during RCT.

The RTC was conducted on metallic materials using inverse analysis to predict the flow stresses[10]. The validated results of FE simulation and RCT data show acceptable results. Hasan Sofuoglu and Jahan Rasty[11] have conducted a series of RCTs to find the effect of calibration curves on material properties and the applicability of calibration curves for all types of materials. They conducted the experiments using physical modelling techniques and performed the FE analysis. In conclusion, they observed the effect of the material and the metal flow on the calibration curves. To minimise the differences between the FE simulation and the experimental results, an inverse analysis was proposed to find the flow stress of the material[12]. Here the RCT were performed to predict the flow stress and the friction coefficient. The experimental results and the FE simulation results show a reasonable agreement between the experimental results and the inverse analysis approach.

Upper bound theorem by applying a model of triangular ridge block[13], showed its suitability for flow stress analysis especially under low load conditions. The proposed method used the conical geometry rings for flow stress analysis. Michal Gzyl *etal.,*[14] observed the influence of temperature on metal flow under various interfacial conditions. The RCT results for different levels of deformations were simulated in Forge3 software. The goal of the research was to find the performance of lubricants and the effect of temperature on the metal flow and arrived at a standard method of obtaining friction factors using optimisation procedures in software. P Christiansen *et al.*,[15] proposed a simple and alternate method for the determination of flow stress. The results obtained from cylindrical and Rastegaev specimens were combined with the RCT to compensate for the effect of friction while finding the flow stress. The numerical method of finding the stress-strain curves implemented the Coulomb and Constant friction models. Arpit Srivastava *et al.*,[16] have proposed the best environmental and eco-friendly lubricant by conducting a series of RCTs. They have performed the test by changing the load conditions, temperature and the lubricants. The outcome of the results shows that RCT is a suitable method to find the suitability of lubricant and metal flow conditions at various load conditions and temperatures. To investigate the effect of interfacial friction on the ring specimen geometry and the flow behaviour of metal[17], RCT and DEFORMA were used. The friction calibration curves were generated by simulation of RTC in DEFORM 2D and the friction factor required for simulation was calculated by FE simulation. The calibration curves generated by RCT and DEFORM showed good agreement. Also, they established a relation between the sensitive change in the inner diameter of the ring, friction condition and the angular velocity during the RCT. The RCT evaluation[18] of friction coefficient, measurement of flow stress and developing flow stress equations under bulk deformation processes at elevated temperatures confirmed with acceptable lesser errors. Here, flow stress equations for Q420 steel and high-speed carbon steel specimens have been demonstrated.

Because of the influence of friction between the workpiece and the die interfaces measurement of flow stress under high strain is a difficult task. Recently, Junfu Chen *et al.*,[19] have proposed a hyperbolic specimen. This specially designed shape of the specimen was used to estimate the flow stress in bulk deformation. Upsetting the test or RCT method for evaluating the mechanical properties of materials has become a common method. In such cases, the flowability of the material depends on the interfacial frictional conditions, the temperature of operation, strain and strain rate. Different methods are used to experiment on friction at the tool-workpiece interface and flow stress in the bulk deformation processes. The methodology for determining the interfacial friction between the tool and workpiece varies depending on the specific metalworking process selected. In open and closed die forging, the quantitative evaluation of friction could be carried out by double-cup extrusion and RCT methods. Among these methods, the RCT method has been used by many investigators due to its simplicity and ease of calculations[20]. The RCT is suitable for finding flow stress at high strains. The flow stress data obtained is used to determine the stages of compression required to achieve the final shape of the product. FEA tools, which reduce cost and time from the concept stage to final product manufacture, have been extensively used to study and analyse the metalworking process. The FE simulation result is sensitive to boundary conditions. Among these input boundary conditions as demanded by the software,

the friction coefficient is given as a range of values which does not reflect the realistic values occurring at the interface and a single-valued friction coefficient is the input.

In addition to these, many researchers have proposed the suitability of RCT to estimate the coefficient of friction and friction factors. Kozo Osakada *et al.*,[21] have performed a series of RCT on ring specimens made of different materials. They obtained the coefficient of friction at the interface of the die and specimen using different lubricants like Vaseline. The flow stress is estimated by them without controlling the friction. Santosh *et al.*,[22] have evaluated the friction coefficients for different geometries. These geometries do not follow the dimensional ratio proposed by Hassan. The coefficient of friction obtained for the non-conventional rings and the standard rings were compared and the process of RCT was simulated via FE. The predicted results do not show deviation. Another work performed by Shrishail Kakkeri *et al.*,[23] obtained friction coefficient under lesser deformation loads using RCT and its FE analysis shows acceptable results.

Dawei Zhang *et al.*,[24] observed the variation in the friction condition, the lubrication effect and the surface roughness with the deformation levels. The research's RCT results show an increase in friction factor and friction coefficient with an increase in percentage deformation. Khoddam *et al.*,[25] has proposed a closed-form solution which provides the instantaneous values of friction factor in the RCT. They have verified the experimental data with the Feb simulations. Also, they have compared the values of the friction factor with the reference benchmarks. Guangzhao Han *et al.*,[26] have proposed the RCT test to find the modulus of elasticity, stress-strain relations and yield and tensile strengths. The results of experiments show a consistent relation with FE simulation results. In addition, they have performed the RCT for several metallic materials to obtain the mechanical properties. The RCT and the predicted results from uniaxial loading have good agreements. Since the consumption of material in the RCT is lesser as compared with the standard uniaxial loading method, it gained additional attention to find the mechanical properties of metallic materials. Jacob Hatherell *et al.*,[27] have proposed the RCT method to evaluate the relationship between the instantaneous friction coefficient values with contact pressure. Since the friction values do not remain constant concerning the other variables like the surface morphology, surface roughness contact pressure and strain rate, this RCT was found to be the most suitable method to obtain the flow stress and the realistic friction coefficient values.

It has been reported in a few kinds of literature that with an increase in environmental concern, the use of non-biodegradable oils like mineral oil as lubricants in metal deformation will have an impact on the environment. Aiman *et al.*,[28,29] have used Palm Kernel oil as a lubricant in RCT. Shrishail Kakkeri *et al*[23], have used castor oil as a lubricant for RCT. They have shown the performance of these biodegradable oils with other lubricants in the RCT. Hence, in the present work, castor oil has been used as a lubricant, to find the flow stress in the ring materials.

Since the RCT is one of the reliable methods to find the flow stresses in the material, it has become a popular method. In the present experimental work, the RCT is performed for dry, and lubricated conditions, and the flow stress equations were proposed for these interfacial conditions, namely castor oil, grease and dry conditions. The Al6063 specimens were used to perform RCT. The change in dimensions of the test ring by compression test was used to find the friction coefficients. The flow stress empirical equations were developed in terms of its strength coefficient and strain hardening coefficient.

## 2.0 Materials and Methods

The experiments were conducted on a Universal Testing Machine (UTM) with a suitable required setup for displacement measurement and provision for locating the top and bottom platens. Table 1 shows the specific gravity and viscosity of selected lubricants (Castor oil and Grease) for the experiment. The specimens used to conduct the experiments were cut down from a forged circular rigid rod of Al6063. Table 2 shows the composition by weight of Al6063.

Figure 1 shows the specimens used for the RCT and the deformed specimens. The hollow ring specimen is measured for the Outer Diameter (OD), Inner Diameter (ID) and Thickness (T). To avoid errors, dimensions are noted from four locations (i.e. diametrically opposite) and

**Table 1.** Specific gravity and viscosity of lubricants[23]

| Liquid | Specific gravity | | Viscosity | |
|---|---|---|---|---|
| | Temp. °C | Based on water = 1 at 15.5°C | Temp. °C | Centistokes |
| Castor oil | 20<br>40 | 0.96<br>0.95 | 37.8<br>54.4 | 259-325<br>98-130 |
| Grease | 16 | 1.8531 | 38<br>99 | 148<br>45 |

**Table 2.** Composition by weight of Al 6063[23]

| Sl No. | Constituents | Percentage by weight | Sl. No. | Constituents | Percentage by weight |
|---|---|---|---|---|---|
| 1 | Mg | 0.78 | 5 | Si | 0.36 |
| 2 | Cu | 0.08 | 6 | Fe | 0.12 |
| 3 | Cr | 0.05 | 7 | Ti | 0.01 |
| 4 | Mn | 0.06 | 8 | Al | Remainder |

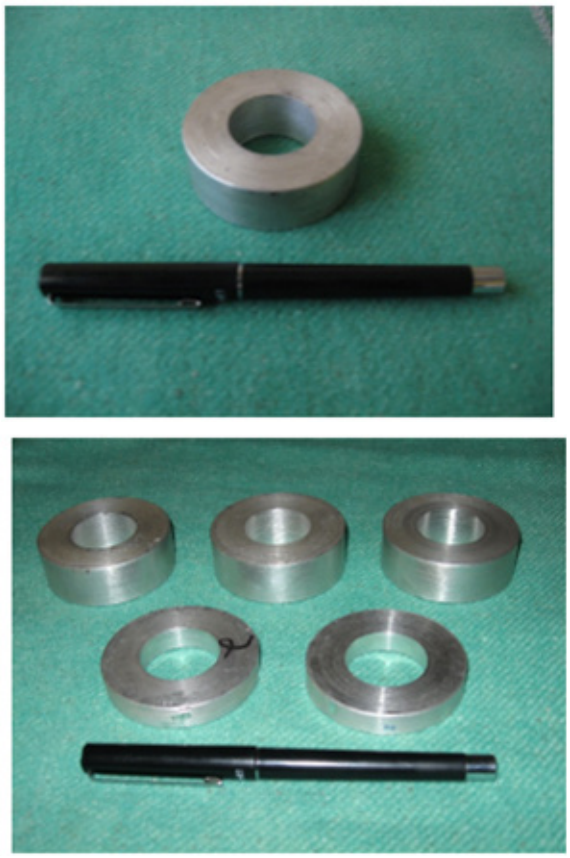


**Figure 2.** Al 6063 specimens used for the experiment.

the average of these has to be considered for further calculations.

The procedure for conducting the experiments was according to the ASM B938-16 standards. The specimen was cleaned and located between two platens. No attempts were made to finish the surface. The experiments were conducted approximately at a controlled strain rate between 0.02 s-1 – 0.05s-1. For lubricated interfacial conditions, for every stage of deformations, lubricant was applied to the specimen before the next stage of deformation. The dimensions of the specimens have the same ratio of 6:3:2 for the test using lubricants and 6:3:1 for dry conditions respectively (OD: ID: T). The specimens were cleaned and no attempts were made to finish the surface of the specimens. The specimens' initial thickness and inner-outer diameters were recorded (average of four readings taken diametrically opposite). The specimen was loaded on UTM by applying the lubricant, for a pre-determined thickness reduction, the change dimensions were measured at four locations and the average values were recorded as shown in Table 3 and Table 4. The experiments were repeated for different height reductions.

## 3.0 Results and Discussions

The percentage change in the thickness and percentage change in the inner diameter values were used to construct the Friction Calibration Curves (FCC) as shown in Figure 2 and Figure 3. The percentage change in inner diameter and the percentage change in the thickness of the test rings were used to construct the FCC. At threshold load, observed sensitive deformations were measured along with the load applied. The flow stress equations were constructed by considering the true stress-strain curves and the flow stress curves. Figure 1, shows the FCC of the Male, Cocroft and superimposed curve for AL 6063 using castor oil as lubricant. At the initial stage of up to 35% of deformation, the friction coefficient is between 0.02 and 0.04. At the initial stage of compression, the ring specimen may not have uniform contact between the die platens due to the elastoplastic deformation of asperities present on the workpiece. Anyhow, during the quantitative analysis of the friction coefficient prevailing at the interfaces, the asperity deformations have not been considered. Using castor oil as a lubricant, the coefficient of friction attained a value of 0.06 for 45% deformation of the specimen.

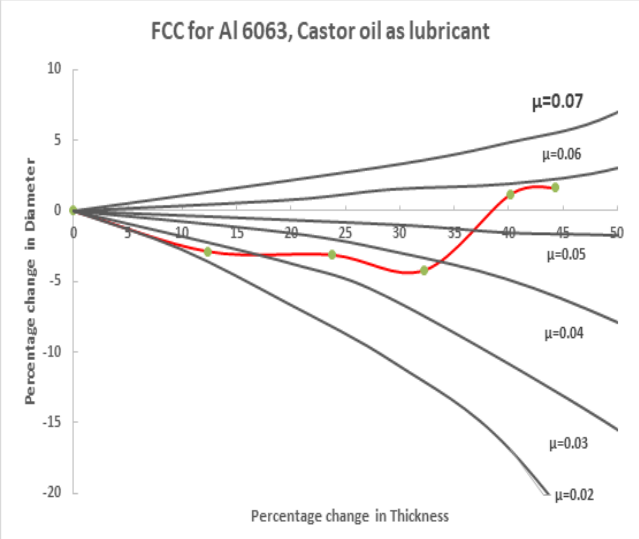



**Figure 2.** Friction coefficient for Al 6063, using castor oil as lubricant.

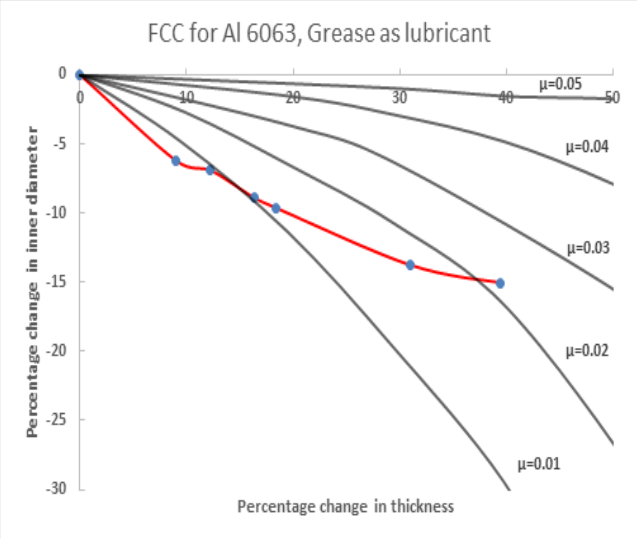



**Figure 3.** Friction coefficient for Al 6063, using grease as lubricant.

**Table 3.** RTC of Al 6063, castor oil as lubricant
(Initial specimen data: OD: 60.12mm, ID: 29.60mm and T: 19.81mm)

| Experimental Readings | | | | | | Calculated Values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Change in OD (mm) | | Change in ID (mm) | | Thickness T (mm) | Load (kN) | %Av. ID | %T | ε | σ MPa | μ |
| Interface | Middle | Interface | Middle | | | | | | | |
| 63.67 | 63.82 | 30.57 | 30.33 | 17.36 | 373.95 | -2.87 | 12.37 | 0.132 | 152.64 | 0.02 |
| 66.55 | 67.02 | 30.64 | 30.40 | 15.11 | 542.25 | -3.11 | 23.73 | 0.270 | 197.82 | 0.03 |
| 70.01 | 70.47 | 30.92 | 30.77 | 12.42 | 678.05 | -4.21 | 32.26 | 0.389 | 218.82 | 0.04 |
| 72.03 | 72.92 | 29.47 | 29.02 | 11.84 | 834.80 | 1.20 | 40.23 | 0.515 | 246.05 | 0.06 |
| 73.73 | 74.80 | 29.82 | 28.41 | 11.03 | 891.85 | 1.64 | 44.32 | 0.586 | 249.74 | 0.06 |

At various stages of percentage deformations of the specimen, the quantitative values are tabulated in Tables 3, 4 and 5. These tables also show the experimental observations and calculated values for castor oil, grease and dry interfacial conditions respectively. Table 3 shows the friction coefficient prevailing at the s interface of the die and specimen using grease as a lubricant. Figure 2 shows the value of the friction coefficient as 0.02 for 40% deformation of the specimen. For dry interfacial conditions, the friction coefficient has a value of 0.12 for 25% deformation of the specimen as shown in Figure 3. Figure 4 shows the load variation during RCT, using castor oil, grease and dry interfacial conditions.

It indicates that, with an increase in friction coefficient values at the interface of the die and the specimen, a maximum amount of load is required. Hence, an interfacial condition in RCT shows a minimum load requirement for castor oil and grease as lubricant. Figures 5, 6, 7 and 8 describe the procedure to construct the flow stress equation in the form of $\sigma = K\ \varepsilon n$. Hence the flow stress equation for a particular interfacial condition can be formed in RCT and is independent of the frictional

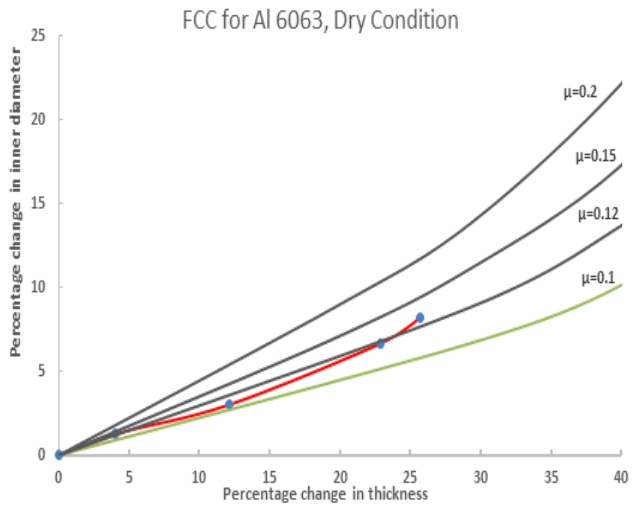



**Figure 4.** Friction coefficient for Al 6063, dry interfacial conditions.

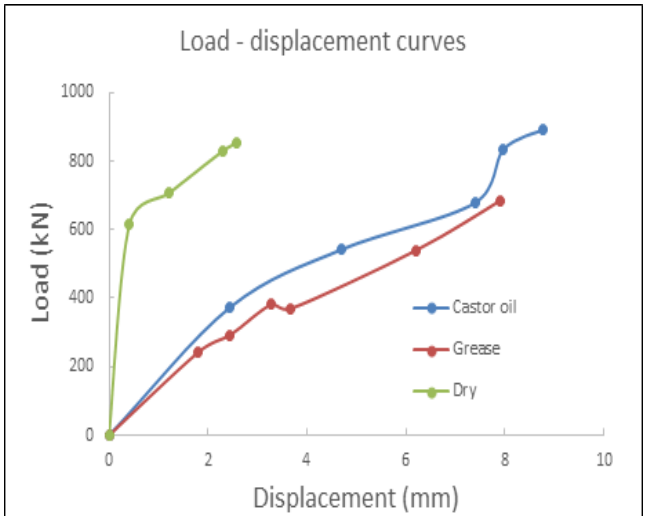



**Figure 5.** Variation of load-displacement curve for Al 6063, under various interfacial conditions.

**Table 4.** RTC of Al 6063, grease as lubricant
(Initial specimen data: OD: 60mm, ID: 30mm and T: 20mm)

| Experimental Readings | | | | | | Calculated Values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Change in OD (mm) | | Change in ID (mm) | | Thickness T (mm) | Load (kN) | %Av. ID | %T | ε | σ MPa | μ |
| Interface | Middle | Interface | Middle | | | | | | | |
| 61.43 | 61.47 | 31.48 | 31.32 | 18.19 | 243.15 | -6.224 | 9.05 | 0.095 | 111.27 | 0.010 |
| 62.47 | 62.63 | 31.63 | 31.57 | 17.55 | 293.05 | -6.901 | 12.25 | 0.131 | 128.57 | 0.010 |
| 63.15 | 63.79 | 32.23 | 32.16 | 16.72 | 382.10 | -8.913 | 16.40 | 0.179 | 161.49 | 0.010 |
| 64.76 | 65.00 | 32.45 | 32.35 | 16.33 | 369.50 | -9.607 | 18.35 | 0.203 | 149.78 | 0.015 |
| 68.52 | 69.24 | 33.70 | 33.55 | 13.80 | 539.70 | -13.751 | 31.00 | 0.371 | 193.06 | 0.015 |
| 72.55 | 73.15 | 34.04 | 33.97 | 12.10 | 684.35 | -15.036 | 39.50 | 0.503 | 212.28 | 0.02 |

**Table 5.** RTC of Al 6063, dry lubrication condition

(Initial specimen data: OD: 60.04mm, ID: 30.04mm and T: 10.08mm)

| Experimental Readings | | | | | | Calculated Values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Change in OD (mm) | | Change in ID (mm) | | Thickness T (mm) | Load (kN) | %Av. ID | %T | ε | σ MPa | μ |
| Interface | Middle | Interface | Middle | | | | | | | |
| 61.44 | 61.47 | 29.78 | 29.65 | 9.67 | 615.05 | 1.279 | 4.067 | 0.0415 | 271.16 | 0.20 |
| 62.98 | 63.19 | 29.33 | 29.06 | 8.86 | 707.50 | 3.007 | 12.103 | 0.129 | 290.00 | 0.18 |
| 66.20 | 66.33 | 28.32 | 27.86 | 7.77 | 830.80 | 6.678 | 22.917 | 0.260 | 295.44 | 0.15 |
| 66.91 | 67.12 | 27.79 | 27.48 | 7.49 | 854.00 | 8.190 | 25.694 | 0.297 | 293.50 | 0.15 |

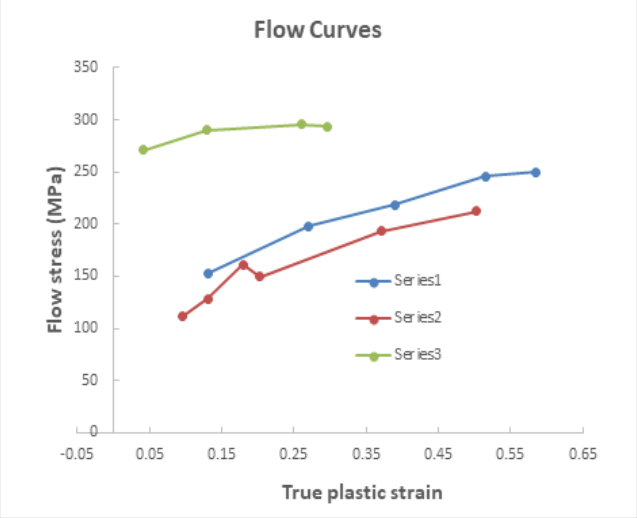



**Figure 6.** Experimental flow curves for Al 6063, under various interfacial conditions.

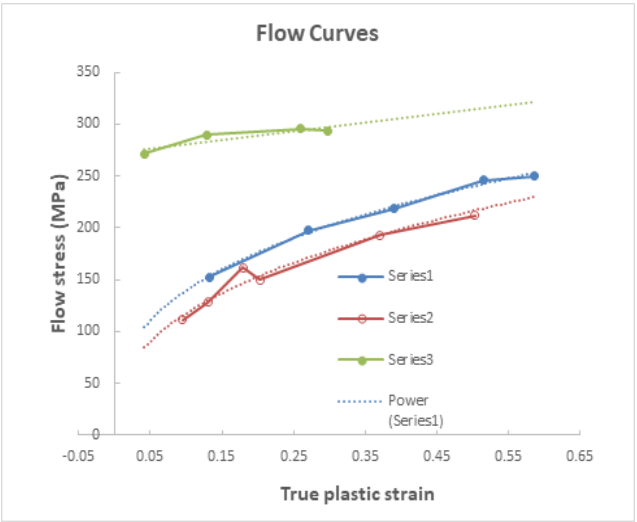



**Figure 7.** Experimental and extrapolated flow curves for Al 6063, under various interfacial conditions

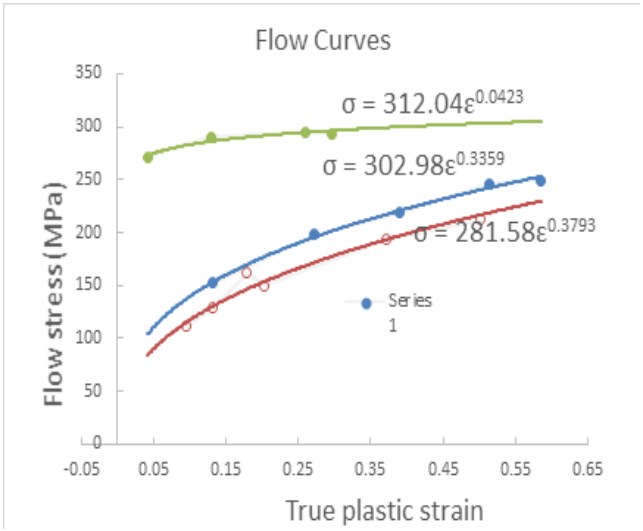



**Figure 8.** The flow stress power curves for different interfacial conditions in Al6063 RCT.

coefficient. Where K is the strength coefficient and n is the strain-hardening exponent. From Table 6, it is observed that the strength coefficient decreases with a decrease in friction coefficient and the strain hardening will have higher values with a decrease in coefficient of friction during RCT.

**Table 6.** The flow stress power curves for different interfacial conditions: Al 6063

| Interfacial Condition | Power Curve (Flow stress Equation) | Friction Coefficient (μ) |
|---|---|---|
| Dry | $\sigma = 312.04\ \varepsilon^{0.0423}$ | 0.12 |
| Castor oil | $\sigma = 302.98\ \varepsilon^{0.3359}$ | 0.06 |
| Grease | $\sigma = 281.58\ \varepsilon^{0.3793}$ | 0.02 |

From Table 6, averaging the values of K and n for grease and castor oil as lubricants, a new mathematical relation model for Al 6063 was obtained $\sigma = 292\varepsilon^{0.5}$. Figure 7 shows the flow stress curve obtained from this relation in comparison with experimentally determined curves using grease and castor oil as lubricants. The mathematically modelled curve is in good agreement with the experimentally determined curves and hence the above relation could be used as a mathematical model of Al 6063. The observations made by Li et al.,[30] show that the flow stress is not affected by the presence or absence of lubricant. The present investigation indicates that, for all the interfacial friction conditions and different materials the flow stress shows small variations under lubricated conditions and appreciable variations under dry conditions.

## 4.0 Conclusion

The RCT test has been performed using Al 6063 material for the ring specimen. The male and Cocroft Calibration Curves were used to estimate the friction coefficient at various stages of deformations using castor oil, grease and dry interfacial conditions. It has been observed that the influence of fraction coefficient on the load-displacement, with an increase in friction at the interface during RCT, the flowability of material will have restrictions and required maximum load. In the forming of metals, the forming load is decided by the flow stress of the material, which in turn is dependent on temperature and strain rate. Using standard ring geometry and various lubricating conditions the values of K and n in the relation were evaluated, where K is the strength coefficient and n is the strain hardening coefficient. The values of K and n reveal that for the identical materials and forming conditions with different lubricants, the flow stress values differ whereas the flow stress is expected to remain constant. This indicates that the flow stress tends towards being dependent on the interfacial friction. It has been observed from the experiment that, with an increase in interfacial friction coefficient, the strength coefficient attains the maximum value and the strain hardening exponent attains the minimum value. The process of constructing flow stress equations for various lubrication conditions shows that these equations can be formulated without considering the friction coefficient.

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