Applying the friction ring test on a micro and meso scale

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Abstract: This study analyses the friction between a micro/meso part and a tool using the friction ring test. Four different materials were analysed, SAE1020 steel, AISI304 stainless steel, AA6531 aluminium and C34000 brass. Compression tests were performed on the four materials to determine the material flow stress curves of two different test specimen sizes and look at the size effect on the compression test. Three different ring sizes in four different materials analysed were used for the friction ring tests, applying molybdenum bisulphide-based lubrication. Based on the results of the flow stress curves, the calibration curves were performed with the SIMUFATC software for each material and size of friction ring using the Amontons-Coulomb friction model. The results of the experiments indicate a reduction in friction as the part becomes smaller, and the factor material influences the reduction of friction between the part and the tool.

Keywords: friction ring test; micro parts; calibration curves; manufacturing systems.

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1 Introduction

Geiger et al. (2001) defined microforming as a manufacturing technique for very small materials, particularly for mass production (Krishnan et al., 2005).

Authors like Vollerten (2004), Watanabe et al. (2001) and Qu et al. (1997) demonstrated the importance of the study and application of Microparts in the production of micro electromechanical systems (MEMS) for cell phones, MP3 format music players, digital cameras, and medical equipment in general. This can be called micro systems technology and it is also used for other applications.

Research of macro manufacturing systems cannot be applied entirely to micro processes due to effects resulting from part size (Fleischer et al., 2006), where the difference between the macro and micro sized parts, number of grains present in the metallographic die influence the final result of the forming process.

In a micro part manufacturing process, such as micro extrusion, friction between the part and the tool is one of the most important factors determining the surface quality of the material, influencing the force applied to form the material (Schaeffer, 2004). Other factors that influence metal forming are the chemical composition of the material, the heat transfer coefficient and the mechanical properties expressed by the behaviour of the material being deformed (Rudkins et al., 1996).

The importance of friction in the deformation process is clearly shown by its contribution to the success or failure of the process to meet its goals.

It is important to understand the friction phenomenon, since it shows what happens between the part surface and the surface of the forming die in different forming process conditions according to Sofuooglu and Rasty (1999). Friction occurs on the contact surface between the forming die and the part, and it plays a major role in the material flow in the die (Petersen et al., 1998).

The objective of this study is to determine if the friction ring test can be used to determine the friction between a micro/meso size part and a tool.

This method is frequently used in macro size parts, but other methods are used for micro and meso size.
2 Theoretical fundamentals

2.1 Surface roughness

One of the basic premises of friction is that apparently polished surfaces present imperfections when seen on a microscopic scale.

Sahin (2007) says that these imperfections are known as roughness, representing the coarseness of the material surface. The dies, punches and tools are characterised by surface roughness which affects the friction between the tool and the part, especially at the beginning of the forming process.

Roughness is a way of describing the surface quality of forming tools, where, to achieve the best result with the tools at low cost it is essential to keep control of the quality of the tool surface. In order to keep this control, there are several methods to determine the surface roughness, ranging from visual inspections with a magnifying glass to scanning electron microscopy. However, the most frequent method in industry to measure roughness uses electronic scanning and tracing equipment called a portable surface roughness tester.

At the beginning of the forming process, friction is determined by roughness distribution, and depending on roughness variation in the tool, there can be considerable changes in friction during the forming process.

2.2 Ring compression test

The ring compression test was initially suggested 50 years ago by Kunogi and developed by Male and Cockcroft who, in the 1960s began to use the method to measure friction in a forging process (Anderson et al., 1996).

Figure 1 shows the design of the compression ring used in a friction test.

Figure 1 Design of a model used in a compression test

Source: Hartley et al. (2007)

The ring compression test consists in using a disk similar to that in Figure 1, with a size ratio of 6:2:3. In other words, if the outer diameter of the ring is 24 mm, the inner diameter will be 12 mm, half the outer diameter, and the height of the disk will be one-third, i.e., 8 mm.

The ring is placed between two compression plates and reduced between 20% and 60% of the initial height with a constant velocity (Dutton et al., 1999). As the height is reduced, the outer diameter of the disk increases. If the influence of friction between the
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plate and ring is equal to zero, both the inner and outer diameter increase radially with the same magnitude as a solid disk. With increased friction, the inner diameter is smaller, and there is a limit friction condition where the inner diameter does not increase.

The advantage of using the friction test with a compression ring is that it is not necessary to know the force needed to compress the ring, nor the flow stress of the material, using only the inner to outer diameter ratio (An and Vegter, 2005).

The use of lubricants in the ring compression test simulates the use of lubricant in the forming process to which the material is to be submitted.

Lubricants are essential for some cold forming processes such as deep drawing where friction between the tool and the part can break the part before the process is ended.

Figure 2 shows the effect of lubricant on a same compressed material.

Figure 2  Effect of lubricant on compression rings

Low friction  High friction

Source: Robinson et al. (2004)

By using lubricants in the friction test, the effect of each type of lubricant on the formed material can be determined, showing which type achieves a greater reduction in friction between tool and part.

2.3 Mathematical friction models

In a mechanical forming process, friction between the part and the tool greatly depends on the surface roughness, but other factors also influence the process, such as part temperature, deformation velocity, contact pressure, and others (Brito and Schaeffer, 2008).

Mathematical models were developed to determine friction behaviour between part and tool, such as the Amontons-Coulomb which describes the friction model as being:

\[ \tau = \mu \times p \]

where \( \tau \) represents shear stress, \( p \) the normal stress of contact between the surfaces and \( \mu \) the friction coefficient. This model is valid for elastic contacts and also for forming processes with low interface pressure, \( p / \sigma_o < 1.5 \).

Another friction model works with interface friction, where shear stress is highest at the contact interface between the material and the tool. This model considers shear stress of friction as a fraction of the flow stress limit in shear, given by:

\[ m = \frac{\tau}{k} \]

where \( m \) is the friction factor and \( k \) the stress limit of elasticity in pure shear. This model is appropriate for high normal pressures (Brito and Schaeffer, 2008) \( p / \sigma_o > 4 \).

The value of \( m \) varies between 0 \( < m \leq 1 \), and the maximum value of friction reached is \( \tau = k \). Thus, applying the criterion of Von Misses:
\[ m = \frac{r \times \sqrt{3}}{\sigma_0} \]  \hspace{1cm} (3)

In this way, there is a relationship between the values of \( \mu \) and \( m \):

\[ \mu = \frac{m \times \sigma_0}{\sqrt{3} \times p} \]  \hspace{1cm} (4)

### 2.4 Calibration curves

Calibration curves are theoretical curves of a superficial friction model using finite elements. The curves are determined using computer software, taking into account the flow stress curves of the material and the compression ring geometry. The calibrations curves can be determined through analytical methods, but they are not studied in this paper.

For this type of numerical modelling there are two symmetry axes, one axis that follows the direction of compression and one that follows the perpendicular plane, where contact occurs between the compression plate and the compression ring.

Adjusting a given deformation velocity, it is possible to simulate the ring deformation, adjusting the programme for a few friction coefficients, beginning with low friction and raising it at every simulation.

Each of the simulations will generate a curve in a graph. This curve is then called calibration curve, and several of these curves represent the calibration curves.

### 3 Experimentation

#### 3.1 Material used

Four types of materials were used for this experiment, two ferrous, SAE1020 steel and AISI304 stainless steel, and two non-ferrous, AA6531 aluminium and C34000 brass. The chemical composition of each material was analysed by optical spectrometry.

The chemical composition of all materials used in the experiment is shown in Table 1.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Fe %</th>
<th>C %</th>
<th>Mn %</th>
<th>Cr %</th>
<th>Si %</th>
<th>Pb %</th>
<th>Al %</th>
<th>Ni %</th>
<th>Cu %</th>
<th>Zn %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE1020 steel</td>
<td>98.70</td>
<td>0.14</td>
<td>0.59</td>
<td>-</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td>0.17</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AISI304 steel</td>
<td>71.20</td>
<td>0.06</td>
<td>1.76</td>
<td>18.15</td>
<td>0.42</td>
<td>0.14</td>
<td>7.74</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AA6531 aluminium</td>
<td>0.18</td>
<td>-</td>
<td>0.49</td>
<td>-</td>
<td>0.92</td>
<td>-</td>
<td>97.41</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C34000 brass</td>
<td>0.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.09</td>
<td>-</td>
<td>-</td>
<td>64.98</td>
<td>31.12</td>
<td>-</td>
</tr>
</tbody>
</table>

The chemical components found in the materials are the most relevant values. Other elements were found, but only in small amounts.
3.2 Annealing and solubilisation

Before the tests, the materials underwent heat treatments to eliminate possible residual stresses of the manufacturing process. A Jung oven, model 2,513, with a 220 kg capacity and a thermal tank with a heat treatment system using oil or water with temperature control were used for heat treatment.

The SAE1020 steel underwent a full annealing process before the tests, with a temperature rise rate of 10°C/minute until it reached 880°C. Then the material remained at this temperature level for 180 minutes and cooled down to 30°C in the oven.

The AA6531 aluminium underwent a full annealing process with a heating rate of 10°C/minute until 350°C. The material was treated with heat for 200 minutes and cooled down to 32°C in the oven.

The C34000 brass underwent a full annealing process with a heating rate of 10°C/minute up to 600°C. The time of stay at the annealing temperature level was 200 minutes, and the material cooled down to 25°C in the oven.

AISI304 stainless steel underwent a solubilisation process with a heating rate of 10°C/minute to 1,100°C. The time of stay at this temperature level was 200 minutes. Immediately after the 200 minutes, the material was removed from the oven and cooled in a tank containing water at ambient temperature.

3.3 Flow stress curves

In order to determine the calibration curves, the flow curves of the tested material must be obtained through references in the literature or by compression tests. For this experiment, compression tests were performed on test specimens with different sizes for each type of material.

The test specimens were turned in a Mascote model, Nardini mechanical lathe, with lathe plate rotation at 1,200, and advance regulated in the 0.053 mm Norton Box by rotation. An interchangeable tool was utilised for turning with manual refrigeration using cutting fluid appropriate for all metals.

Figure 3 shows a drawing of one of the two test specimen models used in the compression test.

Figure 3 Drawing of the test specimen for the compression test (see online version for colours)

Table 2 shows the measures and quantities of parts turned for the compression test.
Table 2  Test specimen measures

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varnothing_1$ (mm)</th>
<th>$L$ (mm)</th>
<th>$\varnothing_2$ (mm)</th>
<th>$L$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE1020</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>AA6531</td>
<td>6</td>
<td>9</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Brass C34000</td>
<td>6</td>
<td>9</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>AISI304</td>
<td>5</td>
<td>8</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

Where $L$ is the length of the test specimen and $\varnothing$ the pin diameter. An EMIC model DL10000 universal testing machine was used for the compression tests. The compression velocity of the equipment was programmed for 5 mm/minute and the deformation applied to the test specimens was around 0.8 of real deformation for the larger diameter test specimens and 0.7 real deformations in length for the smaller diameter test specimens.

Figure 4 shows the test specimen assembly schematic in the testing machine.

Figure 4  Assembly schematic for compression test (see online version for colours)

The lubricant used between plate and test specimen was Teflon\textsuperscript{®} tape. The load cell used has a capacity of 100 kN and the extensometer used to measure plate displacement has a capacity of 50 mm to 100 mm.

The data obtained from the test machine were the force used by the machine and the displacement of the plate. These data were analysed with Microsoft Excel\textsuperscript{®} software, generating the flow curves of the materials analysed and the curve equations, performing a linear adjustment of the points captured in the test.

The test specimens were measured before and after the tests using a 0–25 mm Mitutoyo millesimal resolution external micrometer.

Forty test specimens in all were turned, five for each size of test specimen and type of material.

In order to ensure parallelism between the test specimen surfaces, they were turned on a table turning machine, a device that ensured that the test specimens would be fixed to the magnetic table of the lathe. The table lathe used was a Model P36 Mello.

3.3.1 Compression test

With the data obtained from the universal testing machine, compiled in the Excel\textsuperscript{®} software, the test results took on the form of a flow stress curve. Figure 5 shows the flow stress curves for SAE1020 steel where $\sigma$ is the value of the flow stress and $\varepsilon$ is the value of true deformation of the material.
One of the effects of the test on the test specimens used was that some samples suffered lateral displacement of the drawing caused by the small non-parallelism between the testing machine plates. This effect was more intense for the smaller diameter test specimens. The tests that had problems were discarded and not used for data analysis.

Figure 5 shows a few results of the SAE1020 steel compression test.

**Figure 5** SAE1020 steel flow stress curve, diameter 4 and 5 mm (see online version for colours)

![SAE1020 Steel Flow Stress Curve](image)

Taking the values of the graph that represent the elastic part of the material, the values were linearised using the base 10 logarithm. In this way the values of C and n can be measured on the flow curve.

Table 3 shows the results of C and n of the flow curves for the $\varnothing 5$ mm test specimens, for SAE1020 steel.

**Table 3** Values of C and n for the flow curve

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>C (MPa)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>771.26</td>
<td>0.2518</td>
</tr>
<tr>
<td>2</td>
<td>732.48</td>
<td>0.2443</td>
</tr>
<tr>
<td>3</td>
<td>736.20</td>
<td>0.2377</td>
</tr>
<tr>
<td>4</td>
<td>781.63</td>
<td>0.2645</td>
</tr>
<tr>
<td>Mean</td>
<td>755.39</td>
<td>0.2496</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>24.72</td>
<td>0.0115</td>
</tr>
</tbody>
</table>

The same procedure was used for smaller diameter test specimens. The test result generated an equation for test specimens with $\varnothing 5$ mm:

$$k_f = 755.39 \cdot \phi^{0.2496}$$

For $\varnothing 4$ mm test specimens the result of the flow stress curve was:

$$k_f = 751.65 \cdot \phi^{0.2363}$$

Calculating the mean of the two equations for SAE1020 steel the equation will be:

$$k_f = 753.52 \cdot \phi^{0.2429}$$
The same procedure was performed to analyse the other materials, and the results are shown in Table 4.

**Table 4** Values of C and n for the flow curve of the material analysed and standard deviation (SD)

<table>
<thead>
<tr>
<th>Materials</th>
<th>C (MPa)</th>
<th>SD (MPa)</th>
<th>n</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6531 aluminium</td>
<td>193.44</td>
<td>6.03</td>
<td>0.1883</td>
<td>0.0107</td>
</tr>
<tr>
<td>AISI304 stainless steel</td>
<td>1,580.92</td>
<td>30.10</td>
<td>0.4528</td>
<td>0.0093</td>
</tr>
<tr>
<td>C34000 brass</td>
<td>633.14</td>
<td>19.14</td>
<td>0.3596</td>
<td>0.0147</td>
</tr>
</tbody>
</table>

### 3.4 Friction ring test

The friction ring test was performed on the four materials analysed in this experiment. In order to perform the friction ring test for each material, rings of different sizes were turned to measure the influence of size reduction.

Figure 6 shows the drawing of the compression rings used in the experiments.

**Figure 6** Measures of the friction rings used in the test (see online version for colours)

The parts were turned using a Mascote model Nardini mechanical lathe, with a lathe plate rotation of 800 rpm and advance of 0.033 mm per rotation regulated in the Norton Box.

An interchangeable tool was used for turning with manual cooling with cutting fluid appropriate for all metals. In order to bore a hole in the rings, quick steel drills were used for the larger diameters and a centering drill with Ø1 mm and cutting length of 3 mm. The disks were cut with a parting tool made of hard metal sharpened as needed.

Thirty parts in all were turned each material for SAE1020 steel, 30 for 304 stainless steel, 30 for AA6531 aluminium, and 30 for C34000 brass. The 30 parts of each material were divided into three groups, ten parts with measures shown in Figure 6. Some parts were not used in the experiments, so that they could remain as models of turned parts.

Each part was measured before and after it was compressed in a Mitutoyo profile projector with a 0.005 mm resolution. The results were compiled on Excel® software.
The base of the lubricant used in the experiment was MoS$_2$, manufactured by Fuchs Lubritech, model Tribotec Dry Lube in Spray.

Some rings were not lubricated and others were, in order to allow analysis of the effect of lubricants on friction rings.

The rings were compressed in a press with a 30 ton capacity, with several degrees of deformation, reaching a height deformation of 60%.

Besides the profile projector, a Mitutoyo millesimal resolution external micrometer of 0–25 mm was used for measuring.

3.5 Calibration curves

The calibration curves were done simulating the compression of the compression rings in the three types of rings shown in Figure 6. The calibration curves were prepared taking into account the flow stress curves of each material, with a press velocity of 2 mm/s and cold deformation.

The SIMUFACT software was used for the Amontons-Coulomb friction model ($\mu$). For each material and ring size, series of simulations were performed with friction beginning at 0 and increments of one decimal until the value of four decimals.

Each ring compression simulation was recorded at six moments during the press stroke, measuring the height and inner diameter values of the rings.

Since four different materials were analysed, with three ring sizes, and four values for friction and six readings for deformation, 288 analyses in all were performed by the software.

4 Results and discussion

The results of the friction ring tests were placed on the graphs with the calibration curves performed using SIMUFATC software.

Figure 7 shows the simulation of the deformation using Simufact software.
The simulations indicate that the calibrations curves are similar to the tree ring types used in the simulation. Thus, only the calibration curves of the type 1 ring size shown in Figure 6 is used at the analyses.

Figure 8 shows the shows the C34000 brass ring after the ring test.

Once the results of the calibration curves are obtained, the ring test results are placed in the calibration curve graphic separated according to type of material.

4.1 SAE1020 steel

Figure 9 shows the calibration curves and the friction values for rings with and without lubrication.

In Figure 9, the points represented with a square, are type 2 rings, the triangle type 1 and a circle type 3 all sizes shown in Figure 6 with a 6:3:2 size ratio.
The calibration curves were performed with friction values $\mu$ between 0 and 0.4. The values in black indicate the rings that were not lubricated and the red values indicate the rings that were lubricated. The friction values were low only for rings that were not much deformed. The lubricant layer broke down in the more deformed rings, and the values were similar to the rings that had not been lubricated.

The points on the graph were the values taken from ring compression experiments, measuring the variation of the inner diameter by variation of ring height.

The same process applied to 33.3% smaller rings, showed the tendency to reduced friction between ring and tool as the ring becomes smaller. When the size of rings compared to the previous test diminishes by 50%, once again there is a tendency to diminished friction between the rings and the press tool.

This tendency had already been observed in studies by Linfa Peng et al. (2010) who worked with the effect of part size operating with finite elements to determine friction through the radial friction force.

4.2 AA6531 aluminium

The same analysis procedure as for SAE1020 steel was performed with AA6531 aluminium. Figure 10 shows the calibration curves and the friction values for rings with and without lubrication.

Figure 10  Calibration curves for AA6531 aluminium (see online version for colours)

In Figure 10, the points represented with a square, are type 2 rings, the triangle is type 1 and a circle is type 3, all size shown in Figure 6, with a 6:3:2 size ratio.

The black values indicate the rings that were not lubricated and the red values indicate the rings that were lubricated.

The same diminished friction effect occurred with aluminium, except that in this case the molybdenum bisulphide-based lubricant applied in spray form increased friction instead of reducing it.
4.3 AISI304 stainless steel

Stainless steel was the most difficult material for sample preparation, both in turning and in tests performed. Its capacity for mechanical hardening increased the difficulties, both as to breakage of turning tools and breakage of some polished plates made of ASTM D-2 steel, that were between the test specimens and the press base to reduce press tool friction.

The same analysis process of SAE1020 steel was performed with the stainless steel. Figure 11 shows the calibration curves and the friction values for rings with and without lubricant.

![AISI304 stainless steel](image)

In Figure 11, the points represented with a square, are type 2 rings, the triangle is type 1 and a circle type 3, all sizes shown in Figure 6, with a size ratio of 6:3:2. The black values indicate the rings that were not lubricated and the red values indicate the rings that were lubricated.

As with SAE1020 steel and AA6531 aluminium, friction tends to be reduced as the friction ring size diminishes. What makes stainless steel different from the other two materials is that the lubricant causes a small reduction in friction between the ring and the compression plate.

As in the case of the other materials, friction diminishes when the test specimen is smaller. The lubricant has moderate action, slightly reducing the friction between the ring and the test specimen.

4.4 C34000 brass

Brass was the material with the best machinability of all. In the compression tests it was the only material that broke down due to low elasticity of the material, caused by the great amount of lead present in its chemical composition.

The same analysis process as for SAE1020 steel was performed on the brass. Figure 12 shows the calibration curves and the friction values for rings with and without lubrication and with the size shown in Figure 6.
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Figure 12 Calibration curves of C34000 brass (see online version for colours)

As with the aluminium, the un-lubricated rings did better than the lubricated ones, but even so they presented the lowest friction value among the materials analysed. This is due to the natural characteristic of copper alloys being used as bushings of sleeve bearings because of their low friction, such as bronze alloys.

Differently from the SAE1020 steel that presented the same variation as stainless steel, brass did not present much friction variation in reducing the size of the friction ring.

In Figure 12, the points represented with a square, are type 2 rings, the triangle is type 1 and a circle is type 3, all sizes shown in Figure 6, with a 6:3:2 size ratio.

The black values indicate the rings that were not lubricated and the red values indicate the rings that were lubricated.

The smaller rings for brass had very similar friction results to those of larger sizes, with lower friction coefficients among the materials analysed. For this reason, some gears are made of brass because of their resistance to friction wear (Geier, 2007).

In general, the lubrication procedure used in the experiment proved inefficient when a layer of molybdenum bisulphide was applied only to the part, leading to the same conclusions as Brito and Schaeffer (2008) in studies involving friction ring tests that presented the same result regarding lubrication of the rings only. This tendency of aluminium and brass was already expected, but the effect of lubrication on the steels was unknown, showing some efficiency only for stainless steel.

In the case of aluminium, the performance of the lubricant increased the friction between part and tool. For this type of solid lubricant, the mechanical strength of the materials only influenced friction as shown in the experiment, where the aluminium was the material a lower strength value for deformation, increasing gradually for the other materials, and for the stainless steel, lubricant helped to reduce friction.

The reduction of friction when the friction ring size was diminished, occurred not only with the aluminium studied by Linfa Peng (2010), but also for the other materials, with a greater effect on the steels analysed than on the brass itself, but even so there is a reduction. Thus, the effect of diminishing friction on meso and micro parts compared to macro sized materials is due more to the effect of size, less contact area between part and tool, than to the type of material used. The effect of the friction ring material lies in the
magnitude of the friction reduction between part and tool, even in the case of copper alloys such as brass, with its resistance to wear reducing the effect of diminished friction as the test specimen is reduced.

Calibration curves for the smaller rings are practically identical, but for the larger rings, the curves show a small difference.

5 Conclusions

The friction ring test is very important in the mechanical forming industry. The results obtained are very reliably applied in the production process. The use of compression ring tests for micro/meso parts is a field of study that has been recently applied due to the greater difficulty in the turning and analysis of small parts.

As the size of parts diminishes, there is a small tendency to reduce the friction between the ring and the press tool in all materials analysed. The effect of type of material, its deformation capacity, its mechanical hardening and resistance to wear affect the friction reduction, as in the case of brass, where the friction reduction, as in the case of brass, where it is not very representative.

Further studies should be performed with smaller ranges of friction calibration curves to determine more precise friction reduction values.

The lubricant used was not effective to reduce friction. Results were found only in a few cases, such as AISI304 stainless steel. The MoS₂ lubricant begins to reduce friction between the tool and ring only when more force is needed to deform the material.

References


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