Tribological evaluation through Stack Ring Compression Test

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July 2017

Abstract

Recently, a new manufacturing technology, that combines sheet forming with tridimensional loads that are usually utilized in bulk forming, known as sheet bulk forming (SBF) has been developed. SBF allows to obtain parts with high complexity details in an economic way, and uses sheet as raw material, making difficult the utilization of the Ring Compression Test (RCT) to characterize friction in the tool-workpiece interface.

The Stack Ring Compression Test (SRCT) is proposed in order to solve the lack of a tribological evaluation experimental test in sheet. The flow curve of the material, a single block of AA6061-T651 Aluminum alloy, was obtained by means of compression tests carried out on solid cylinder specimens.

Experimental tests of the conventional RCT and the SRCT with 2 and 4 rings, using molybdenum disulphide (M_oS_2) and polytetrafluoroethylene in form of sheets (teflon), were carried out.

The numerical validation of the experimental results were performed by means of load vs. reduction of height (%) curves.

The friction values were obtained by mapping the experimental friction points on the friction calibration curves. Finally, it was confirmed that each lubricant provides identical friction values for the conventional RCT and for the SRCT, allowing the validation of the SRCT for the characterization of friction in sheet.

1. Introduction

The plastic deformation of the material is affected by the pressure transmitted through the dies and the frictional conditions at the tool–workpiece interface greatly influence the stresses acting on the dies. The RCT is the experimental test most commonly used to obtain a quantitative evaluation of friction condition in bulk metal forming [1].

The RCT was firstly proposed by Kunogi [2] with the goal to qualitatively compare different friction conditions in cold forging.

In the RCT, a ring specimen is compressed up to $50\ \%$ of height reduction using a flat die. If the lubricant has a low friction value, the inner diameter (d_i) expands during the deformation, Figure 1.1 (a), and when the friction value is high the d_i shrinks, Figure 1.1 (b) [3].

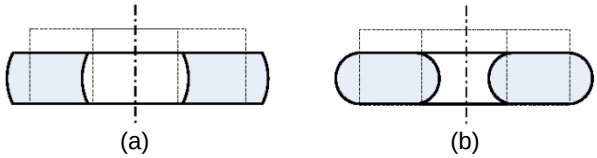


Figure 1.1- Ring compression test: (a) low friction; (b) high friction

Later, Kudo [4] analyzed the RCT using the upper bound method. Male and Cockcroft [5] developed the first set of friction calibration curves assuming the Coulomb friction model, using ring shaped specimens with an initial dimensional relation of external diameter: inner diameter: height = 6:3:2.

The theoretical approaches to obtain the friction calibration curves for the RCT are based on the slab method, the upper-bound method and the finite element method, considering a friction model that better suits the process [6].

The work of Merklein et al. [7] was very important for the recognition of SBF as a new manufacturing technology. Once SBF uses tridimensional loads and sheet as raw material, it is crucial to develop a new test to evaluate sheet.

Bay et al. [8] published a work with the goal to present and validate different lubricant tests used in Sheet Forming processes, thus these tests aren't stubbles to apply in SBF due to the type of the material deformation.

The aim of this work is the development of a new tribological experimental test that consists in pilling rings with equal value of height, resulting in specimens with the same dimensional relation as the RCT, kwon as Stack Compression Ring Test.

The experimental results, in terms of load vs. reduction of height (%) curves, were numerically validated. Finally, by comparison of the friction values obtained from the SRCT and the RCT tests for each lubricant, it was possible to validate the SRCT applicability.

2. Experimentation

The material used on the current work was a single block of AA6061-T651 Aluminum alloy cast. This material was submitted to a heat treatment and was cooled at room temperature.

The AA6061-T651 Aluminum alloy is known as a material with good mechanical properties and it is used on applications that combine high strength, good workability and high resistance to corrosion. Mainly, this material is used in the production of car components, machine parts, etc.

This section begins with the characterization of the material by means of cylindrical compression tests. Then, it is presented the RCT, the SRCT tests and the methodologies used during the tests.

The tests were performed using a hydraulic testing machine INSTRON model SATEC 1200 with a constant value of speed, using flat dies.

2.1. Mechanical characterization of the Aluminum AA 6061-T652

In the present work, compression tests were performed to obtain the material characterization. The specimen geometry and parameters used in the compression tests followed the E9–89a (2000) [8] standard.

With the goal of verifying the presence of anisotropy on the material, were performed compression tests on three cylindrical specimens in different directions (x, y, z), using $MoS2$. The results are presented on Figure 2.1.

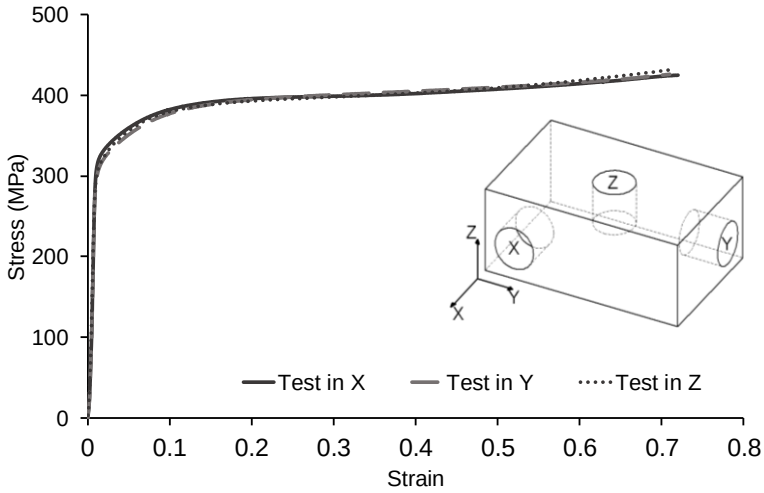


Figure 2.1-Stress-strain curves for 3 different directions of compression.

The stress-strain curves obtained for the 3 directions remain closer to each other, thus indicating a low value of anisotropy, which allows to assume that the AA6061-T651 Aluminum alloy is an isotropic material. Therefore, specimens aligned with the z axis orientation were considered for the rest of the experimental tests.

With the goal to characterize the material, it was considered two different lubricants and two lubrification methodologies. Therefore, it was performed tests with teflon and $MoS2$ considering a unique lubrification and periodical lubrification in each $5\ \%$ of height reduction [9].

Finally, the resulting stress–strain curve of the periodical lubrication with teflon were utilized to characterize the material, allowing to obtain the following Ludwik–Hollomon's equation.

$$\sigma = 431.7.\varepsilon^{0.068} \quad MPa \tag{2.1}$$

2.2. Conventional RCT and SRCT

Although the RCT is the experimental method most commonly used for the tribological characterization of friction, it is not standardized yet. However, the geometrical relation of the ring $(6:3:2)$ has been used as a standardized relation in the scientific community [10]. Figure 2.2 presents the geometry and dimensions of the RCT specimen and the SRCT.

(mm)

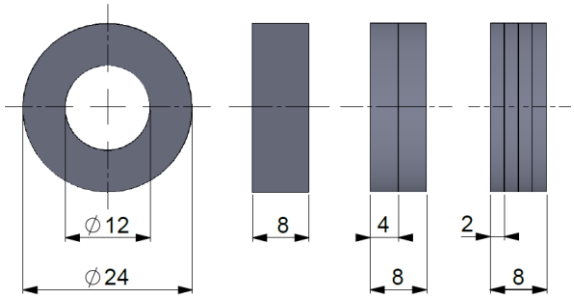


Figure 2.2-Geometry and dimensions of the conventional RCT specimen, the SRCT with 2 and 4 rings

The proposed SRCT can be considered a variant of the RCT, enabling the characterization of friction in processes that use sheet as raw material. Therefore, the rings are piled until the desirable relation of geometry is achieved. Finally, Table 2.1 presents the plan of experiments, considering polished and rough dies with average roughness of $0.1\,\mu m$ and $0.533\,\mu m$, respectively.

Table 2.1- Plan of experiments for the RCT and the SRCT tests

Type of test	Die	Lubricant condition	Number of specimens
RCT	Polished*	$MoS2$	3
		Teflon	3
	Rough*	Dry	1
SRCT with 2 rings	Polished	$MoS2$	3
		Teflon	3
	Rough	Dry	1
SRCT with 4 rings	Polished	$MoS2$	3
		Teflon	3
	Rough	Dry	1
Total number of the specimens			21

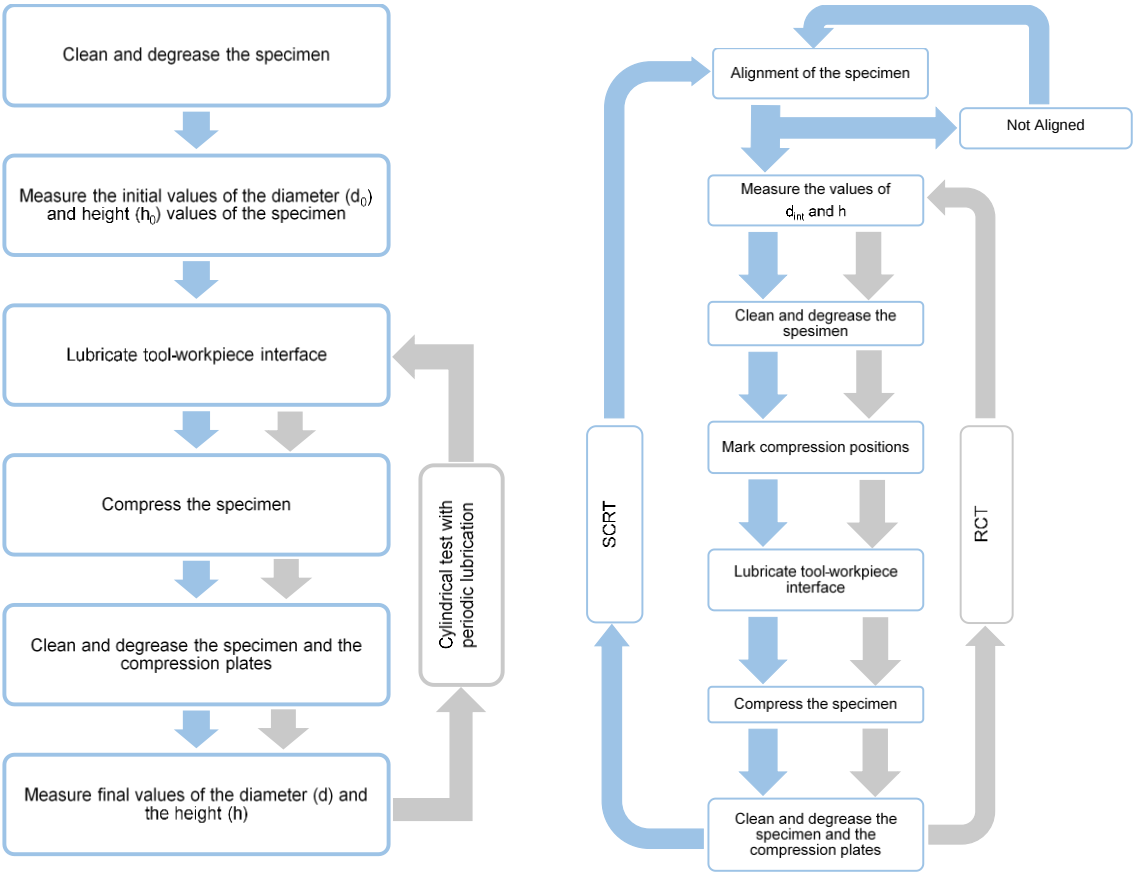
2.3. Experimental procedure

The methodologies used for the experimental work were obtained considering a unique and periodical lubrication [11].

Figure 2.3 (a) presents the methodology used during the cylindrical compression tests with unique lubrication (blue) and periodical lubrication (gray).

It was considered the use of a periodical lubrication for the realization of the friction tests and Figure 2.3 (b) presents the methodology used during the SRCT (blue) and the RCT (gray) tests.

All the dimensions needed were obtained in three different points, using a digital caliper.



(a) (b)

Figure 2.3-Methodologies used in the different compression tests: (a) Compression of a cylindrical specimen considering unique (blue) and periodic lubrication (gray); (b) Conventional RCT (gray) and SRCT (blue)

3. Finite Element Modelling

To validate the experimental results, several numerical simulations were performed for the conventional RCT and the SRCT. The simulations were conducted through the finite element modelling program I-form, considering a bi dimensional model [12]. To obtain good values for the simulations parameters and understand the geometry influence on the results, a set of sensitivity analysis was carried out for the SRCT with 4 rings.

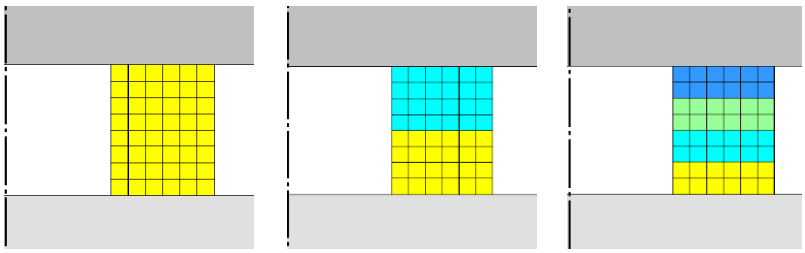
Table 3.1 presents the parameters utilized for the numerical simulations, according to the sensitivity analysis.

Table 3.1-Parameters used on the numerical simulations for the RCT and SRCT.

	RCT and SRCT
Mesh type	Quadrangular
Element size (mm)	1
Increment time (seg)	0.1 seg
Geometry type	Axisymmetric
Material type	Rigid plastic
Plasticity criterium	Von Mises
Speed deformation $(mm/\min)$	5
Friction law	Prandtl
Friction value m_d*	0.65*
Average Computing Time (seg)	30

*friction value between the rings and only is used for the SRCT.

Figure 3.1 present the schematic representation of the simulation model for the different tests performed in this work. From the sensibility analyses it was confirmed that when the friction value between the rings is higher than the friction of the tool-workpiece interface, the results are similar to the ones obtained for the Conventional RCT, up to 50% of height reduction.



(a) (b) (c)

Figure 3.1-Schematic representation of the simulation model (considering an axisymmetric representation) for the: a) Conventional RCT; b) SRCT of 2 rings; d) SRCT of 4 rings

4. Results and Discussion

This section is divided in three parts. The first part is focused on the numerical validation of the experimental results, by analyzing load vs. height reduction (%) of the specimen.

In the second part, the friction values for the conventional RCT, the SRCT with 2 and 4 rings are obtained for the utilization of M_oS_2 and teflon.

Finally, the third part presents an exploratory work with a goal of obtain a high friction value in the tool-workpiece interface, considering the conventional RCT, the SRCT with 2 and 4 rings.

4.1. Numerical validation

Once it was possible to confirm that the numerical results obtained from the SRCT are equal to the conventional RCT, when the friction value between the rings is higher than the tool-workpiece interface, the experimental results were validated by means of the RCT numerical simulations.

For each test condition were considered 3 specimens, as it can be seen in Table 2.1, making possible the repeatability of the obtained results. Therefore, only the results of one specimen for each test condition are presented.

Figure 4.1 presents the comparison (for each lubricant), in terms of the load vs. height reduction (%) of the specimen, between the numerical curve (FEM) and the experimental curves obtained for the conventional RCT, SRCT with 2 and 4 rings. The numerical curves were obtained from the simulation of the RCT and was considered a friction value equal to 0.10 for the teflon and 0.20 for the $MoS2$.

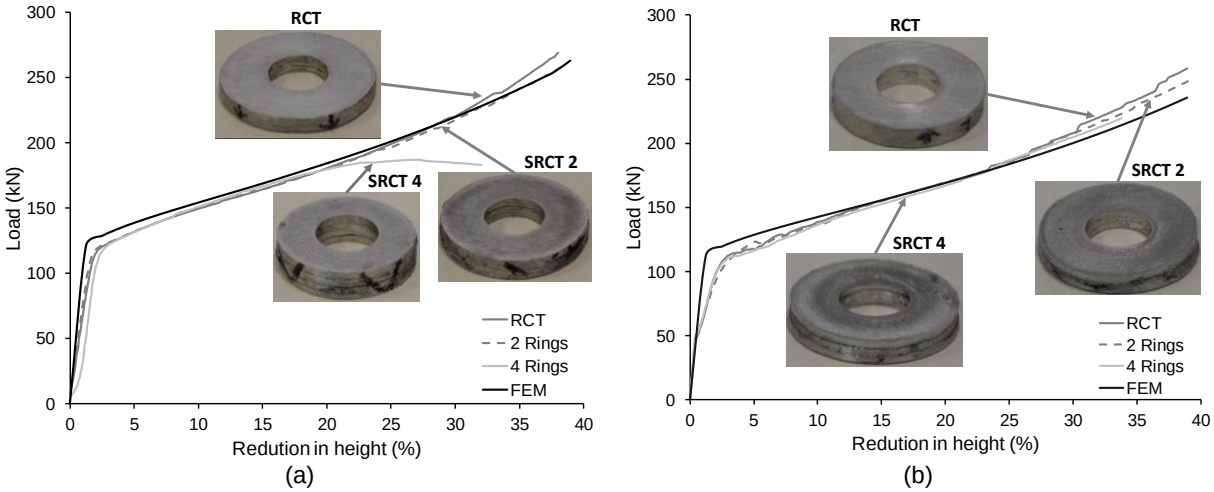


Figure 4.1-Numerical validation of the experimental results in terms of the load vs. displacement evolution: (a) $MoS2$ paste; (b) Teflon

For the $MoS2$ (Figure 4.1 (a)), it is verified that the FEM curve predicts the conventional RCT curve up to 30% of height reduction and, after, the RCT curve tends to increase more sharply. This is explained by the fact that when the pressure reaches high values, the $MoS2$ is expelled from the tool-workpiece interface, resulting in a higher friction value.

When analyzing the SRCT with 2 rings (Figure 4.1 (a)), it is verified that this curve is similar to the FEM curve during the entire test. In this case, the $MoS2$ is also expelled but there is a compensation due to the existence of slightly misalignment of the rings, resulting in a decrease of the contact area between the rings (Figure 4.2 (a)).

(a) (b)

Figure 4.2- Illustration of the misalignment of the stacked rings with $MoS2$ paste: (a) 2 stacked rings; (b) 4 stacked rings

By comparing the curve of the SRCT with 4 rings (Figure 4.1 (a)) with the FEM curve, it is verified that the FEM curve predicts the test up to 20% of height reduction, and thereafter the SRCT with 4 rings curve tends to be constant. For this case, it is considered that there is a non-homogenous circumferential lubrication (Figure 4.2 b)).

From the experimental results obtained for the use of Teflon (Figure 4.1 b), it is verified that the conventional RCT curve is equal to the ones obtained for SRCT with 2 and 4 rings up to 30% of height reduction. From this value of height reduction, the SRCT curves present lower values of force due to the slight misalignment of the rings. These differences are irrelevant for adapted ranges of height reduction.

However, it is confirmed that the FEM curve predicts the tests up to 25% of height reduction and, after this value, there is a sufficient direct contact area between the specimens and the dies due to the earlier tear of the teflon after each 5% of height reduction, resulting in a higher friction value.

4.2. Friction determination

As it was considered for the numerical validation, the calibration curves of friction were obtained considering the conventional RCT for different values of friction (m).

Figure 4.3 presents the calibration curves and the mapping of experimental frictional points obtained for the conventional RCT, the SRCT with 2 and 4 rings, using $MoS2$ and teflon.

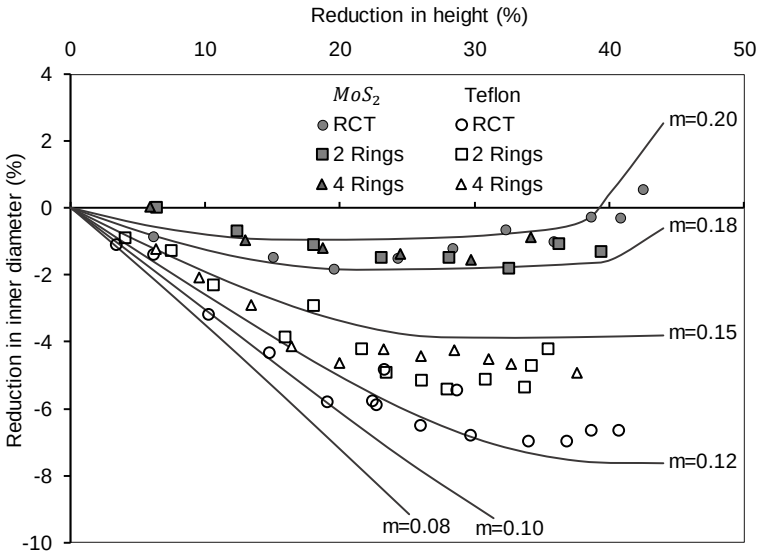


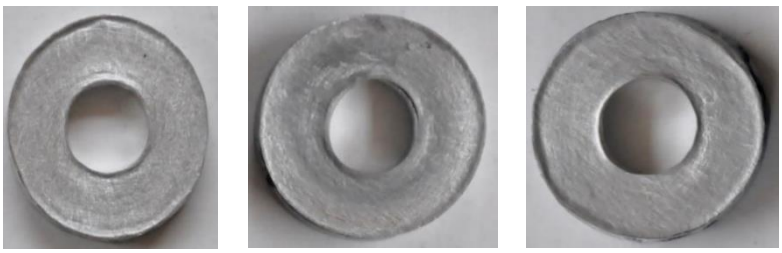
Figure 4.3-Representation of the calibration curves and mapping of the experimental frictions points obtained for the RCT and the stacked rings test for $MoS2$ paste Teflon

The experimental points of friction, using $MoS2$ for the RCT and the SRCT tests, are almost identical and they are characterized by a range of friction values equal to $0.18 < m < 0.20$. However, it should be highlighted that the misalignment of the rings (mostly in SRCT with 4 rings) affects the experimental measurements of inner diameter.

When using teflon, the experimental points of the SRCT with 2 and 4 rings are very similar $(0.12 < m < 0.15)$ and they are slightly different than the conventional RCT experimental points $(0.10 < m < 0.13)$. When there is a low friction condition, the influence of anisotropy is more visible on the ring geometry, originating an elliptical deformation. The existence of an elliptical geometry on the ring provides difficulties to obtain the measurements of the specimen (Figure 4.4 a)) [13].

During the SRCT tests, the rings are elliptically deformed and there is a high probability to exist ellipses with different axis orientation. This makes possible to obtain specimens that are limited

by the lower value of the rings inner diameter, originating a slight higher value of friction than the conventional RCT (Figure 4.4 (b) and (c)).

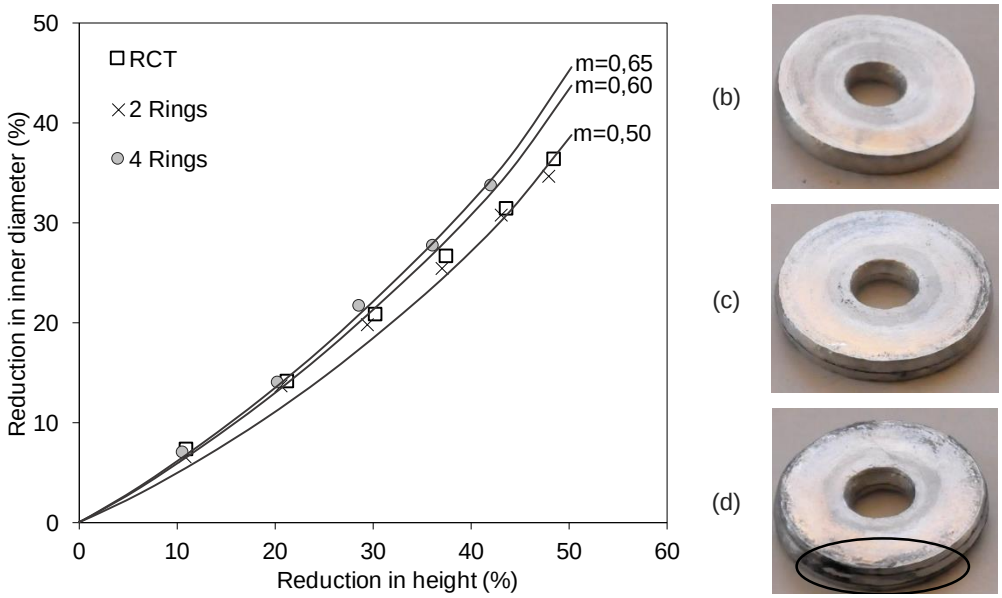


(a) (b) (c)

Figure 4.4-Ilustration of the elliptical problem on measuring the ring internal diameter: (a) RCT; (b) SRCT with 2 rings; (c) SRCT with 4 rings

4.3. High friction value condition

In this section, it is presented an exploratory work with the goal to simulate a high friction value condition. As shown in Table 2.1, it was considered the use of dies with a higher roughness value without any lubrication. Figure 4.5 (a) presents the mapping of the experimental points in the calibrations curves. Figures 4.5 (b), (c) and (d) the specimens after the tests.



(a)

Figure 4.5- Data obtained from the conventional RCT, the SRCT with 2 and 4 rings using rough plates in dry condition: (a) Mapping of the experimental friction points on the calibration curves; (b) RCT specimen; (c) SRCT specimen with 2 rings; (d) SRCT specimen with 4 rings

For these values of friction, the calibration curves tend to be less sensitive to the changes of the inner diameter and, when there is a slight misalignment of the rings (Figure 4.5 (d)), it affects the experimental points of friction.

From the appearance of the specimens, figure 4.5 (b), (c) and (d), it is clear that the surface of the specimens are more polished due to the absence of lubricant.

5. Conclusions

This document proposes the Stack Compression Ring Test (SRCT) for the characterization of friction in processes that uses sheet as a raw material, by means of experimental and numerical works. From the compression tests results, it was assumed that the AA6061-T651 Aluminum alloy is an isotropic material.

The numerical results obtained from the SRCT are equal to the ones obtained for the RCT, considering higher values of friction between the rings. It was possible to verify the similarities of the conventional RCT and the SRCT results, in terms of load vs reduction in height (%) curves.

The tests were numerically validated and it was verified that the SRCT has a limited level of deformation due to a non-homogenous deformation of the specimens. The friction values were obtained by mapping the experimental points of friction on the calibration curves. The SRCT was successfully validated by comparing the friction values for each friction condition.

6. References

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