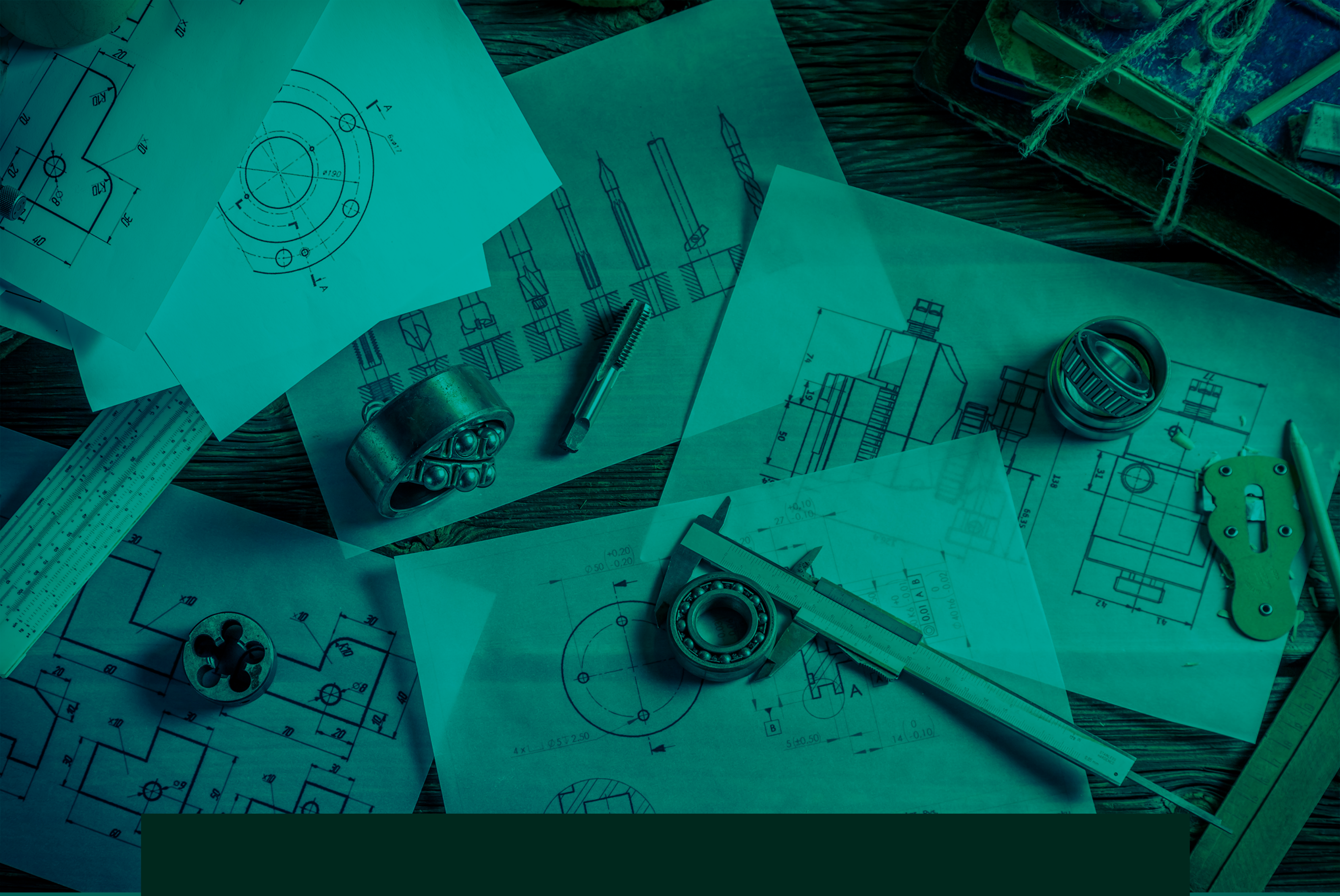

Henrique Ajuz Holzmann
(Organizador)

A Aplicação do Conhecimento Científico na Engenharia Mecânica

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APRESENTAÇÃO

A Engenharia Mecânica pode ser definida como o ramo da engenharia que aplica os princípios de física e ciência dos materiais para a concepção, análise, fabricação e manutenção de sistemas mecânicos. O aumento no interesse por essa área se dá principalmente pela escassez de matérias primas, a necessidade de novos materiais que possuam melhores características físicas e químicas e a necessidade de reaproveitamento dos resíduos em geral.

Nos dias atuais a busca pela redução de custos, aliado a qualidade final dos produtos é um marco na sobrevivência das empresas, reduzindo o tempo de execução e a utilização de materiais.

Neste livro são apresentados trabalho teóricos e práticos, relacionados a área de mecânica e materiais, dando um panorama dos assuntos em pesquisa atualmente. A caracterização dos materiais é de extrema importância, visto que afeta diretamente aos projetos e sua execução dentro de premissas técnicas e econômicas.

De abordagem objetiva, a obra se mostra de grande relevância para graduandos, alunos de pós-graduação, docentes e profissionais, apresentando temáticas e metodologias diversificadas, em situações reais.

Sendo hoje que utilizar dos conhecimentos científicos de uma maneira eficaz e eficiente é um dos desafios dos novos engenheiros

Aos autores, agradeço pela confiança e espirito de parceria.

Boa leitura

Henrique Ajuz Holzmann

SUMÁRIO

CAPÍTULO 2

MANUFACTURE OF COMPLEX PARTS IN THIN SHEETS OF COMMERCIALLY PURE ALUMINIUM USING INCREMENTAL SHEET FORMING METHOD

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ABSTRACT: This work aims to study the process of Incremental Sheet Forming (ISF) on a pure aluminum sheet. Four tests were made using a CNC machining center, 0.5 mm thickness sheets of commercially pure aluminum, a plate press support and a forming tool with semi-spherical tip. It was assessed in the tests how the pure aluminum plate responded to the variation of feed speed of forming tool. In addition, other test was performed without lubrication in order to verify effects of dry condition in characteristics of final part. Roughness measurements were carried to evaluate surface quality and metallographic analysis were performed on the stamped plates as way of verifying deformation of the sheet in its thickness direction. A good conformability of aluminum plates was found, and it was demonstrated how lubrication has crucial importance through the process. It was also shown that feed speed has great influence in final part aspects such as cumulated deformation and surface finishing.

KEYWORDS: incremental sheet forming, commercially pure aluminum, feed speed, lubrication.

1 I INTRODUCTION

Used in the production of series and prototyping, incremental sheet forming (ISF) is a major technological development, being able to minimize utilization of expensive tooling and specific equipment in forming processes, thus reducing final cost of products (Daleffe, 2008). Unlike the traditional processes used for stamping of sheets, which usually rely on hard steel dies and hydraulic or mechanical press, simple, low-cost tools are employed in this process. Since the required time to perform incremental sheet forming process is high, it is not a recommended for producing large batches, being more advantageous for small batches and rapid prototyping (Fritzen, 2012). Though it is still not widely used, its main applications could be in aerospace and medical industry, for example in production of prosthetic devices and or the nose of airplanes. In its most simple configuration, it consists of using a Computerized Numerical Controlled (CNC) machine to drive a rotating tool with spherical tip against the fixed sheet in a determined path, sequentially deforming it at each pass of tool until the desired shape is obtained. The tool path is produced through use of CAD/CAM software (Cardoso, 2018), creating a numerically controlled movement.

Deformation in this process naturally occurs in a localized manner, allowing greater deformations of sheet than it is normally achieved in conventional sheet deformation processes (Silva et al., 2007). The process is governed by several input parameters such as sheet thickness, tool diameter, wall angle, step size, tool rotation and feed speed (Golabi et al., 2014).

The use of lubrification influences directly on many factors like tool wear, surface roughness, reduction of sheet thickness due to stretching, localized temperature, friction, vibration and noises (Castelan, 2007). Some of the common lubricants employed are tallow, oil mixed tallow and lithium-based grease (Daleffe, 2008). Zhang et al. (2010) studied the impact of solid lubricants such as solid graphite, $K_2Ti_4O_9$ and MoS_2 during hot incremental forming on sheets of magnesium alloy AZ31. Results suggested that lubrication methods using solid lubrication have excellent performance with good surface quality as indicated by roughness mesasurements.

Aluminum is the third most abundant material in the Earth's crust and widely used in industrial applications (Budd, 1999). Compared to other engineering materials it has low melting temperature, around 660 °C (Callister, 2002), which facilitates its metallurgical manipulation. In addition, aluminum contains a much higher ductility than others metals (Manna and Bhattacharyya, 2003), withstanding great plastic strain upon forming.

This material is used in a broad range of applications, from conditioning containers for food and beverages to machines and equipment of high technology as in the aeronautical, naval and automobile industry (Araújo, 2013; All Wood et al., 2014). Its characteristics guarantees good advantages among other materials, like reasonable toughness, good thermal conductivity, excellent corrosion resistance and low specific weight. It also can be easier deformed through lamination, which allows it to be produced as plates without any major concerns (Chiaverini, 1986).

The motivation of this work is to evaluate the effects of ISF process parameters in characteristics of an aluminum final part, regarding feed speed and the lubrication. Also, it aims to investigate the stampability of the material and its performance in the processing conditions employed.

2 I METHODOLOGY

The experimental tests were carried out in a CNC ROMI Discovery 760 machining center. In order to generate tool path and simulate it according to the desired geometry of final part and its dimensions, FUSION 360® software from AUTODESK® was used to generate the code G, which is responsible for trajectory of the tool and helicoidally movement of machine axis (X,Y,Z). To ensure fixation of the plates, a system was developed with four holders having 4-holes each as show at Fig. 1, in such way that the workpiece can be clamped to it.

Figure 1. Support for fixing the pure aluminum sheet.

Stamping tool used in the tests was turned from a rod of AISI 52100 steel, being 98.5 mm long with tip in hemispherical shape having a diameter of 5.65 mm. It was placed in the machine tool holder in place of the usual milling tool. These are shown in Fig. 2.

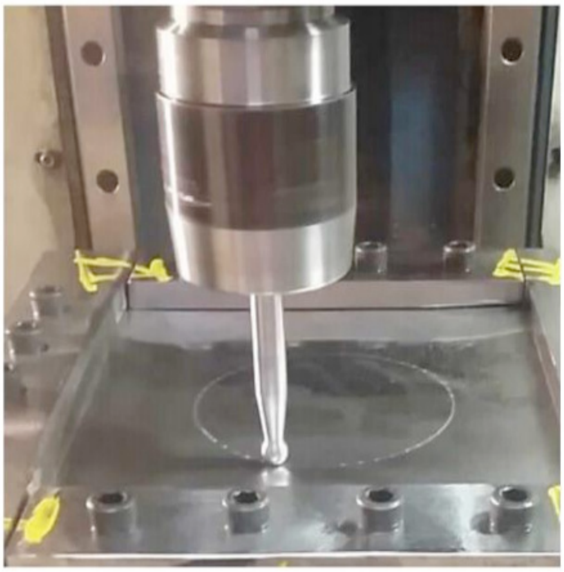


Figure 2. Hemispherical tip tool fixed at the mandrel at CNC machine.

The plates used were made of commercially pure aluminum (Al) with 0.5 mm thickness. These were acquired with width 1000 mm and 500 mm length, from which samples were cut in square shape of 240 mm wide through the use of electrical scissors. The geometry chosen for this work was a cone trunk with a higher diameter of 120 mm and a depth of 75 mm, yielding a wall angle of 54°. Fig. 3 shows a 2D geometry representation of the theoretical final form of stamped sheet, in software FUSION 360®. A SAE 5W30 oil was used as lubricant. An oil film was poured onto the plate and as the experiment was run, small amounts of lubricating oil were progressively added into the generated cavity since part of it evaporated due to heat generation. In addition, a test was performed with no lubrication (dry condition), with the goal of analyzing the influence of the lubricating fluid.

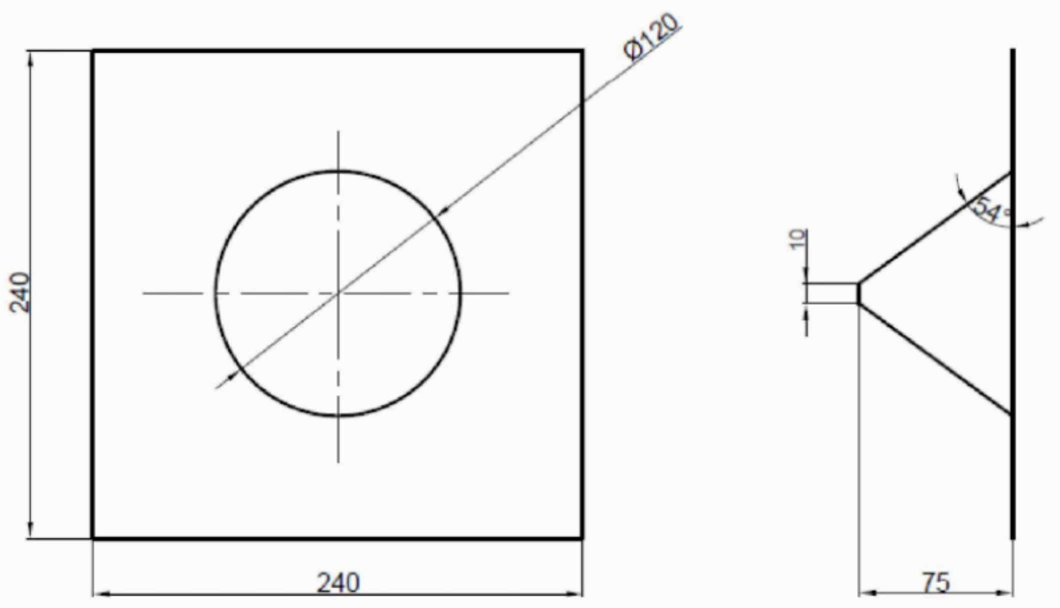
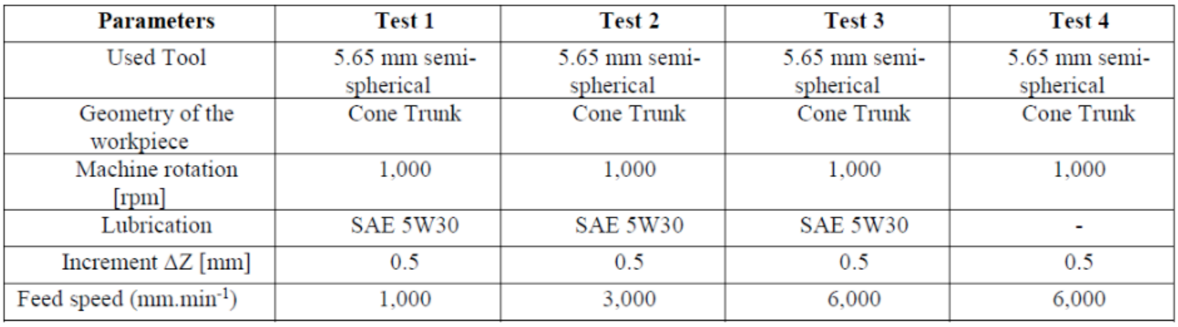


Figure 3. 2D geometry representation of the piece to be stamped.

Square samples of 12 mm width of the aluminum material was removed prior to the stamping tests for metallographic analysis, containing only the rolling stresses. In addition, samples of same dimensions were cut for each test after stamping, in order to compare the metallographic structure after deformation from the process. Samples were grinded in sandpaper of mesh 80, 220 and 320, and then etched with a chemical solution composed by 10 mL of sulfuric acid, 15 mL of concentrated hydrochloric acid, 25 ml of concentrated nitric acid and 50 ml of distilled water.

For each test samples were removed from the stamped region for roughness measurement using a disc saw, in order to obtain the relation between test parameters and the surface roughness achieved. 5 measurements were performed for each part, and the mean and standard deviation of the measured values were then calculated. The parameters evaluated were Rq, Rt and Ra with a cut-off of 0.8 µm and a sampling lenght of 4.8 mm.

Before each test the tool was visually inspected for wear signs and was grinded in 320 mesh sandpaper when excessive wear was apparent. The parameters employed in the tests, both the constant and the varied ones are shown in Fig. 1.



Parameters	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Used Tool	5.65 mm semi-spherical	5.65 mm semi-spherical	5.65 mm semi-spherical	5.65 mm semi-spherical
Geometry of the workpiece	Cone Trunk	Cone Trunk	Cone Trunk	Cone Trunk
Machine rotation [rpm]	1,000	1,000	1,000	1,000
Lubrication	SAE 5W30	SAE 5W30	SAE 5W30	-
Increment ΔZ [mm]	0.5	0.5	0.5	0.5
Feed speed (mm.min^{-1})	1,000	3,000	6,000	6,000

Table 1. Incremental sheet forming parameters.

3 I RESULTS AND DISCUSSIONS

For test 1, with a feed speed of 1000 mm.min-1 the test was performed until the end of the process without any interruption, and the generated part along the surface reached a depth of 73.1 mm which is close to the desired 75 mm. Therefore the elastic recovery of the work material was 2.53%. For test 2, in which feed speed was increased to 3000 mm.min-1, test was also performed until the end, producing a cone trunk 72.3 mm deep and with a elastic return of 2.7 mm, i.e. 3.6% less than when compared with generated model predicted by FUSION 360®. In test 3, with a feed speed of 6000 mm.min-1, surface appeared to be much coarser when compared to tests 1 and 2. The depth measured was 71.6 mm deep, yielding an elastic return of 4.53% in relation to the designed model. For test 4 done in dry condition and using a feed speed of 6000 mm.min-1, operation had to be interrupted after 18 minutes of duration due to cracking of stamped part. Noise was also much greater, indicating a higher friction coefficient. Besides, a completely degraded surface could be seen. These factors are believed to relate to high temperatures developed during the process, which diminishes material toughness and causes it to reach maximum strain with lower stresses. By the time the trunk was broken as show in Fig. 4(d), it had a depth of 14 mm.

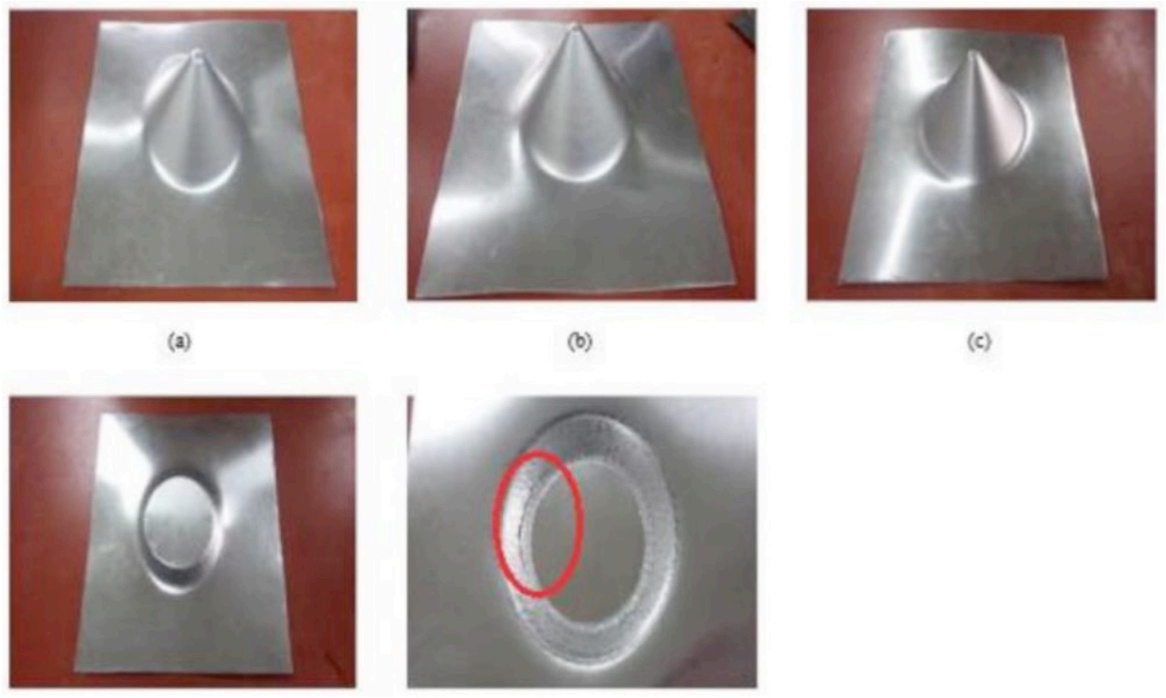


Figure 4. a) Stamped sheet after test 1; b) after test 2; c) after test 3; d) after test 4; e) Detail of surface finish and crack produced in test 4.

Elastic return was slightly enhanced when feed rate increased. The elastic return phenomenon occurs because of regions of the stamped part that were subjected to stresses lower than the yield limit of material, mainly close to the holders of the clamping device. Since the depth reached by the tool in CNC system is fixed, the results indicate that the deformed region of parts was slightly shorter for samples processed at greater feed rates, considering direction Z. It is likely that the greater strain rates produced more heat which resulted in instantaneous decrease of maximum tensile strength on material beneath the tool-workpiece contact area. This way the necessary pressure to deform the material in the trunk cone region was smaller, and a greater part of the force was supported by the elastic deformed zone outside the cone. Since a greater proportion of the sheet was stretched in elastic regime, the return was also greater after tension was removed from the sheet.

It was evident that for commercially pure aluminum in the conditions tested it is essential to use lubrication, since dry condition generates a big friction coefficient at tool-chip interface. Due to tool rotation heat concentration occurs close to this interface, which diminishes material resistance. As the tool revolves in a helicoidally path, several temperature variations occur at the piece during the test. These variations originate traction and compression stresses in the sheet. This effect contributes to generation and propagation of cracks, as occurred in test 4. Therefore, in order to improve surface quality, decrease frictional forces, temperature of the plate, and improve heat dissipation, lubricant utilization is imperative.

3.1 Roughness analysis

Figure 5 shows the average values of roughness parameters Ra, Rq, Rt, the most commonly measured. Ra is the arithmetic mean of the distance of peaks and valleys to the average line. Rq is the RMS (Root Mean Square) value of the roughness in the evaluation length. Thus, this parameter tends to present greater values than Ra, since it accentuates the values of peaks and valleys that deviate from the mean. Finally, the roughness parameter Rt defines the greatest peak to valley depth measured within the evaluation length range (Cavaler, 2010). Analyzing the graph of Fig. 5 it is possible to notice that while the feed speed increased, the surface and its roughness parameters tend to increase as well. Because of the greater strain rate and heat generation of this condition, it is likely that the sheet was more prone to deform locally in the interface region during tool passage, increasing the spatial frequency of the asperities. In test 4, in which there was no lubrication, a high value of roughness is noticed in comparison to the other ones, result already expected, due to apparent poor quality of produced surface.

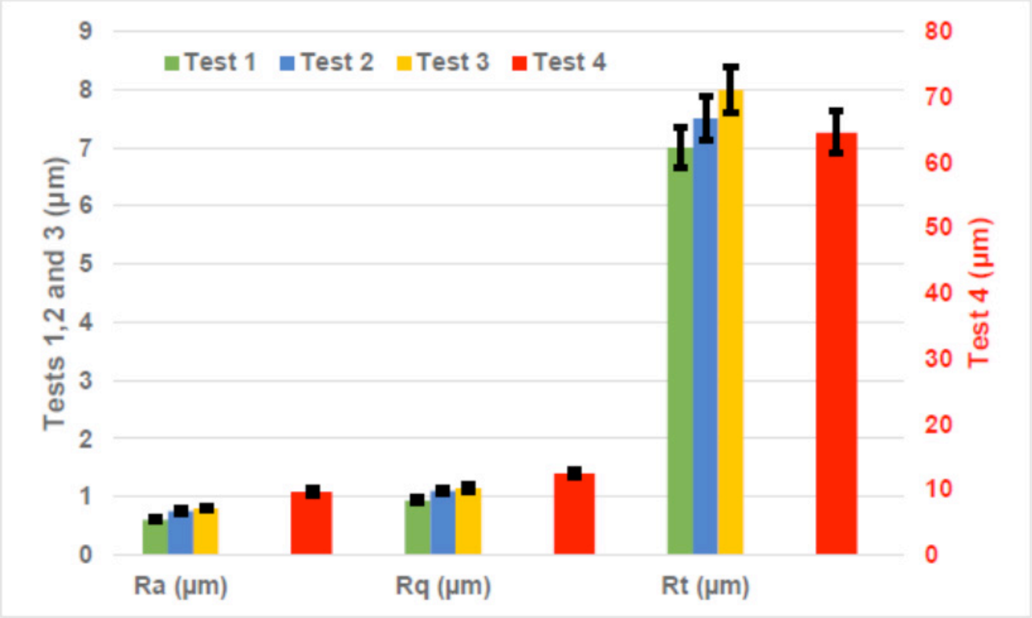


Figure 5. Graph showing results for the roughness parameters Rt, Rq and Rt after ISF tests.

The process is slow, taking from 3h for lower feed speeds and 2h for higher values of this parameter. For this reason, it is not effective to serial production when the work pieces show simple shapes. On the other hand, in case of complex shapes, this process could be used for manufacturing of medium size batches of work pieces without the need of previous molds and dies manufacturing, reducing substantially the costs of the final product.

3.2 Metallographic analysis

As a criterion for comparison, an aluminum sample was taken before the tests to analyze the change in microstructure of the material due to ISF processing. Figure 6(a) shows the microstructure of the aluminum sheet before the tests. The gray color indicates the aluminum matrix (solid solution α phase) with dispersed particles, while the black spots represent micro-constituents in the matrix. Figure 6(b) shows the microstructure after test 1. It is possible to see a small increase in the amount of micro-constituents and an increase in particle size of the aluminum matrix. Although heating time for a determined point in the sheet is limited, due to low recrystallization temperature of aluminum it is possible for this phenomenon to have taken place in the deformed sheet. In test 2, shown in Fig. 6(c), a significant increase was observed in the micro-constituents quantity along the aluminum matrix, and also an increase of larger precipitates with more rugged characteristic. In test 3, from Fig. 6(d) the trend to increase of the amount of micro-constituents was maintained, and there was also the appearance of large number of gray spots with clearer characteristics in its structure. In test 4, from Fig. 6(e), it is possible to see a rougher structure with a relief characteristic, and larger micro-constituents. Through the metallographic analysis it was not possible to identify the directions of lamination or the grain boundaries in the structure. However, it was possible to verify small surface modifications in the structure in each test and this behavior indicate the anisotropy of the material due to the different angles which the samples were cut off from the work material and its lamination direction. With the increase of the feed speed, a gradual increase of micro-constituents in the structure was generated, mainly in the micrograph of test 4, which was performed without lubrication.

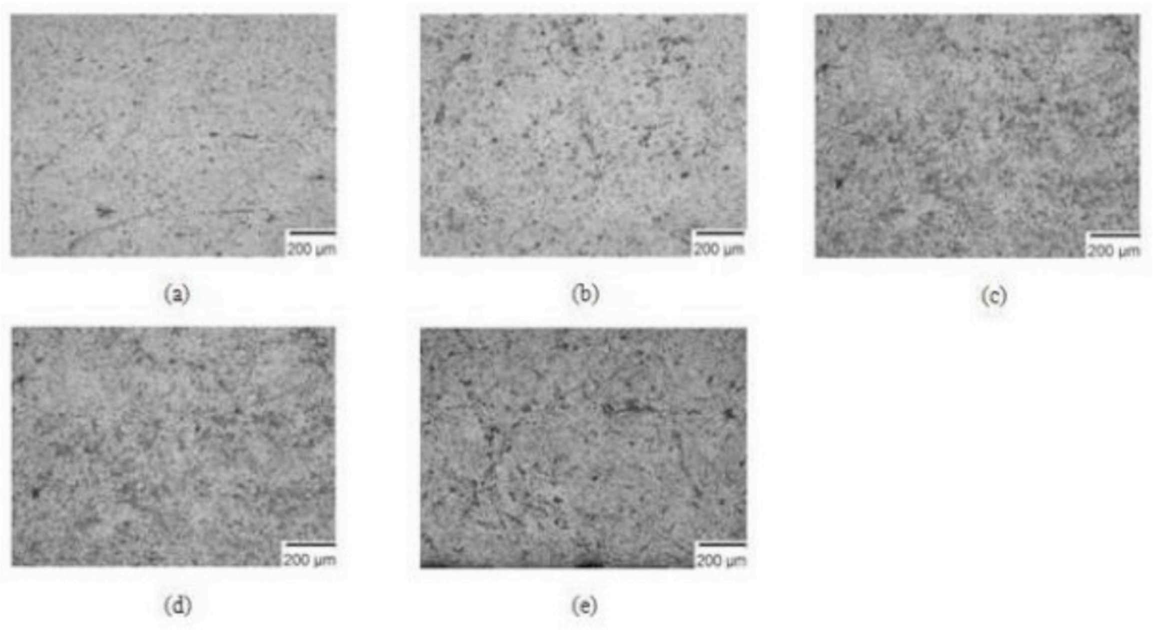


Figure 6. Micrographs of incremental sheet forming tests: a) non-deformed sheet; b) test 1; c) test 2; d) test 3; e) test 4.

4 I CONCLUSION

After this study the following conclusions could be drawn:

- The application of the ISF process has been effective for use with CNC machines. The process is slow (2 to 3h per piece) and for this reason it is not effective to produce large batches when desired part has simple shape.

- Commercially pure aluminum proved to have an excellent behavior for incremental sheet forming, once the produced parts had low roughness and the elastic recovery was relatively low. This effect can be further controlled during the tool path generation when it is previously known or when forming is first simulated by Finite Element Method (FEM), or also through accumulated know-how of the process.

- Lubrication proved to be essential during the process. In the test made using dry condition the sheet fractured and presented the poorest surface quality measured.

- Variation of the feed speed, which was main parameter of this work, presented differences in the geometric aspect, surface quality and microstructural changes. Greater strain rates can be associated with greater heat generation, which leads to decrease of mechanical properties of the material.

- Analyzing the increase in feed speed, it could be concluded that it is prone to increase the elastic recovery, besides damaging the roughness of the part. Microstructural analysis indicates that this higher feed also causes several microstructural variations, indicating that the obtained plastically deformed part is very sensitive to actuating shear forces and strain rates.

It is then possible to conclude that, for smaller feed speed, a better workpiece finish is achieved, but it will take longer machining time. Therefore, for economic purposes one must choose an ideal value to be defined as a parameter in order to achieve required quality of the part with the shortest production time.

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