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OPTIMIZATION OF SINGLE-POINT INCREMENTAL FORMING PROCESS OF ASTM A653 CS-A STEEL SHEETS THROUGH TAGUCHI METHODS

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ABSTRACT

Incremental sheet forming (ISF) is a free forming process of parts in a specific equipment like CNC machining centers or special hexapod robots. It stands out for its high formability and low production cost, being ideal for prototypes and small batches. The main design parameters are the wall angle, material and sheet thickness and, most of the cases, they cannot be modified or even adjusted to improve the manufacturing performance. On the other hand, the main process parameters that impact the product total quality are tool rotation, vertical step size, lubrication and all of them can be continuously optimized. Thus, these last three process parameters are widely investigated in several kinds of research. This paper investigates the effects of applying different tool rotation when shaping a truncated cone of ASTM A653 CS-A steel sheets - 0.43mm thick - with different types of lubrication and vertical step size. It was chosen three level for each factor: 600, 1200 and 1800rpm for tool rotation n; 0.6, 0.8 and 1.0mm for vertical step size Δz and dry, mineral oil and molybdenum disulfide grease for lubrication condition. The statistic Taguchi method was applied to evaluate and optimize the maximum depth of forming and better surface quality (roughness Ra and Rz). The results confirmed the use of mineral oil as the most predominant factor in the process for minimum roughness, maximum forming height, and minimum deformation levels. Hence, the best set of parameters was 600rpm, 0.6mm vertical step size and mineral oil as a lubricant. The parts tested did not show any defects. Additionally, it was verified that the increase of the tool rotation negatively impacts the ISF formability in the case of a thin specimen due to the increment of temperature.

INTRODUCTION

Incremental sheet forming (ISF) is a free-form stamping process, where the sheets are fixed at their peripheries and formed by the tool, generally a semi-spherical punch, which moves through a predefined path [1, 3]. Although its application seems current, the process had already been patented by Edward Leszak in 1967, long before it became feasible [4 - 7]. Compared to conventional stamping processes, the ISF has advantages because of its simplicity, it doesn't need the traditional and expensive dies [8 -10]. Besides that, it is possible to perform in CNC machining centers, with three or more axes, programmed by CAM direct from CAD projects [11, 12]. So that, the deformations are imposed incrementally by the tool through path strategies, until obtaining the desired geometry [13]. Due to its advantages, incremental forming is shown to be satisfactory and feasible even with longer production time, being ideal for prototypes and small batches in the automotive, aerospace and biomedical markets [15, 16].

Since the process has become attractive in recent decades, many articles have been written to evaluate the parameters involved in it and to improve incremental forming techniques [17]. Jeswiet et al. 2005 [7] performed one of the main studies related to this subject, evaluating a large part of the parameters and they concluded that the significant variables in the process are: the sheet thickness t; the maximum wall angle α; the vertical step size on the z-axis, Δz; the tool diameter d; and the tool feed f. Other parameters are also considered important in the process, such as the tool rotation n, and the lubrication condition.

Moreover, Micari et al. 2007 [12] found that, thanks to the tool-induced deformation, the formability at ISF is greater than the conventional stamping, so the rotation parameter becomes very interesting for evaluation.

This article aims to investigate how tool rotation impacts the incremental forming process of ASTM A653 CS-A commercial steel. In addition to the rotation, it was monitored also the vertical step size Δz and the lubricant at the interface between the tool and the sheet. To evaluate the results, the maximum forming height h_{max} was measured as well as the surface quality roughness R_a and R_z.

Thus, for the accomplishment of the experiment it was chosen to follow the Taguchi method L9 orthogonal arrays with three factors and three levels. So that, it was possible to evaluate the signal/noise ratio results and to estimate the higher h_{max} and better roughness for the set designed, as well the influence of each variable in the process. The tool rotation range was 600, 1200 and 1800rpm, the vertical step size Δz was 0.6, 0.8 and 1.0mm and two types of lubricants, solid and oil, were used in addition to dry experiments. In the experiment, circular meshes were also recorded in the specimens in order to evaluate the deformations imposed by the process.

METHODS AND MATERIALS

Single point incremental forming tests were carried out on ASTM A653 CS-A rounded tablets sheets of 68mm diameter and 0.43mm tick to investigate the influence of tool rotation, vertical step size and lubricant condition. The maximum forming depth h_{max} and quality surface R_a and R_z were the outputs to be optimized.

Thus, Design of Experiments was applied, DoE aims to determine the influence of different variables on a given process. Therefore, it is essential to develop experiments because a well-defined planning enables the reduction in variability of the results as well as optimizes its performance by reducing the costs and time involved. Taguchi et al. 1990 [14] argue that poor quality in a process affects not only the manufacturer, but also society. Its method is to produce high quality products at low production costs.

The design parameters related to the maximum signal/noise ratio guarantee robust quality, with performance less sensitive to noise signals. The equations for the calculation of the S/N ratios for the characteristics used in this experiment are: Larger is better, Eq. (1); Smaller is better, Eq. (2), where n is the number of replicates in the tests.

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{1}$$

$$S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n}y^2\right) \tag{2}$$

It was decided to use the Taguchi method, with its orthogonal arrays delineation L9 and, thus, to analyze the answers through the signal noise, being larger is better for h_{max} and smaller is better for the roughness (R_a and R_z). For the current experiment there are three factors with three levels each, Table 1.

Table 1. Experiment factors and levels.

Factor		Level 1	Level 2	Level 3
F1	Rotation (rpm)	600	1200	1800
F2	Vertical step size Δz (mm)	0.6	0.8	1.0
F3	Lubricant	Dry	Mineral Oil	Solid

The appropriate orthogonal array L9 with three replications that means 27 tests, could be seen in Table 2.

Table 2. Orthogonal array L9.

Test	Factor			Replication		
	Rotation (rpm)	Step Size Δz (mm)	Lubricant	1	2	3
1	600	0.6	Dry	$y_{1,1}$	$y_{1,2}$	$y_{1,3}$
2	600	0.8	Mineral Oil	$y_{2,1}$	$y_{2,2}$	$y_{2,3}$
3	600	1.0	Solid	$y_{3,1}$	$y_{3,2}$	$y_{3,3}$
4	1200	0.6	Mineral Oil	$y_{4,1}$	$y_{4,2}$	$y_{4,3}$
5	1200	0.8	Solid	$y_{5,1}$	$y_{5,2}$	$y_{5,3}$
6	1200	1.0	Dry	$y_{6,1}$	$y_{6,2}$	$y_{6,3}$
7	1800	0.6	Solid	$y_{7,1}$	$y_{7,2}$	$y_{7,3}$
8	1800	0.8	Dry	$y_{8,1}$	$y_{8,2}$	$y_{8,3}$
9	1800	1.0	Mineral Oil	$y_{9,1}$	$y_{9,2}$	$y_{9,3}$

In this work was applied 68.0mm diameter specimens of ASTM A653 CS-A, with a thickness of 0.43mm and supplied by CSN Company in Brazil, Figure 1.

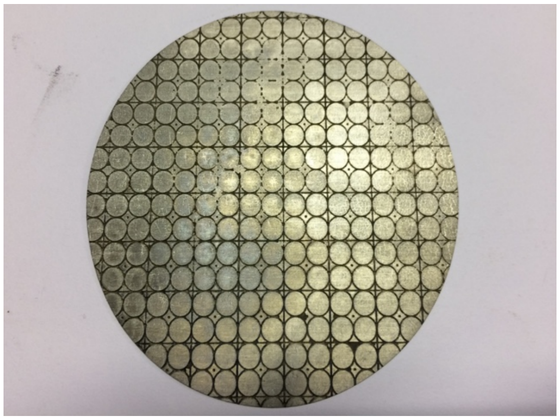

Figure 1. Specimen with 68.0mm diameter and t=0.43mm.

So that, following studies already carried out by Valle et al. [15] with the same material and dimensions, it was suggested the tool feed at 200mm/min and the wall angle at 45° to enhance the expected results. The punch with a diameter of 8.0mm was performed. Besides that, the specimen was deformed in a concentric truncated cone geometry from the periphery to the center. Thus, to prevent the tool breakage from working too close to the fastener the maximum stamping depth was limited.

Two types of lubricants were applied. The first one was the Mineral Oil Lubrax GL 5 90. It was chosen because its viscosity is close to the oil used in the conventional forming process. The solid lubricant Molybdenum Disulfide Grease developed for operations up to 350°C and supplied by Quickshot was the second type – solid lubricant.

In order to measure the deformations imposed by the punch during the ISF process, a mesh of circles with a diameter of 4.0mm was recorded on the outer surface of the specimens by the photo-corrosion process.

The ISF process is simpler than the conventional one so that, the execution of the tests needs only three equipment: the CNC vertical machining center, the punch itself and the ISF device for fixing the test body. The CNC machine was the ROMI Discovery Model 4022 – MACH 9 command, Figure 2.

Figure 2. CNC vertical machining center.

The punch was carbide hemispheric tool obtained by powder metallurgy and coated with TiAlCN, Figure 3.a. The tool hardness is 2600HV.

The ISF device, Figure 3.b, used for fixing the specimen was made by heat treated steel SAE4140 and mounted over the machine table. It was also composed of base and plate presses according to Figure 3.c and it was attached to a chuck of three nuts. The center of the device was aligned with the z-axis of the CNC machine.

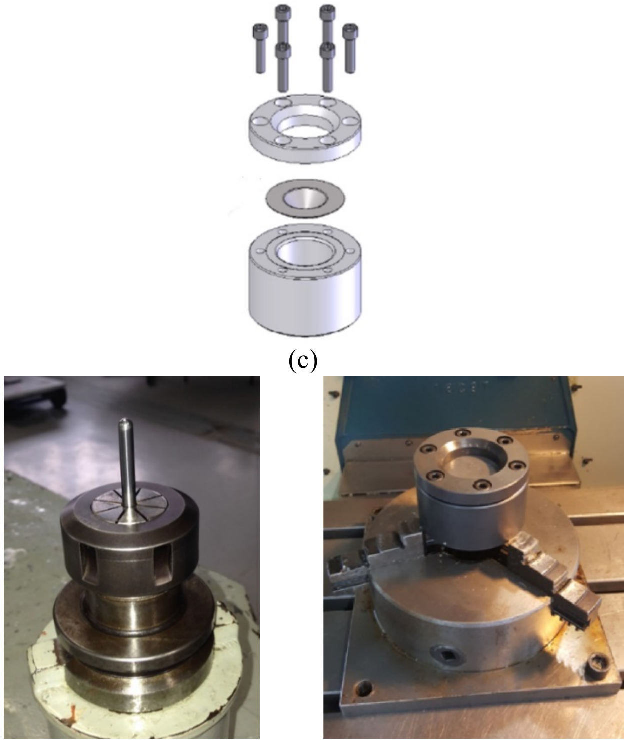
(c)
(a) (b)

Figure 3. (a) Punch; (b) Device; (c) Exploded vision.

In addition to the equipment mentioned above, it was required other ones to measure the output parameters. The deformations were obtained by a caliper with a resolution of 0.02mm and the roughness was measured with a Taylor-Hobson Surtronic S-128, Figure 4. The R_a and R_z values were measured in direction of the vertical step size of the inner surface of formed cones. The cut-off was 0.8mm for this level of expected roughness [2]. It was measured 3 lines of roughness, one each 90°, and the average was the final parameter to be applied. The last quarter of 90° was unvalued due to increment marks in z-direction.

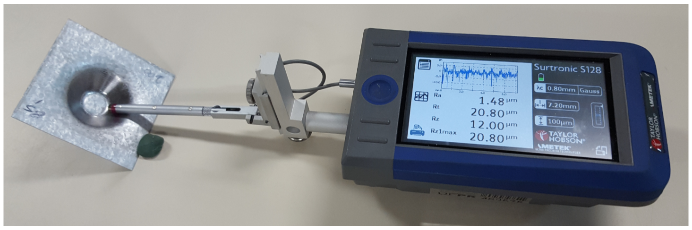

Figure 4. Taylor Robson roughness tester.

The tests were performed according to the planning following a randomized order to avoid unforeseen external factors that could interfere in the final results. In order to evaluate the criterion of maximum depth h_{max} it was necessary to carefully monitor the progress of the process and, at the moment of the failure, stop the machine avoiding damages to the equipment, Figure 5.a. The rotation direction of the tool was programmed to discordant once McAnulty et al. 2016 [11] evaluated this parameter and concluded that this direction minimizing friction better than concordant.

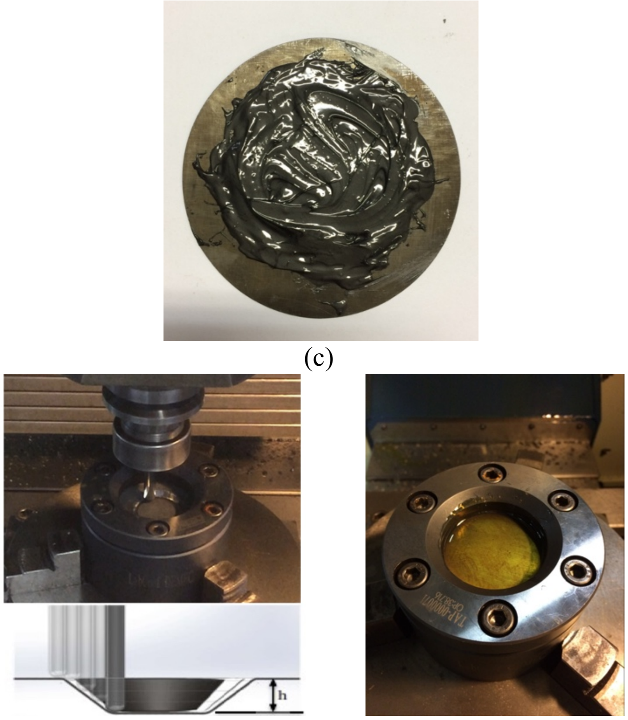

Figure 5. (a) Dry and h_{max}; (b) Mineral oil; (c) Grease.

The mineral oil was applied by a manual spray pump after specimen fixation in the device, Figure 5.b. On the other hand, it was necessary to apply the molybdenum disulfide grease by a brush for better spreading on the test body surface, Figure 5.c.

ANALYSES AND RESULTS

Table 3 brings all the experiment results under different lubricant condition following the Taguchi design.

Table 3. Experiment results.

Test	Rotation (rpm)	Step (mm)	Lubricant	h_{max} (mm)	Ra (μm)	Rz (μm)
1	600	0.6	dry	17.4	2.03	13.00
2	1200	1.0	dry	5.0	1.37	8.83
3	1800	0.8	dry	16.8	2.17	11.17
4	1200	1.0	dry	17.0	5.87	31.17
5	1800	0.8	dry	3.2	1.70	11.83
6	600	0.6	dry	17.4	1.27	7.83
7	600	0.6	dry	9.6	0.83	4.67
8	1200	1.0	dry	4.0	3.07	17.83
9	1800	0.8	dry	16.8	1.57	10.00
10	600	0.8	oil	16.8	0.80	5.33
11	1200	0.6	oil	17.8	0.70	4.83
12	1800	1.0	oil	17.0	0.97	5.33
13	1800	1.0	oil	17.0	1.10	5.17
14	1800	1.0	oil	17.0	1.03	5.00
15	600	0.8	oil	16.8	0.73	4.17
16	600	0.8	oil	16.8	0.90	5.83
17	1200	0.6	oil	17.8	0.70	4.17
18	1200	0.6	oil	17.8	0.73	4.17
19	600	1.0	solid	17.0	1.57	10.33
20	1200	0.8	solid	12.8	1.67	10.83
21	1800	0.6	solid	9.6	1.83	11.17
22	1800	0.6	solid	10.2	1.27	9.17
23	600	1.0	solid	17.0	1.90	12.83
24	600	1.0	solid	17.0	1.60	10.50
25	1200	0.8	solid	12.0	2.13	13.50
26	1200	0.8	solid	12.0	1.60	11.17
27	1800	0.6	solid	9.6	1.33	9.50

It can be noticed irregular behavior in dry-formed sheets, independent of the vertical step size and tool rotation. It could be due to high friction and heat generated in this set of tests, where no lubricant was applied and, consequently, significant damage was verified, Figure 6.

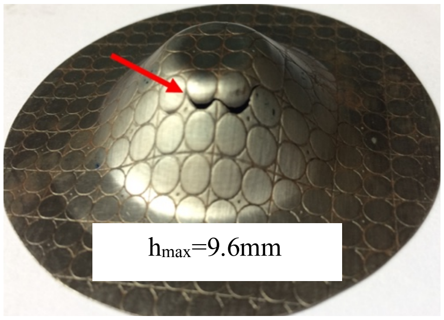

Figure 6. Specimen breakage (dry, Δz=0.6mm and 600rpm).

On the other hand, this behavior was not observed on the specimens formed with lubricant on the surface - mineral oil or solid.

When forming with mineral oil it was not possible to visualize the internal surface because the oil layer became dark as the vertical step size was applied cycle by cycle. Nonetheless, all formed bodies by mineral oil lubrication reached the maximum height without failure for all tests. It means, reaching maximum height (h_{max}=17.4mm) when vertical step size was set to 0.6mm and 29 cycles were performed. Maximum height also was reached (h_{max}=16.8mm) when vertical step size was set to 0.8mm and 21 cycles were performed. Maximum height was (h_{max}=17.0mm) when vertical step size was set to 1.0mm and 17 cycles were performed.

Additionally, there was no material added on the tool nose surface and the visual aspect proved to be much better than the other lubricant conditions too.

The use of molybdenum disulfide grease shows that the behavior of the specimen was standardized, the failures occurred when applying greater rotation, 1200rpm and 1800rpm with h_{max} around 12mm and 10mm respectively. No one test body failed with 600rpm and grease. It was possible to verify the formation of gases due to the heating of the grease, being harmful to the environment and operator.

Applying MiniTab Statistical Software the signal/noise graph was generated so that it was possible to evaluate which factors were most significant in the experiment. Where larger is better in terms of depth h_{max} that means the lubricant is the main parameter in this case, Figure 7.

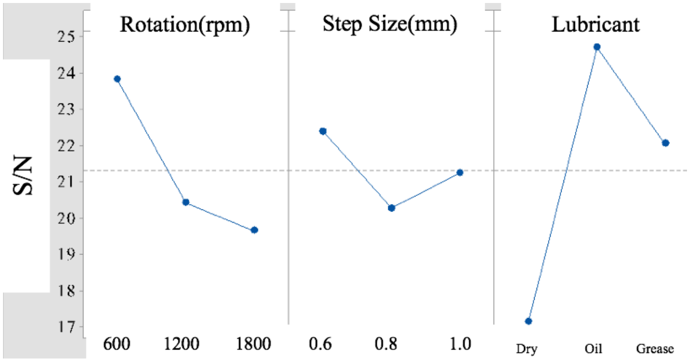

Figure 7. Signal/noise graph – larger is better to h_{max}

For the best lubricant verified, mineral oil, the regression equation of h_{max}, Eq. (3) was generated, with a confidence level of 95%, the R^2 value was 100%, this value is due to the fact that all the test specimens in this situation reached the maximum height without showing rupture, confirming the fact that mineral oil is the main parameter in the study.

$$h_{max}=18.80 + 0.000667\eta - 3\Delta z \tag{3}$$

The specimen formed with mineral oil obtained the best results in terms of roughness with R_a varying from 0.7 to 1.1μm and R_z from 4.17 to 5.83μm. In the second was the body formed with grease, R_a ranged from 1.27 to 2.13μm and R_z from 9.17 to 12.83μm. The dry stamped sheets showed large deviations in the measurements, thus being the worst case, R_a ranged from 1.27 to 5.87μm and R_z from 4.67 to 31.17μm.

Figure 8 shows some aspects of these three sets of experiments based on lubricant.


(a) (b) (c)

Figure 8. (a) Dry, 1200rpm and Δz=1.0mm (b) Mineral Oil, 1200rpm and Δz=0.6mm (c) Graese, 600rpm and Δz=1.0mm

The analysis of the S/N - smaller is better, for the measured roughness, clearly indicates the superiority of the mineral oil in relation to the other lubricants and confirms what was concluded by Hirt et al. 2005 [6]. In addition, it is noticed that with the increase of vertical step size the surface quality of the formed sheet worsens. However, in relation to rotation additional studies are needed to better understand the behavior of the parameter.

For the best lubricant condition verified, mineral oil, the regression equation of R_a, Eq. (4), and R_z, Eq. (5) was generated, with 95% confidence level, R^2 value was 87, 32% and 38.36% respectively. One of the tested specimens presented a large noise in R_z, impacting the reliability of the equation.

$$R_a=0.207 + 0.000068\eta + 0.704\Delta z \tag{4}$$

$$R_z=3.333 - 0.00037\eta + 2.5\Delta z \tag{5}$$

The signal/noise graph was generated to evaluate R_a factor, where smaller is better in terms of roughness that means the lubricant is the main parameter in this case, Figure 9.

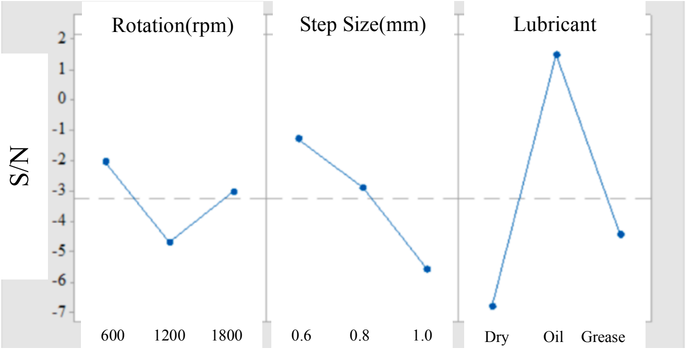

Figure 9. Signal/noise graph – smaller is better to R_a

Figure 9 shows that R_a value decreases with the rise in punch diameter. Higher tool diameter allows a reduction in waviness on the tool-sheet interface resulting in a better quality surface.

On the other hand, the influence of rotation and lubricant on a quality surface is not completely clear in this research. So that, it must be investigated in further work.

The signal/noise graph was generated to evaluate also R_z factor, where smaller is better in terms of roughness that means the lubricant is also the main parameter in this case, Figure 10.

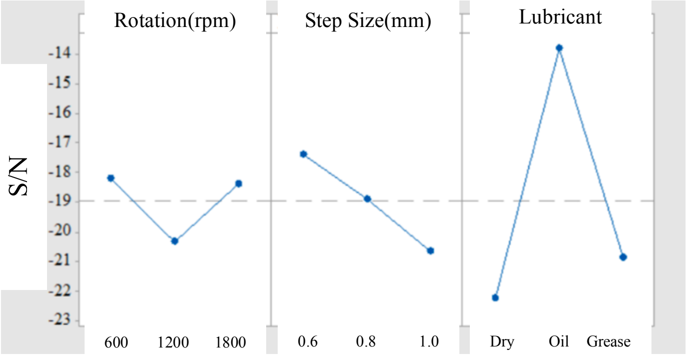

Figure 10. Signal/noise graph – smaller is better to R_z

Figure 10 shows that the behavior of R_z has a similar trend to the Ra. In fact, when spindle speed is increased from 600rpm to 1200rpm, proper lubrication at the contact zone of tool-sheet reduces scratching on the formed surface and results in decreasing average roughness.

However, when spindle speed is increased from 1200rpm to 1800rpm the quality surface decrease this may be due to the fact that low viscous forming oils are not able to withstand high forming temperature and squeezed out from tool-sheet contact zone.

At least, residual plots showed that normal distribution of data is valid as all the points reside along a straight line.

CONCLUSION

Among the lubricant factors, the one with the greatest impact on the forming depth h_{max} is the mineral oil that ensures the highest performance to the ISF process. Molybdenum disulfide grease can be applied, however, it does not present as satisfactory results as mineral oil and has a high cost. The solid lubricant has also formed gas during the process that can be harmful to the operator and the environment. At least, the worst case was the dry condition.

In general, increased tool rotation n reduced the formability of ASTM A653 CS-A steel sheets because the high temperature tends to fragilize the material. So that, in this work the best rotation found was at 600rpm.

The vertical step size Δz, when evaluated under the conditions of rotation, did not affect conclusively the forming depth h_{max}, but it caused greater impact in the surface. It confirms studies carried out by several authors previously where increasing the vertical step size causes higher peaks and valleys and thus the roughness is higher.

Therefore, the best set of parameters was 600 rpm, 0.6mm vertical step size and mineral oil as a lubricant in terms of h_{max} and roughness R_a.

In the future, it is indicated to carry out a complementary study to evaluate in a deeper way the formability of sheets under the lubrication effect with mineral oil. Applying greater wall angle and optimizing the maximum depth h_{max}. As the results were satisfactory for this case, it is interesting to direct some additional study to verify the relation with the tool feed, allowing smaller times in the process, which is very attractive.

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