



## SURFACE ROUGHNESS IN THE INCREMENTAL FORMING OF AISI 304L STAINLESS STEEL SHEETS

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### Abstract

The aim of this study is to verify the resulting surface roughness of parts formed by the Single-Point Incremental Forming (SPIF) process for an AISI 304 austenitic stainless steel. The tests are based on a variation of the Incremental Forming Process, called SPIF. The tests have been carried out in a vertical machining center, using a CAD/CAM software. The blanks of AISI 304 steel sheets of 0.5 mm of thickness have been fixed by a rig and cemented carbide tools with a hemispherical tip of 8 and 10 mm of diameter are employed. Some of the tools are PVD multi-coated. A combination of wall angle and vertical depth simulating critical working conditions has been set for the process. The finishing roughness parameter  $R_z$  has been measured for the different process conditions. The results found indicate that  $R_z$  roughness decrease with the increase of the vertical depth  $d_z$  and with the use of coating.

Keywords and phrases: incremental forming, stainless steel AISI 304L, roughness behavior.

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**Notation**

$d_z$ [mm]	Vertical depth
$R_T$ [mm]	Tool radius
$R_z$ [ $\mu$ m]	Average of roughness
$v_{fn}$ [mm/min]	Feed rate
$\alpha$ [°]	Wall angle

**1. Introduction**

The sheet metal industry often employs different forming methods which are based on the use of punches and dies with the accurate geometry of the part to be formed. These methods are normally used for mass production, since the high cost of the dies does not play a big role when a large quantity of parts are produced in a relatively short period of time. However, when small series production is required, the costs of die production are considerably high in the balance making not feasible the use of conventional methods, like stamping or drawing. Therefore, emerging production methods like Incremental Forming should be considered in these cases as an alternative to fulfill the properties and production requirements imposed by the low series production industries [1].

The Incremental Sheet Forming process can be implemented rapidly and with a reasonable precision. Drawings from CAD (Computer Aided Design) are converted into CAM files (Computer Aided Manufacturing) containing the information of the three-dimensional path that should be developed by the tool in the process. Therefore, the tool path is totally controlled by the CAM program as in the usual Numerical Control technology. In this process, the total deformation is reached by the sum of the incremental steps with only small strains involved in each step [2].

The strain in the blank can be reached in two different ways: the forming tool has a support below the sheet (Two-Point Incremental Forming - TPIF) or the forming tool has a single point (Single-Point Incremental Forming - SPIF), this means there is no support below the sheet [3]. In the TPIF process, with a partial positive die as the support fixed below the blank convex surfaces can be produced, while in the SPIF concave surfaces are produced.

Surface quality of the formed parts is a very important aspect in metal sheet forming, which is directly related to several parameters as the forming strategy, lubrication and materials involved. In the Incremental Sheet Forming the main factors that affect the roughness related to the strategy employed are vertical depth  $d_z$ , tool radius  $R_T$ , the wall angle  $\alpha$  and the relative motion between tool and formed part [4, 5, 6].

## 2. Experimental Procedure

Fundamentally the set-up consisted of a Vertical Machining Center ROMI DISCOVERY 4022, a forming tool, a rig, and the CAD/CAM software EdgeCAM®. A portable surface tester, DIGIMESS TR100, was used to measure roughness.

The main geometrical parameters of the employed tools are presented in Table 1, tool radius, total length, run-out and overhang.

**Table 1.** Characteristics of the tools

Tool nr.	Tool radius $R_T$ [mm]	Total length [mm]	Run-out [mm]	Overhang [mm]
1	8	98.4	0.04	74
2	10	147.6	0.05	74

The run-out is an initial problem when good surface quality is desired. The largest value of the tool eccentricity will determine the amplitude of the run-out. In this paper, these effects were eliminated acceptable levels.

Figure 1 shows the forming tool mounted into collet chuck.



**Figure 1.** Tool forming mounted into collet chuck.

In Table 2, the tests proposed with uncoated and coated tools are presented. The parameters employed for the uncoated tools consist of the tests number 1 to 6, while the parameters employed for the coated tools consist of the tests number 7 to 12. The goal by using a TiAlN-PVD coating on the hemispherical tip of the tool was to increase hardness and reduce friction in the specimen/tool interface.

**Table 2.** Parameters of forming using uncoated and coated tools

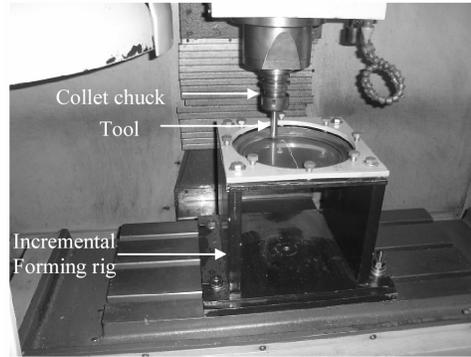
Test nr.	Tools radius $R_T$ [mm]	Wall angle $\alpha$ [°]	Vertical depth $d_z$ [mm]	Feed rate $v_{fh}$ [mm/min]
1	8	60°	0.4	1500
2	8	60°	0.6	1500
3	8	60°	0.8	1500
4	10	60°	0.4	1500
5	10	60°	0.6	1500
6	10	60°	0.8	1500
7	8	60°	0.4	1500
8	8	60°	0.6	1500
9	8	60°	0.8	1500
10	10	60°	0.4	1500
11	10	60°	0.6	1500
12	10	60°	0.8	1500

The employed coating was a commercial available one composed by several alternate layers of TiAlN and DLC (Diamond Like Carbon).

The choice of tool radius  $R_T$  of 8 and 10 mm and a wall angle  $\alpha$  equal to 60° is explained by the fact that these parameters simulate conditions that are considered critical to work with.

The feed rate  $v_{fh}$  was fixed experimentally at a level where the process remained stable which was 1500mm/min. This was based on preliminary tests carried out in a previous phase of the research.

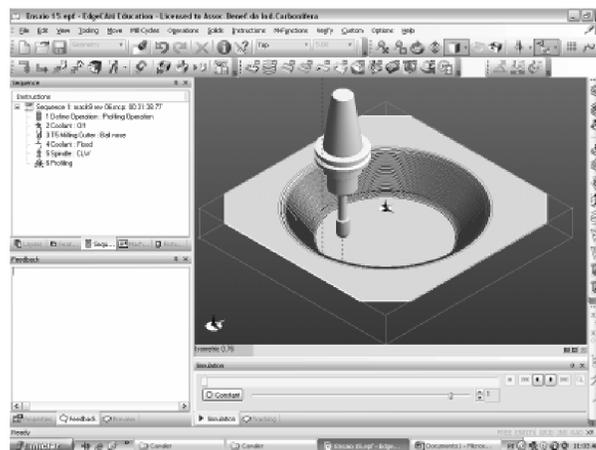
In order to carry the experiments a rig was developed (Figure 2) in which the sheet was attached.



**Figure 2.** Incremental forming rig mounted on the table of a vertical machining center.

The methodology used in the tests was based on the SPIF (Single Point Incremental Forming) process. In this system, the tool movement is in  $Z$  direction, while the blank moves simultaneously in  $X$  and  $Y$  directions with no support from below. After preliminary tests were conducted, the decision was made to leave the tool unlocked for rotation, i.e., the tool is free to rotate as the forming process takes place.

The surface generated is similar to a truncated cone. To generate this geometry, a helical conical strategy was used through the EdgeCAM® software. In this type of strategy, the tool executes a conical helical path and it is always in contact with the blank. Figure 3 shows the forming simulation made through this software.



**Figure 3.** Incremental forming simulation.

The tests were performed for austenitic stainless steel AISI 304L blanks with dimensions of  $0.5 \times 295 \times 295$ mm. The blanks have a chamfer of  $70\text{mm} \times 45^\circ$  in the corners to facilitate the assembly in the forming rig. This steel presents yield strength of 258 MPa, ultimate strength of 786 MPa in the longitudinal direction, and medium anisotropy  $r_m$  of 0.99. A chemical analysis revealed the composition as given in Table 3.

**Table 3.** Chemical composition of austenitic stainless steel AISI 304L (wt.%)

C	Si	Mn	S	Cr	Ni	Fe
0.001	0.6	1.2	0.002	16	9	rest

For lubrication of the tool/workpiece interface, a grease consisting of a soap containing lithium (Unilit MPA-2) was used. This grease presents the following characteristics: consistency 2 (NLGI-2), application temperatures below  $130^\circ\text{C}$  and drop point of  $185^\circ\text{C}$ .

### 3. Results and Discussion

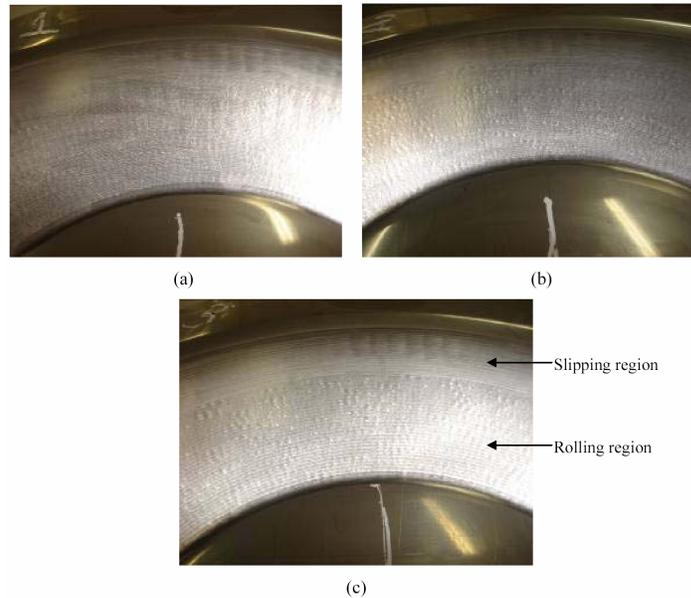
The forming process behaved as expected, that is the tool slid over the part in an adequate way and free from vibrations.

It was observed at the beginning of the test that the tool slips and, from a certain depth (Table 4), the tool began rotating with the test specimen. The possible cause is the increase of friction due to a larger contact area between the tool and blank.

**Table 4.** Depth at which rotation of the tool started

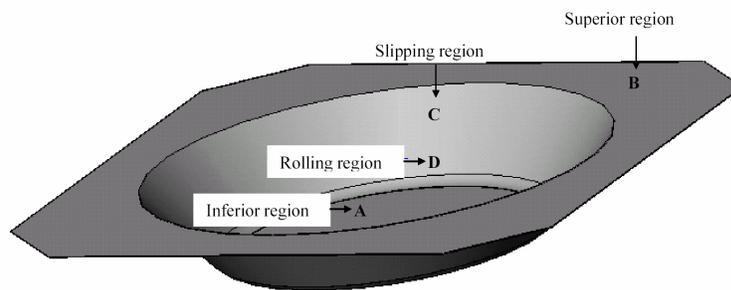
Test nr.	Depth that began the tool revolution [mm]
1	6.4
2	6.3
3	7.3
4	6.4
5	6.8
6	7.6
7	6.4
8	6.4
9	7.1
10	6.7
11	6.9
12	7.1

Figure 4 shows clearly differences in the surface aspect of the blanks with and without rotation of the tool. The larger the increment is the more visible are the texture differences between these two regions.



**Figure 4.** Regions with different textures: a - test nr. 1  $d_z = 0.4\text{mm}$ , b - test nr. 2  $d_z = 0.6\text{mm}$ , c - test nr. 3  $d_z = 0.8\text{mm}$ .

In order to verify the roughness produced by the different tools and procedures, the parameter  $R_z$  was measured in the forming region. Figure 5 shows the regions where roughness measurements were carried out.



**Figure 5.** Regions of measurement of roughness  $R_z$ .

At Tables 5 and 6 are presented the values of roughness  $R_z$  produced by the tool action in several tests. Each value of roughness  $R_z$  was the result of an average of three measurements (parallel to rolling direction, transverse direction and at a direction  $45^\circ$  from the rolling direction of the sheet).

**Table 5.** Values of roughness  $R_z$  with uncoated tools

Test nr.	Tools radius $R_T$ [mm]	Wall angle $\alpha$ [°]	Vertical depth $d_z$ [mm]	Measurement region $R_z$ [μm]				Average of $R_z$ [μm]
				Inferior A	Superior B	Slipping C	Rolling D	
1	8	60°	0.4	1.77	1.00	9.03	8.60	8.82
2	8	50°	0.6	1.70	1.23	8.67	7.97	8.32
3	8	50°	0.8	1.27	0.73	10.53	5.60	8.07
4	10	60°	0.4	2.77	1.33	10.90	9.77	10.34
5	10	52°	0.6	2.47	0.57	9.20	7.33	8.27
6	10	50°	0.8	2.50	0.63	8.63	4.50	6.57

**Table 6.** Values of roughness  $R_z$  with TiAlN coated tools

Test nr.	Tools radius $R_T$ [mm]	Wall angle $\alpha$ [°]	Vertical depth $d_z$ [mm]	Measurement region $R_z$ [μm]				Average of $R_z$ [μm]
				Inferior A	Superior B	Slipping C	Rolling D	
7	8	60°	0.4	1.87	1.30	11.00	5.70	8.35
8	8	60°	0.6	2.17	1.87	7.67	5.77	6.72
9	8	60°	0.8	1.57	0.87	7.23	7.23	7.23
10	10	60°	0.4	3.10	1.37	8.37	5.67	7.02
11	10	60°	0.6	1.17	1.07	7.53	5.00	6.27
12	10	60°	0.8	0.73	0.93	5.77	5.77	5.77

In all of the tests the measurement direction was in the direction of the vertical step  $d_z$ , because in the perpendicular direction, the measurement became impracticable due to the specimen geometry.

In the last column of Tables 5 and 6, arithmetic averages of roughness were calculated between the region C (slipping region) and region D (rolling region). These averages were done because the forming area is included between these two regions. In order to compare with region A (inferior region) and region B (superior region) that were not deformed, the value of  $R_z$  in the unformed sheet was  $0.78\mu\text{m}$ . The sheet before the forming presented a roughness  $R_z$  ranging between 0.72 and 1.08mm. These values are in agreement with values obtained by Carbó [7].

The tests nr. 2 and 3, were carried out with wall angle  $\alpha$  of  $50^\circ$ , therefore, the test nr. 1 had already ruptured with  $\alpha$  of  $60^\circ$ . The tests nr. 5 and 6 were also respectively with wall angle of  $52^\circ$  and  $50^\circ$  by the rupture in the test nr. 4.

An unwanted effect of which the designer should be aware was observed. At high wall angles  $\alpha$  there is an orange peel effect. According to Jeswiet and Hagan [8] the size of the effect should be influenced by the incremental step size,  $d_x$  and  $d_z$ , and the wall angle  $\alpha$ . According to Hecker and Stout [9] this effect occurs on free surfaces with very large plastic strains and is the result of texture and microstructural effects.

From Tables 5 and 6 it can be verified that the roughness  $R_z$  reduces with the increase of the vertical depth  $d_z$  which allows to state that this parameter influences in the roughness. As it can be observed in Table 6 the smallest value of the roughness average was obtained in the test nr. 12, with tool radius  $R_T$  of 10mm.

In Table 6, it can be verified firstly that the TiAlN coating of the tool collaborated for the friction reduction and consequently for the roughness reduction.

In both Tables 5 and 6, the tendency is a higher roughness in the slipping region than in the rolling region. It is presumed that this behavior must be due to the geometrical conditions in the specimen/tool interface.

For comparison of  $R_z$  roughness values, reference values are needed. On Table 7 mean values of  $R_z$  roughness are shown for different metal forming processes. These values were converted to  $R_z$  by using the ASME B46.1-1995 standard.

**Table 7.** Metal forming process versus  $R_z$  parameter (Adopted from: ASME B46.1, 1995)

Metal forming process	Interval of average values of $R_z$ [ $\mu\text{m}$ ]
Hot rolling	180 to 90
Forging	90 to 23.04
Extruding	23.04 to 5.76
Cold rolling, drawing	23.04 to 5.76
Finishing rolling	2.88 to 1.44

Also in Tables 5 and 6 when compared to Table 7, it is verified that the roughness values of the formed areas are in the range that qualifies conventional forming processes as cold rolling and drawing ( $R_z = 23,04$  to  $5,76\mu\text{m}$ ).

Comparing Tables 5 and 6 with the Junk et al. [12] there is an agreement that with the increase of the tool radius  $R_T$  the roughness  $R_z$  is reduced. Hirt et al. [11] have studied how forming affects the surface roughness. As the tool diameter increases, the surface roughness decreases.

However there is no agreement in relation to the vertical depth  $d_z$ , while in Junk et al. [12] the increase of the vertical depth  $d_z$  leads to an increase of the roughness  $R_z$ . The tendency shown in Tables 5 and 6 is exactly the opposite, i.e., when  $d_z$  is increased  $R_z$  is reduced. Besides that it should be considered that there were differences in materials, thicknesses and different parameters in the technical literature presented in Junk et al. [12] and the present work.

Even using lubrication to reduce the friction during the tests, a removal of a small amount of material of the part was also noticed. This is proved by the change of the color of the lubrication grease from its initially yellow and to gray after the tests.

#### 4. Conclusions

In all the tests the total depth of part was 40mm however, the tool with an average depth of 6.8 mm turned from slipping to rolling. The roughness  $R_z$  measured in the slipping region is larger than in the rolling region. This fact is explained by the increase of friction, due to a larger contact area between the tool and the specimen.

It can be verified that for a coated as well as an uncoated tool the roughness  $R_z$  reduces with the increase of the vertical depth  $d_z$ , and it makes possible to state that  $d_z$  influences strongly the roughness. In the case of the coated tools with TiAlN lower values of  $R_z$  were obtained when compared with uncoated tools. The tendency is that smaller roughness  $R_z$  will be obtained with larger  $R_T$  tool radius.

The values of the roughness  $R_z$  reached in the experiments were close to the values obtained by conventional sheet metal forming processes.

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