

Analysis of the Incremental Forming of Titanium F67 Grade 2 Sheet

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Abstract. Analysis of a formed metal sheet shows the data of the incremental forming process. Variation in sheet deformation results from the process and shows how forming occurred. Another important result is the surface roughness of the sheet, which reports the parameters of the process, machine and tool used. Incremental forming of the titanium F67 grade 2 sheet was performed in the SPIF modality – forming without a point of support, in order to look at the thickness deformations. SPIF incremental forming is characterized as forming that does not use points of support, and therefore simple tooling is used in the process. The following resources were used to perform the practical tests: CAD/CAM software, CNC machining center, incremental die, incremental forming tool and a sheet press device. The results obtained were the finish of the formed surface, measured by the roughness parameter RZ, and the measurement of the true strains (ϕ) and thickness (s_1). Practical tests showed that the limit wall angle (ψ), for the CP Ti grade 2 sheet, 0.5 mm thick, is 47°.

Introduction

Incremental Sheet Forming – ISF is a modern, innovative forming process, which offers a significant saving and advantages due to flexible production and the environment, especially for small scale production and for customized production (made to order), of products derived from metal sheets.

The advantages involving flexibility of the incremental forming process were recently studied, and there is now a consensus about their applicability to produce small series, prototypes of sheet components and medical parts (customized implants).

The process is developed at ambient temperature and requires a CNC machining center, a spherical tip tool and a simple structure to support and fix the sheet in place [1].

Words and terms such as differentiation, cost reduction, minimization of the conception-production cycle, shortened life cycle (but also sustainable manufacturing) are present in current corporate strategies [2].

Incremental Forming ISF

In ISF, the sheet to be formed (blank) is firmly fixed in a mobile rectangular support, independent of the final shape of the sheet. This support can perform controlled movements in the vertical direction, ie., parallel to the Z axis of a CNC system. While the forming is taking place, fixation elements distributed around the sheet prevent it from movement, thus creating a plastic deformation in the sheet. Coupled to the spindle of a CNC device, a tool with a spherical head begins the ISF process by means of continuous movement on the surface of the plate and gradually, by negative vertical increments, carries out the forming, fig. 1 [3].

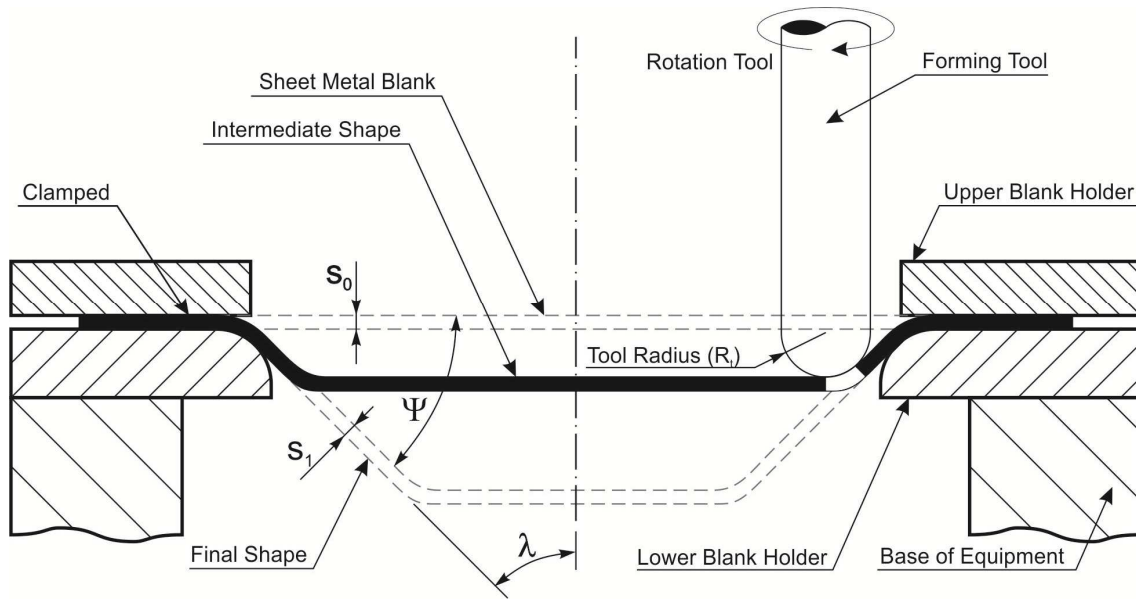


Fig. 1: Principle of the incremental forming process [3].

The deformation trajectory of the tool is based on NC technology which is generated from the normal CAM system [4]. The product of this process can be made directly from a CAD 3D model of finished product, without any kind of die. [5].

The great difference of the ISF is due to the fact that forming can be done with a very simplified die, or even without a die. The process appears to be very useful for small production volumes and for the speedy prototyping of sheet components. [6].

Materials and Methods

The traction test allowed generating the conventional stress-strain curves (τ versus ϵ) for each test specimen taken in relation to the rolling direction, 0°, 45° and 90°.

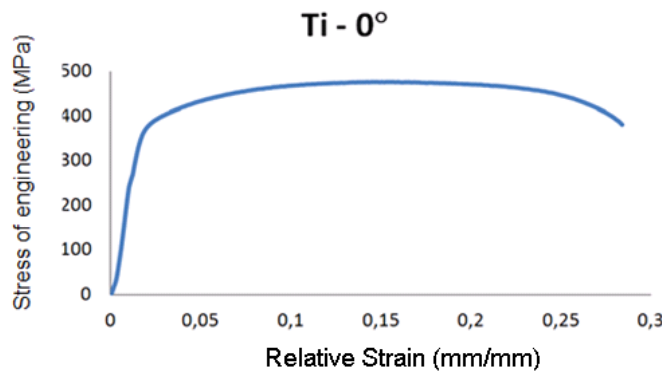


Fig. 2: Conventional curve τ (Engineering Stress - MPa) versus ϵ (Relative Strain – mm/mm) of CP-Ti Grade 2 for rolling angle 0°.

In the test performed at 0° the curve was obtained according to figure 2, with a maximum engineering stress (σ_{max}) of 490 MPa. This curve is close to the one found by [7] where the maximum stress (σ_{max}) was 520 MPa.

The flow curve (k_f versus ϕ) can be defined by a mathematical function:

$$k_f = C * \phi^n \tag{1}$$

where:

k_f = flow stress

C = material constant, when $\varphi=1$

φ = true strain

n = hardening index

For maximum stress instant (σ_{\max}), the true strain is equal to the hardening index:

$$\varphi = n \quad (2)$$

The true strain (φ) is calculated based in the relative strain value (ϵ), corresponding to the maximum engineering stress instant (σ_{\max}):

$$\begin{aligned} \varphi &= \ln(1 + \epsilon) \\ \varphi &= \ln(1 + 0,15) \\ \varphi &= 0,06 \end{aligned} \quad (3)$$

According to (2), $n=0,06$

Obtaining the flow stress:

$$\begin{aligned} k_f &= \sigma_{\max} (1 + \epsilon) \\ k_f &= 490(1 + 0,15) \\ k_f &= 563 \text{ MPa} \end{aligned} \quad (4)$$

Obtaining the C constant:

$$\begin{aligned} k_f &= C * \varphi^n \\ 563 &= C * 0,06^{0,06} \\ C &= 667 \text{ MPa} \end{aligned}$$

Obtaining the flow curve (k_f versus φ)

$$\begin{aligned} k_f &= C * \varphi^n \\ k_f &= 667 * \varphi^{0,06} \end{aligned}$$

And it is graphed represented in fig. 3:

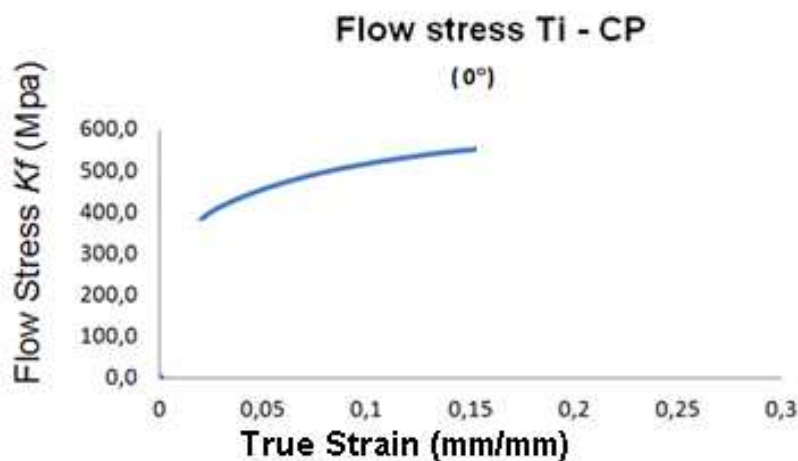


Fig. 3: Flow curve of CP-ti grade 2 tested.

The hardening index (n) is an important indicator of the hardenability characteristics of the materials. The higher the hardening index (n), the greater the hardening of the material. The hardening index (n) can be obtained when the flow stress (k_f) and strain (φ) data are transferred to a log scale diagram, fig. 4. Normally, a straight line is obtained, the value of “ n ” being given by the slope (α) of this straight line ($n = \text{tg } \alpha$) [8].

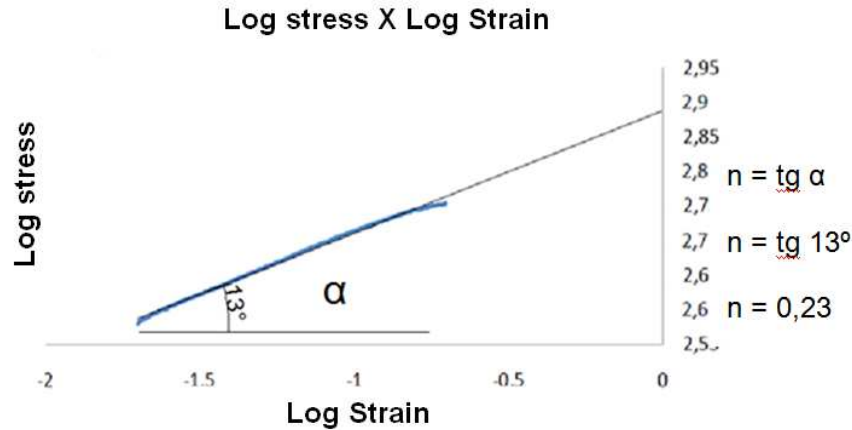


Fig. 4: Flow curve represented with logarithmic axes, test 1 at 0°.

Anisotropy Coefficient

When sheets are cold rolled, a phenomenon occurs in which grains are stretched in the direction of rolling, making the material anisotropic and varying its mechanical properties. The anisotropy coefficient can be determined by the traction test and represents the ratio between plastic strain in width and thickness directions, according to the direction of rolling [9].

Mean anisotropy (r_m) indicates the ability of a metal sheet to resist a diminishing thickness when submitted to traction forces, and it can be calculated using the Eq. 2 [8].

$$r_m = \frac{1}{4}(r_0 + 2r_{45} + r_{90}) \quad (2)$$

where:

r_0 = measurement of anisotropy of a specimen removed in the parallel direction to the rolling direction.

r_{45} = measurement of anisotropy of a specimen removed in the oblique direction to the rolling direction.

r_{90} = measurement of anisotropy of a specimen removed in the perpendicular direction to the rolling direction.

The values in the formulae were substituted finding a mean “ r ” of: 1,688

Machine Used for Incremental Forming

The machine used for the practical tests was a Romi Discovery 4022 Machining Center, with the following physical characteristics: size of the table - 840 x 360mm, stroke axis x - 590mm, stroke axis y - 406mm, stroke axis z - 508mm.

CAD/CAM software was used to program the machining center. The drawing of the part to be formed was used there, which is in a CAD model. After exporting the CAD drawing to the CAD/CAM, the tool path was generated to do the incremental forming. Then the program for the

CNC machine was generated in CAM software and sent through the RS 232 cable off-line (the program is sent at one time to the machine memory).

Fig. 5 shows all resources (software, CNC machine, forming tool and transmission cable) used in the tests.



Fig. 5: Machine and resources used in the practical tests.

Results and Discussion

The practical tests of incremental forming SPIF – forming without a point of support, are for the purpose of determining the limit wall angle for the Titanium F67 grade 2 sheet, 0.5 mm thick, checking the variation of thickness along the formed sheet. Four tests were performed according to table 1.

Table 1: Data on SPIF forming.

Tests	Forming strategy	Simulation time EdgeCAM (h)	Forming time CNC (h)	Vertical increment (mm)	Advance XY (mm/min)	Advance Z (mm/min)	Rotation (RPM)	Wall angle
1	Paralle	00:15:51	00:16:05	1	800	300	0	45°
2	Parallel	00:17:51	00:08:00	1	800	300	0	50°
3	Parallel	00:16:44	00:18:00	1	800	300	0	47°
4	Parallel	00:17:07	00:11:00	1	800	300	0	48°

All the test were performed in the format of the trunk piece of pyramid whose dimensions are 110mm x 110 mm with a forming depth of 50 mm.

The wall angle was changed according to each test performed and the input strategy of the tool adopted was 90° at Z and at X and Y the input was in a radius of 5mm, the same radius of the forming tool shown, because in the three first tests this input strategy showed better results for the titanium F67 grade 2 sheet.

The results of these four tests show the maximum wall angle before the sheet breaks, and also show the format of the breaks for the titanium F67 grade 2 sheet, according to figure 6.

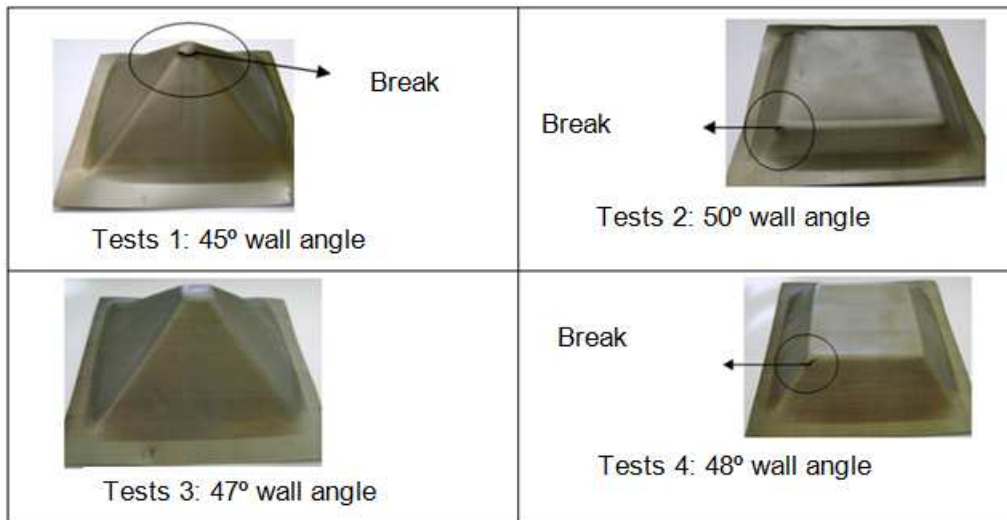


Fig. 6: Result of the four forming tests.

Once these four tests were performed it was possible to determine that the limit angle of wall slope for the titanium F67 grade 2 sheet, 0.5 mm thick, under the forming conditions described in table 1, is 47°, as shown in fig. 6. The first test shows a break at the end of forming process. This fact is due to tool diameter is greater than forming diameter and has no relation with the sheet formability.

Roughness

The value of roughness (parameter Rz) depends on the sheet and tool material, the type of lubrication and the values of the vertical pitch and advance. Taking into account the object of study in this work (cranial implants), the internal roughnesses (where there was contact with the tool) and the external roughnesses were measured, considering that the implant is positioned among the body tissues and the surface roughness influences both sides of the sheet.

To define the external roughness, the four flat faces of the incrementally formed sheet were measured, and the same measurements were performed in the internal part of the sheet.

The roughness of three sheets was measured, changing the angle of slope of the wall, 45°, 47° and 48°. The lubrication, vertical pitch, advance and tool were the same for all tests performed. Roughness was also measured in an unformed sheet. The results obtained are described in table 2.

Table 1: Roughness results.

Measured faces	45° (μm)		47° (μm)		48° (μm)		Flat sheet R_{m} (μm)
	Face ext.	Face int.	Face ext.	Face int.	Face ext.	Face int.	
1	4,10	6,60	5,45	5,50	5,35	4,10	2,00
2	4,60	5,30	5,20	6,10	5,25	4,80	
3	3,30	5,15	4,20	3,90	4,60	5,30	
4	4,60	4,40	3,10	5,30	4,30	5,90	
Mean roughness R_{m} (μm)	4.15	5,36	4.48	5.20	4,87	5.02	

Strains

The part formed at 47° was used to measure strains ϕ_1 and ϕ_2 , with measurements made from the flat portion of the sheet and parallel to the lamination direction. There greater forming depth was obtained without a break. Before forming, circles measuring $\text{Ø}2,5\text{mm}$ were engraved electrochemically on the sheet surface (fig. 7).

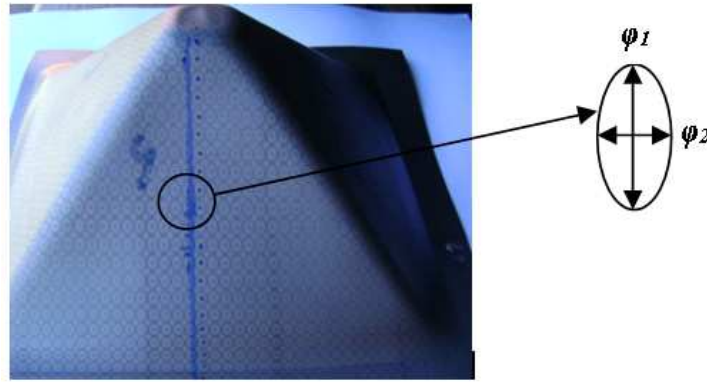


Fig. 7: Electrochemical engraving on the Titanium F67 grade 2 sheet.

Fig. 8 shows results of circle measurements:

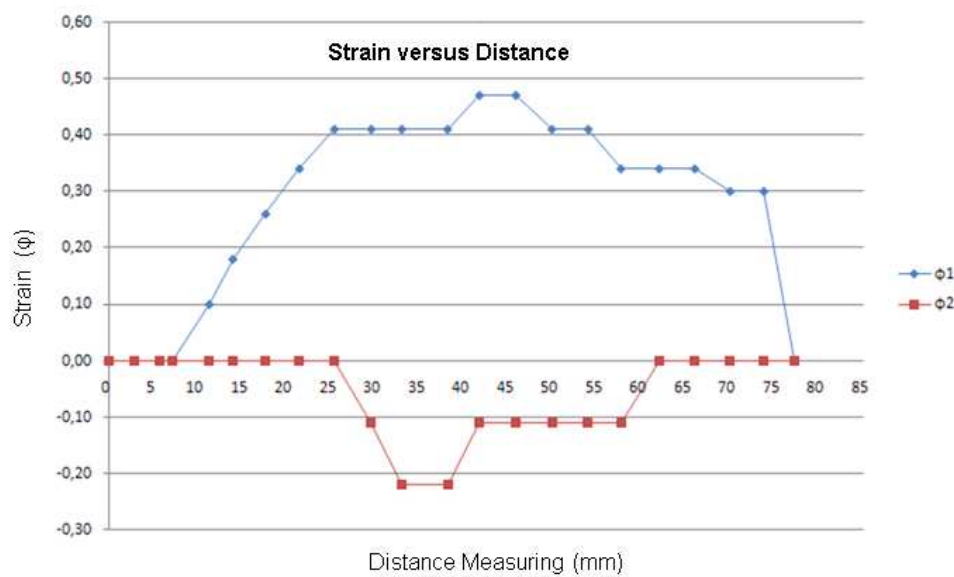


Fig. 8: Graph of strains ϕ_1 and ϕ_2 and Distance x Strain

The values of ϕ_1 and ϕ_2 were obtained using a flexible graduated ruler, printed on (translucent) polyester paper, with the relative and true strains for the circular grid 2.5 mm in diameter. Since the ruler is flexible, it follows the format of the test specimen and the transparency of the paper enables viewing the mesh lines.

Variation of Thickness

The variation of thickness (s_1) is very important information when analyzing sheet forming. After the end of the tests, experiment n^o3 (Wall angle 47°), was cut to measure the thicknesses after the ISF process, as shown in Fig. 9a. A Mitutoyo micrometer with 0.02 mm precision was used to perform the measurements.

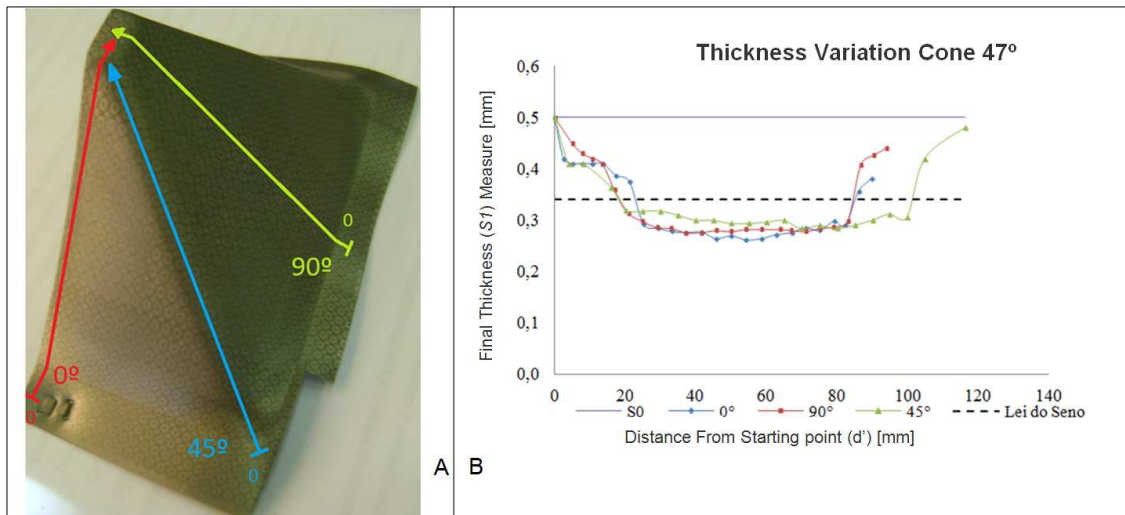


Fig. 9: A) Rolling direction; B) Graph showing variation of thicknesses.

In the graph of figure 9b, the variation of thickness is plotted according to the measurements performed. The graph shows line S_0 , which is the initial thickness of the sheet. It also shows the dotted line, the latter calculated using the sine law. The sine law is defined by equation $t_l = t_0 \cdot \sin(90-\alpha)$, where t_0 is initial thickness of sheet, t_l is the thickness of sheet measured at a given point of forming process and α is a slope angle of sheet in this same point. The other lines show the variation of sheet thickness in all three directions according to the direction of rolling

Conclusions

Practical experiments were used to demonstrate that it is possible to adapt machining resources (CAD/CAM softwares, equipment, tools and CNC machining centers) to manufacture parts by incremental forming.

In incremental forming of Titanium F67 grade 2 sheet, 0.5 thick, using geometries with wall angles greater than 47° , the sheet will fracture.

Measuring the roughness of the formed pieces, it was proved that on the part of the sheet where the tool comes into contact, roughness is $5.19\mu\text{m}$ greater (mean of the three parts), and on the opposite side roughness is $4.50\mu\text{m}$ less, as shown in table 3.

Analyzing the sheet thickness, it was seen that according to the sine law, the thickness is 0.35 mm. According to the measurements performed, the thickness is approximately 0.25 mm.

Acknowledgments

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