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Article

Hot incremental forming of biocomposites developed from flax fibre and a thermoplastic matrix

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Abstract: The use of biodegradable materials has a growing field of application due to environmental concerns, however, scientific research on incremental forming using biomaterials is scarce. Thus, this study focuses on the single point incremental forming (SPIF) process applied to a composite sheet that combines a biodegradable thermoplastic matrix (Solanyl) reinforced with natural fibres (flax). The influence of the process parameters on the final geometry is determined, evaluating the effect of the following factors: step depth, wall angle and temperature reached during the process. Additionally, a heated aqueous medium is incorporated which facilitates the formability of the composite sheets. This method is especially useful for materials that have poor formability at room temperature. The benefits of using controlled heat include the reduction of formation forces applied to the plate, improved accuracy due to the reduction of elastic recovery, and the manipulation of the samples remarkably close to the glass transition temperatures. Through this experimental study with the variables analysed, a maximum shaping depth of 310 mm is obtained. These results confirm that the single point shaping used with bioplastic materials is possible and has positive outcomes for incremental forming.

Keywords: Incremental Forming; Bio-composites; Hot Formability

1. Introduction

Material processing methods are being continuously modified due to technological development and the need to process materials faster. One method of processing materials, called incremental forming, is a technique that progressively deforms a sheet of material, using a tool operated by numerical control machines. The trajectory of the tool is generated with a Computer Aided Manufacturing (CAM) software from a three-dimensional model that reproduces the desired geometry. Initially, the single point incremental forming (SPIF) process was applied to metallic materials for small batch production. This technique is focused on creating prototypes of materials; however, the complex methods of conventional tooling for forming processes represent a limitation due to the high investment for the manufacturing process.

Currently, there are several practical applications of incremental forming in the automotive and aeronautical sector. In Japan, for example, incremental forming is used as an alternative process to add certain features to previously stamped vehicle panels [1]. The fields of application also include the medical sector, where several studies have been carried out for the implementation of this process in the manufacture of a femoral component of titanium-tantalum [2]. In addition, the design and manufacturing process has been analysed for using the same technique in a cranial prosthesis,[3] obtaining quite encouraging results. There are several cold sheet deformation studies across various fields that have shown limited formability of the materials used.

Recently, innovative proposals have been made to the incremental forming process, especially to improve the formability. One of the variations utilised is the application of heat, where incremental forming processes have been carried out by means of localised heating, achieving a high degree of deformation [4]. The initial tests, where higher temperatures were assigned to the areas to be shaped, showed the viability of this technique [5]. There are different techniques for the application of heat, one of which is to use fluid as a heating medium to form magnesium parts. In this case, reduced forces were required for formation at elevated temperatures and improved formability was achieved [6]. It has also been determined that incremental forming with hot air is a suitable method for parts production of prostheses and orthoses, which are implemented in medical applications[7].

Moreover, the incremental forming of polymers with materials such as POM, PE, PA, PVC, PC and its manufacture of complex components has been investigated with the application of heat[8]. Studies show that with polystyrene sheets, where hot air is applied using a nozzle to raise the temperature towards the forming area, the formability is improved[7]. Temperature plays a particularly important role in the behaviour of plastic materials due to their glass transition, fluidity, morphology, and degradation characteristics. In addition, studies of incremental forming in composite materials and their preliminary viability have been carried out using glass fibre reinforced polyamide [9], which is a widely used material in the automotive sector.

One of the other main variables of the incremental forming process is the spindle speed. However, the spindle can consume a large amount of energy. It has been said that the energy consumption will reduce if the tool does not rotate, and if the machining repetitions are decreased. [10] The spindle speed is important as it has the ability to reduce the maximum forming forces needed and increase the formability of the sheet [11].

This study analyses the effects of various parameters (forming depth and force) on the forming behaviour of a biodegradable thermoplastic matrix (manufacture name: Solanyl), which has been combined with short flax fibres, with a length of no more than 3 mm, and a flax reinforcement with a concentration of 10 percent. This material has been injected into 180x150x3mm plates, which are used in the incremental forming process, using a fluid heat source to improve its formation. Polymers reinforced with natural fibres can be used to make lightweight constructions due to their increased strength [12]. The challenge is to present the main forming parameters for prototype production. Therefore, the present study focuses mainly on the evaluation of the maximum forming depth under the influence of a heat source. For this reason, a hot environment is used through a fluid (water), at a temperature based on the obtained working range of the material. In this way, it is determined how the material behaves with the different process parameters, both constant and variables such as feed rate, tool diameter, material elasticity, temperature, spindle speed and step depth.

2. Materials and Methods

The experimental methodology is based on simultaneous sampling of force and temperature applied to the material to analyse the deformation in a sheet of thermoplastic material of natural origin, and in a sheet of composite material, during the incremental forming process. The force (N) that the tool exerts on the material and the temperature applied on the sheet is recorded. The conical geometry formed is shown in Figure 1; where D is the largest diameter of the cone, β is the angle of inclination, and D the total depth reached in the forming process. This is the geometry profile used for the tool trajectory, taking into account that the tool diameter will cause the formation of tracks in the corners of the model.

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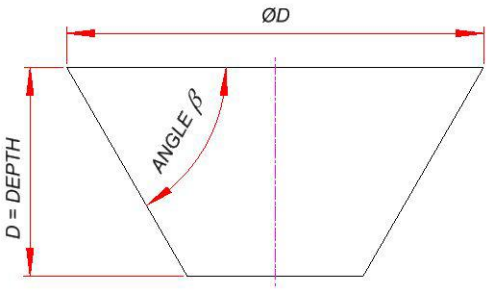

Figure 1. Geometry profile for the incremental forming process.

A spherical-tipped tool was selected, which creates a descending circular path to form the desired geometry. The forming process is carried out inside of an aqueous medium, using an electric heater to increase the water temperature; consequently, the testing sheets are completely submerged into the fluid. The temperature is controlled through an electronic circuit that maintains the selected temperature ranges. The presence of the aqueous heating medium guarantees the heat transfer by convection in a homogeneous way towards the composite sheet. The fluid temperature is monitored by a thermocouple, and the data is collected in real time through a remote-control system. Different parameters were selected that intervene in the incremental forming process, and through this work the impacts caused by these variables and their interactions in the forming of this type of material are studied.

To select the temperature parameters involved in the process, the analysis of Differential Scanning Calorimetry (DSC). Testing for the Solanyl thermoplastic matrix is performed, which is shown in Figure 6.

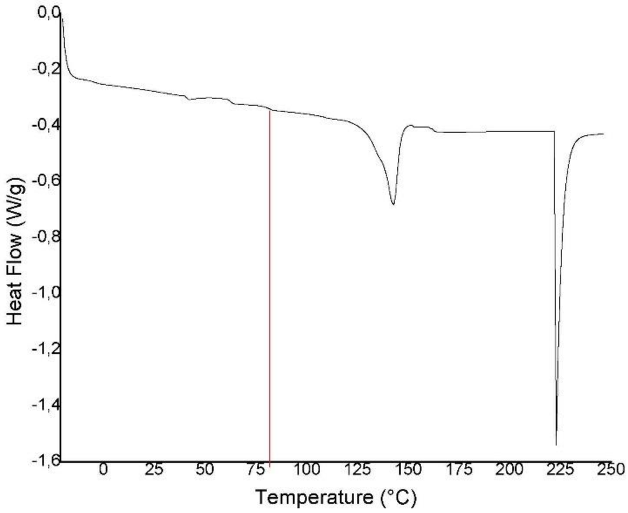

Figure 2. DSC Thermal test results for the sheet of thermoplastic starch matrix, trade name Solanyl.

With this DSC test, the glass transition, melting and degradation temperatures of the original material are obtained, for which it is observed that the working temperature is the exact value of 82°C, the base temperature that has been selected for this study.

2.1 Experimental equipment

In this study, plates injected with a starch-based thermoplastic (Solanyl C1201 from Rodenburg Biopolymers) and a composite material formed by this thermoplastic matrix with a load of 10% of its weight in flax fibre, were used. The manufacturing process of this compound alternates the extrusion and injection process [13]. The tooling and tooling design are made according to similar configurations shown in other studies of incremental shaping [3]. In this case, the main apparatus incorporates the fluid (water) at different controlled temperatures. Figure 2 shows the apparatus used in the study.

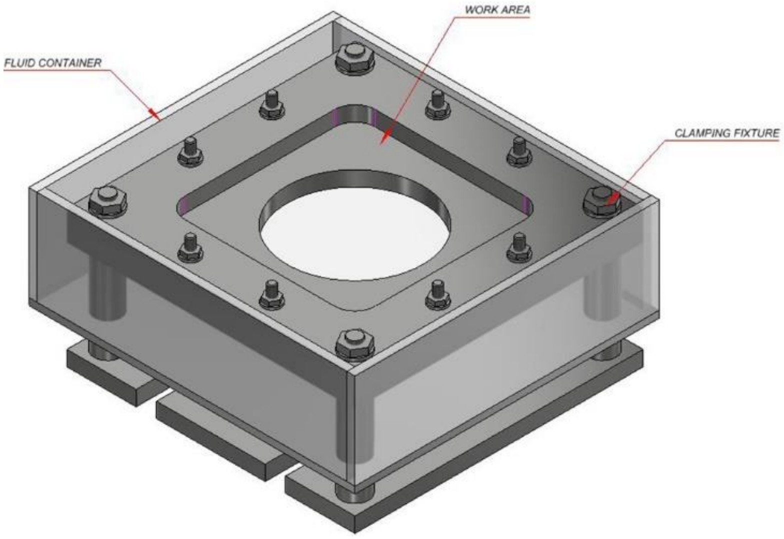

Figure 2. Fluid container used for the hot incremental forming process.

The tool is built using AISI 4340 alloy steel with a spherical tip and 6mm diameter shank, for the forming process; additionally, a SIEG CNC milling machine is used. The machining program is carried out in the Autodesk HSM software, where toolpaths are generated, with Z-Level strategy. The steps are made in the direction of the Z axis, the information is post processed and the machining program is generated in G code, for a FANUC controller. The characterization of the biodegradable materials used in this study, allowed us to understand the physical, chemical, and mechanical properties, in particular, the temperature parameters that are needed to process the material[14], where the elastic modulus is also selected as a reference in order to evaluate the results of the interaction of this parameter with the different variables. In Figure 3, below, the components for the incremental forming process in biodegradable plates are shown, for which a source of heat is applied within an aqueous environment.

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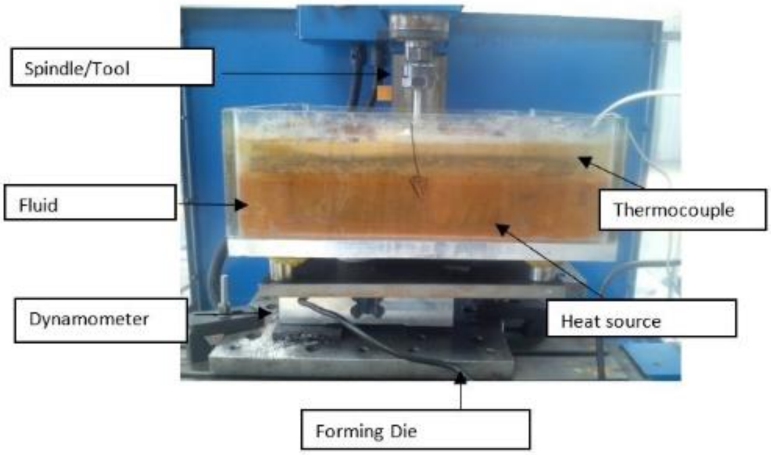

Figure 3. Experimental configuration for hot incremental forming process.

To obtain and transmit data, an electronic circuit consisting of sensors, actuators and a remote-control system that displays data in real time through a user-friendly, human-machine interface has been designed and implemented. For data collection, a K type thermocouple is placed inside the fluid area, which measures the temperature in a range of 0-800 °C, as well as a weight sensor with a capacity of 400Kg between the machine table and the forming matrix which weighs the whole system and this data is then transformed into a force value. The sensors are controlled by an electronic "Arduino Uno" card, and the programming is done in C language, using the Arduino APK environment. Temperature and weight data are obtained by direct connection to the Arduino card; this data is sent to a local server, a Raspberry Pi3 card programmed in Phyton. Figure 4 shows the data collection diagram.

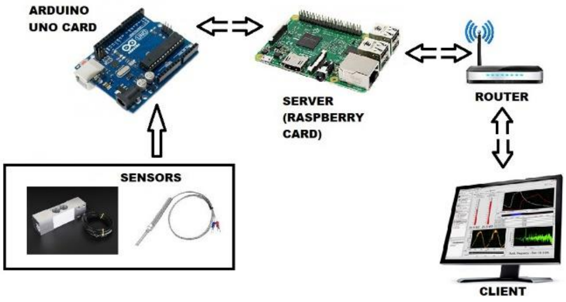

Figure 4. Data collection diagram.

The information collected is sent via ethernet or Wi-Fi to a remote client, in this case a PC, which receives the data through a program carried out in a virtual instrumentation software: Labview, where the value of temperature is received and shown in degrees Celsius and weight is transformed into Force and shown in Newtons. Figure 5, below, shows the LabView program used for data collection.

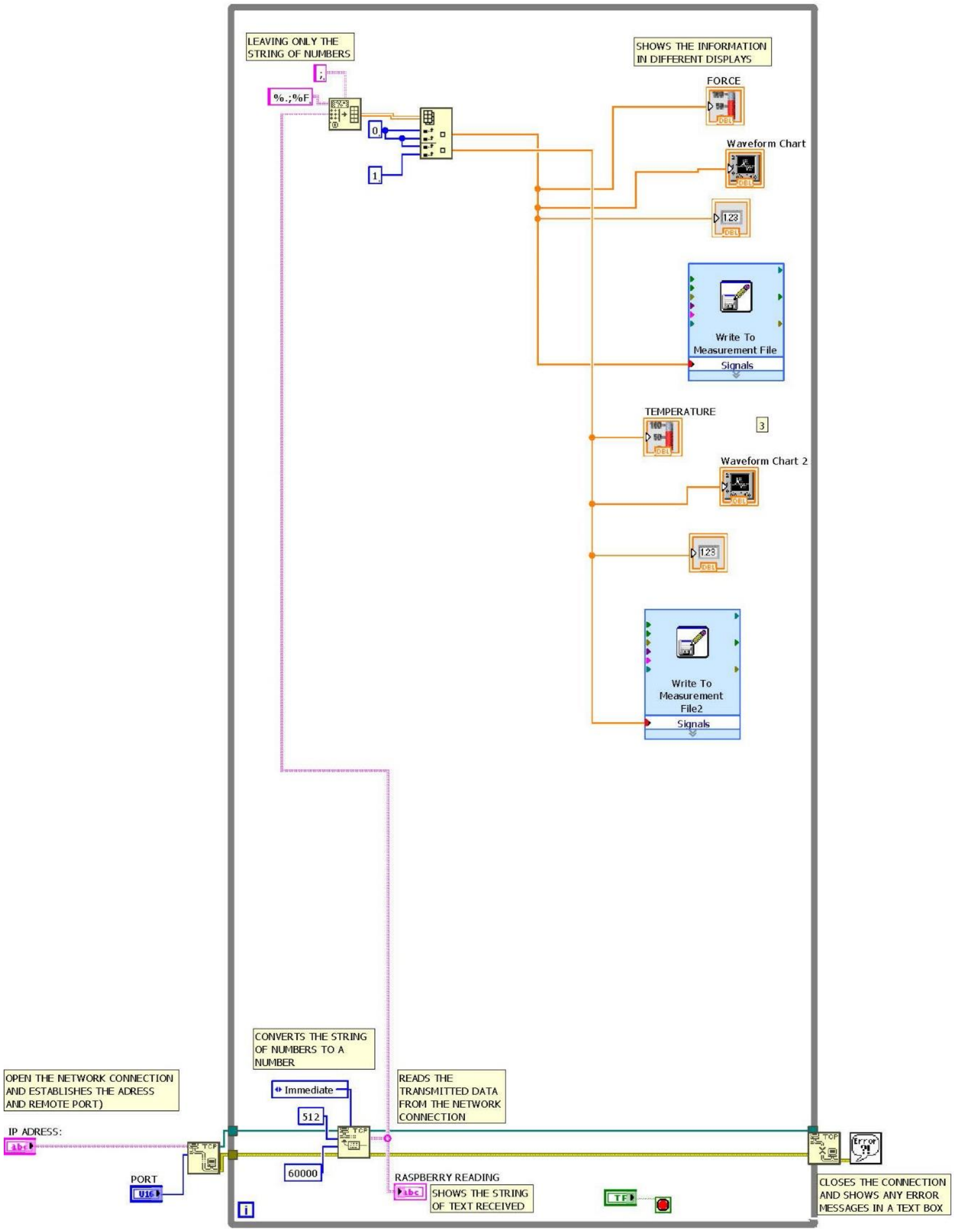

Figure 5. LabView program used for data collection.

3. Results

The experiments are carried out to determine the most influential factors on the total deformed depth with the incremental forming process. For this, the parameters of step depth, wall angle and temperature of the aqueous medium are manipulated. In addition, the behaviour of the force in the incremental forming process is studied. The results obtained from the depth are taken directly from the CNC machine controller, once the material breaks. The table below shows a summary of the variables and parameters involved in the process.

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Table 1. Parameters involved in the incremental forming process

Parameters	Constant
Tool diameter (mm)	6
Feed rate (mm/min)	500
Spindle speed(rpm)	0

Parameters	Variable	
Step depth (mm)	0.2	0.4
Wall angle (°)	45	60
Temperature(°C)	80	90
Elasticity (MPa)	2857(Solanyl)	3076(Composite)

To obtain precise results, a 2^4 factorial design with three replicas is made in Statgraphics. The results are evaluated by analysing the variance (ANOVA), which establishes the level of relationship between the variables. The response variable constitutes the depth reached after the incremental forming process. The factors for the analysis of variance are the following:

Table 2. Factors for analysis of variance.

Factors	Low	High	Units	Continuous
A: Temperature	80	90	°C	Yes
B: Wall angle	45	60	°	Yes
C: Step down	0.2	0.4	mm	Yes
D: Elastic modulus	2857	3076	MPa	Yes

Table 3. Tests performed for analysis of variance.

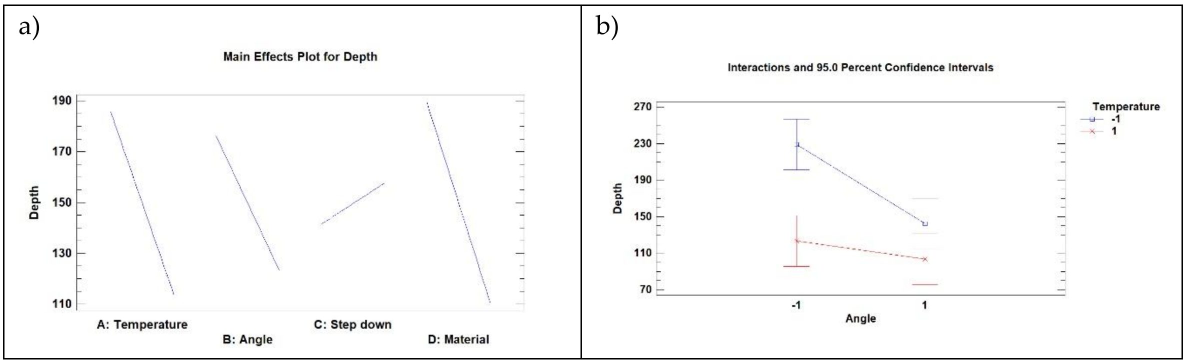
Run	A(°C)	B (°)	C(mm)	D(MPa)
1	-	-	-	+
2	-	+	-	-
3	-	-	-	-
4	+	+	+	-
5	+	-	+	-
6	+	+	-	+
7	+	-	-	-
8	+	+	+	+
9	+	-	+	+
10	-	+	+	+
11	+	-	-	-
12	-	-	+	-
13	-	+	+	-
14	+	+	-	+
15	-	-	+	+
16	-	+	-	+

The purpose of carrying out the tests, shown in Table 3, is to analyse the impact caused by each of these interactions with the response variable. This procedure performs a multifactor analysis of variance for depth. Several tests and graphs are constructed to determine which factors have a statistically significant effect on the response variable. This study also provides sufficient data to test for significant interactions between the factors. For statistical analysis, a significance level of 0.05 is used with a confidence interval of 95%.

Table 4. Data obtained through ANOVA analysis.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
A	62496.3	1	62496.3	195.41	0.0000
B	33814.1	1	33814.1	105.73	0.0000
C	3136.33	1	3136.33	9.81	0.0035
D	74576.3	1	74576.3	233.19	0.0000
AB	13266.8	1	13266.8	41.48	0.0000
AC	2296.33	1	2296.33	7.18	0.0112
AD	7400.33	1	7400.33	23.14	0.0000
BC	44.0833	1	44.0833	0.14	0.7127
BD	1344.08	1	1344.08	4.20	0.0479
CD	85.3333	2	85.3333	0.13	0.6087
T error	11193.5	35	319.814	195.41	
T (corr.)	209739	47		105.73	
R-squared	94.6631 per	1		9.81	

The ANOVA table shows the different factors such as the wall angle, temperature of the heating chamber, elastic modulus of the materials, step down, and its effect on the response variable (depth), as well as the interaction with the different factors. The P values prove the statistical significance of each of the factors, $P < 0.05$ values have a significant effect on the response variable (depth) with a 95% confidence level. Table 4 also shows the value for R^2 (94.66%), which indicates the variability related to the response variable (depth). The significant values are shown in the following graphs, Figure 7, which relate all the factors. The results indicate that the use of temperatures of 80°C(-1), angles of inclination of the geometry of 45°(-1) and the thermoplastic material in a natural state have statistical significance, demonstrating that for incremental forming processes the results are not as encouraging with the use of fragile materials.



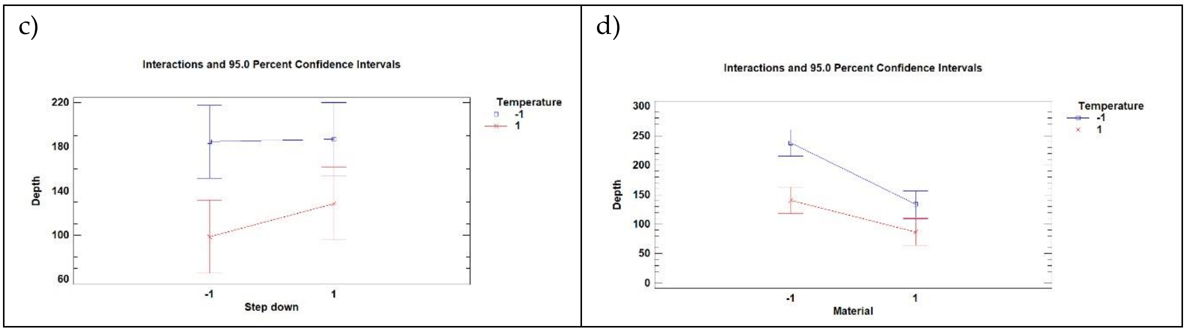


Figure 7. Variable interaction graphics.

It is evident that some factors are significant in the case of forming, as shown in the results. For instance, in Figure 7b, the temperature and wall angle are varied, and it can be seen how the forming depth changes significantly.

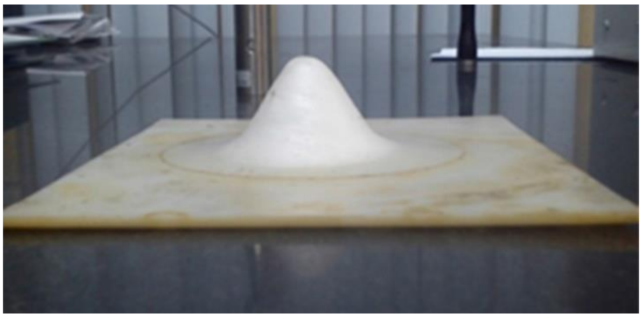


Figure 8. Incremental forming test with heat source in Solanyl thermoplastic material sheet.

Incremental forming test with heat source in Solanyl thermoplastic material sheet, achieving 310mm in Depth, as shown in Figure 8.

Where A: Wall angle, Fz=Step down, T=Temperature, L=Depth, F=Force. The parameters applied in this test are the following:

Table 5. Parameters for greater formability.

Material	A(°)	Fz(mm)	T(°C)	L(mm)	F(N)
Solanyl	45	0.4	80	310	35.26

On the contrary, the parameters that showed the lowest conformability with respect to depth are the following:

Table 6. Parameters for lower formability.

Material	A(°)	Fz(mm)	T(°C)	L(mm)	F(N)
Solanyl(10%)	60	0.2	90	46	172.74

The individual effects of the temperature, wall angle, step depth and elastic modulus factors of each material in the case of the maximum forming depth do not result in a significant effect on the response variable. However, the effect on the depth of each cited factor can be differentiated. Figure 9 shows the contribution of each of the factors with the predominance of temperature for shaping the material as proposed in this work.

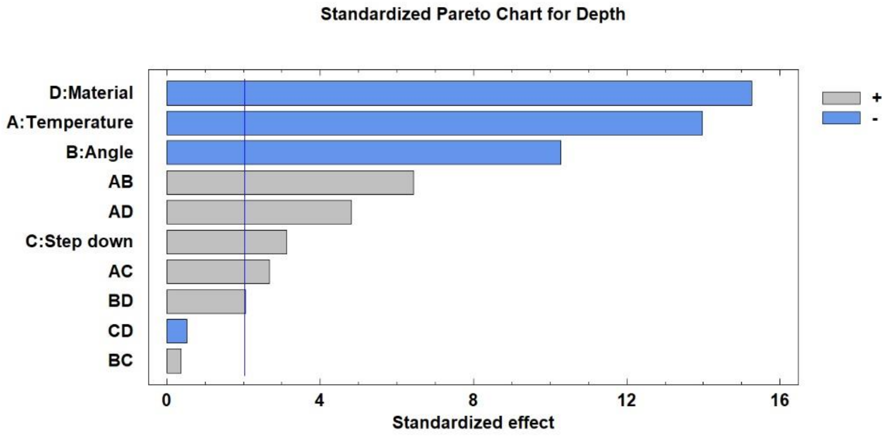


Figure 9. Pareto diagram for contributing factors in the case of depth.

High strength sheet metal materials can barely be formed by conventional single-point incremental forming process [15]. The formed pieces produced using this process, exhibit diminished geometric precision and low forming values; thus, the application of temperature is convenient. In the same way in polymer forming it has been shown that the increase in temperature will improve ductility [16], which contributes to the forming of thermoplastic materials. In this study, a homogeneous temperature was applied on the biodegradable material plate, obtaining a uniform distribution of stress and heat in the process. Unlike cold plastic deformation [9], with controlled temperatures, bio-polymeric plates can result in large deformations when analysing the displaced depth.

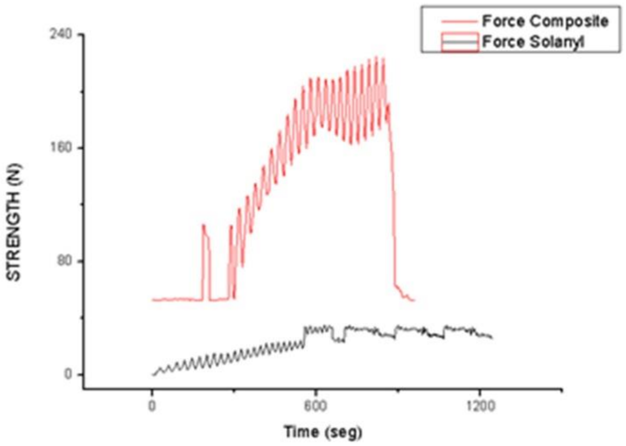


Figure 10. Relation of forces for parameters of the maximum and minimum formability.

4. Discussion

The results show that the thermoplastic matrix in its original state has the greatest conformation, because the material reaches a greater depth. The results presented are summarized to provide an overview of the interaction between the different process parameters and their variables. This information presents an initial model for the conformation of composite materials with thermoplastic matrices. The results highlight factors that contribute to the conformation of these types of materials and their efficacy are identified, as in the case of the forming force. Shown in Figure 10, the forces obtained in the incremental forming process using the parameters that reach maximum forming depth, and the factors with minimum forming depth are shown in Tables 5 and 6 respectively. It is remarkable that a small increase in the temperature value of the sheet can cause some modifications in the molecular structure of the polymer, in the case of the thermoplastic matrix (Solanyl), the temperature of the glass transition shown in the DSC tests is 82°C, when this value increases, the results of the forming decrease. This study shows that the improvement of the conformation in thermoplastic sheets depends on the variation of certain parameters such as temperature, the angle of inclination of the geometry, and the elastic modulus of the material to be shaped.

5. Conclusions

This article gathers the experimental results of the single point forming process in sheets of composite material (Solanyl-flax). According to the multifactor analysis of the variance, it is observed that the temperature of the aqueous medium has a significant effect on the forming process of sheets of the composite material with greater depths achieved at a temperature of 80° C. Additionally, the elastic modulus directly influences the deformation of the composite material, and therefore it is necessary to use less fragile and more ductile composite materials. The main factors that influence the forming of biodegradable composite materials are established, for which it would be important to develop a composite material with better forming properties, since this technique could achieve good results in the manufacture of products with these materials. The methodology used is validated due to the small differences that exist between the different results, showing the significance of each of the factors analysed with the depth reached during the conformation process.

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