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Optimization of the heating parameters of a robotized hot incremental forming of high impact polystyrene

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Abstract. Single point incremental forming (SPIF) is a modern rapid manufacturing technology able to manufacturing complex sheet parts in small quantities. In comparison to conventional deep-drawing process, complex tools can be dispensed in order to reduce tool costs and the time required to achieve the first finished part. This new technology consists of locally and iteratively deforming plastically the sheet material by a punch that is generally hemispherical and of small dimensions, whose trajectory is programmed on a numerically controlled machine or a robot arm. The parts formed are mainly made from metallic materials (steel, aluminum, titanium or copper alloys). Very few studies focus on the incremental forming of thermoplastic parts. Because of the poor formability of thermoplastic parts and the large spring-back at room temperature, the use of heating systems of the work-piece during the forming process is required. In this work, a novel incremental sheet forming assisted by heat transfer was developed to improve the formability of thermoplastic sheet. By means of a series of experimental forming of High Impact Polystyrene pyramid frustum with constant wall angle at different heat temperatures, geometric accuracy was recorded and analyzed. This study aims to evaluate the behavior of polymer material in the hot incremental sheet forming with different pre-heating system using the finite element method.

Introduction

Incremental sheet forming is a promising process, well-suited for small batch production or prototyping, with many advantages compared to traditional forming processes such as low cost and higher flexibility. Most studies concern metallic parts or composite parts manufactured using classical three-axis CNC milling machines [1]. Nevertheless, these machines have a limited workspace and can be used to form only simple shape parts. Larger dimension parts and more complex shapes can be produced by industrial robots. Regarding the materials, the use of composite materials is now increasing in many areas (aeronautic, automotive and medical) due to their mechanical properties and environment concerns [2]. There is little to no literature on the incremental forming of high impact polystyrene, although this polymer is widely used in industry. However, this polymeric material having a poor formability at room temperature, a heating system must be considered. The aim of this research is to study experimentally and numerically the robotized hot incremental forming of polymer cone parts. With the help of design of experiment (DOE), the effects of heating system (tool or sheet or combination) were studied to optimize the process.

Experimental process

The High Impact Polystyrene part considered in this study is a truncated cone with a wall angle of $\alpha = 30°$, a depth of h = 35mm and a base radius of R = 81 mm. The High Impact Polystyrene sheet has a size of (200 x 200 mm^2) and initial thickness of 0.8 mm. Three heating systems are considered:

1. Local heating approach where only the tool is heated by electrical resistor;
2. Global heating approach based on the use of hot air blower to heat the sheet;
3. Combination approach of the two heating methods.

The effects of the heating system (local, global, mixed) and the heating temperature (80, 100, 120°C) on the geometric accuracy and thickness were analyzed using the experimental robotized hot incremental forming set up (see Fig. 1). The forming tool is a copper cylinder with a semi-hemispheric end and a radius of 5 mm. It can be electrically heated to the performed temperature. For the global heating approach, the polymer material sheet is globally heated by hot air convection to a desired temperature with respect the thermal properties of the polymer sheet.

The clamping system consists of two wooden planks with circular shaped holes of 190 mm diameter pinching evenly the material with enough clearance on each side to allow the deformation of the sheet part. It needs to be closed enough to the tool path to minimize the spring back effect. The aim was to study the influence of the heating systems on the accuracy of the formed part (especially to minimize the shape errors occurring during and after the incremental forming process).

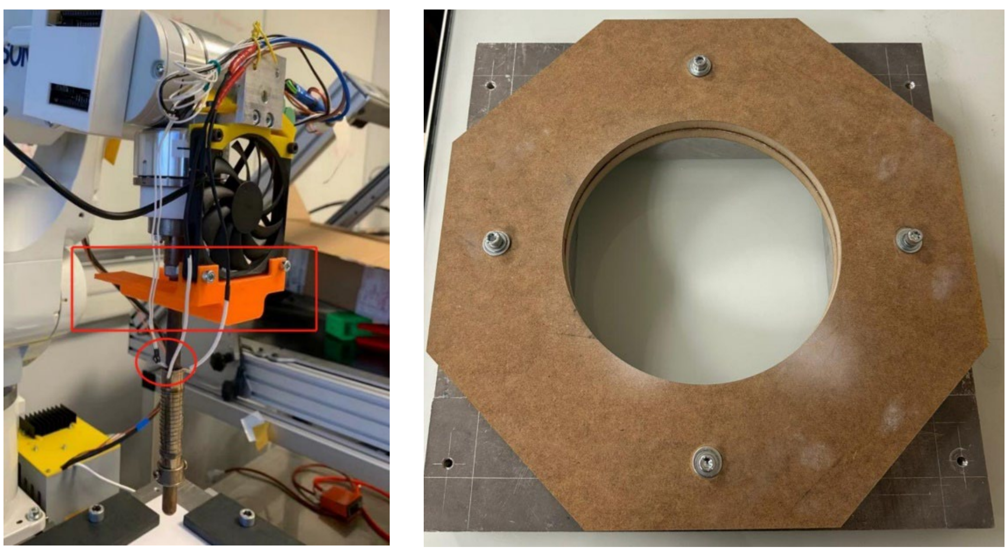

Fig. 1 – Experimental tool and clamping system for the hot robotized incremental forming

The toolpath used during the incremental forming process is generally realized by computer-aided manufacturing (CAM) software. The tool trajectory has a significant effect on different aspects like dimensional accuracy, thickness distribution, processing time, and surface roughness. It is also necessary to develop specific toolpath generation to improve its efficiency. In this work, a procedure based on the mesh of the part has been developed to generate the incremental toolpath and to take into account the radius of the hemispherical tool (see Fig 2).

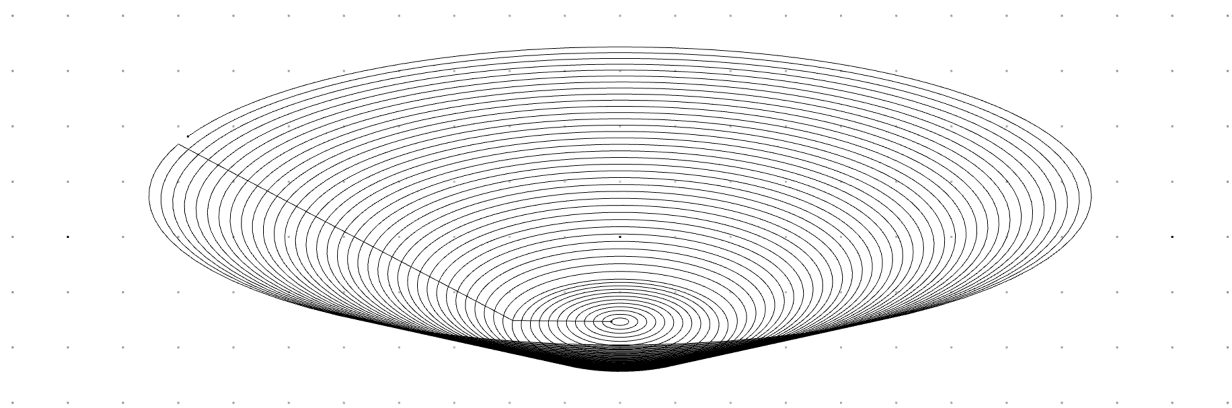

Fig. 2 – Generated toolpath for the cone part manufacturing and the simulation

In order to characterize the melting temperature T_m, glass transition temperature T_g, specific heat capacity and other related kinetic properties of High Impact Polystyrene, a Differential scanning calorimetry (DSC) is used. By analyzing the obtained curve (Fig. 3), there are two crystals (or structures molecular) inside the material, one of which it begins to melt at about T_m = 125°C and the other at about 148°C. Therefore, the temperature of the used material should not exceed 125°C throughout the forming process. In order to minimize the friction between the thin sheet and the rigid heated tool, the forming speed was set at 10 mm/s and the depth increment of Δz = 1 mm was used.

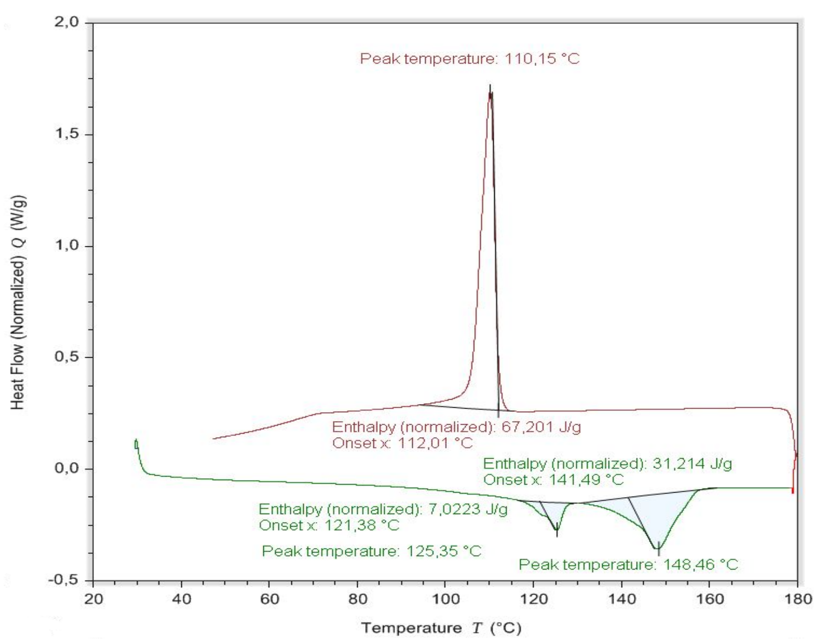

Fig. 3 – DSC test on High Impact Polystyrene material.

Effect of heating system

The effect of the heating system (Local, Global and Mix) and the temperature value (80, 100, 120°C) on the final geometry was studied (see Table 1). In order to study the contribution of each factor and optimize the forming parameters, DOE method design was used to conduct the experiments. Fig. 4 presents the final forming part obtained with local heating at 120°C (test 3). Parts realized with the global heating system presented cracks and the forming process couldn't be performed completely. Fig. 5 presents the final obtained profile of all the experimental tests except those carried out with the global heating system (tests 4, 5 and 6). Experimental results show that the parameter having the greatest effect on the final profile is the heating system followed by the local temperature value. The curves show that a reduction in global temperature allows to reduce the spring back and obtain a result closer to the desired profile angle. Test 3 is the best performing heat parameter with low spring-back effect and overall good deformation. However, the combination of the two heating systems did not bring interesting results (tests 7, 8 and 9).

Table 1– Experimental plan of temperature.

Experiment Number	Test	Input Temperature (°C)
1	Local	$T_{tool} = 100$
2	Local	$T_{tool} = 110$
3	Local	$T_{tool} = 120$
4	Global	$T_{sheet} = 100$
5	Global	$T_{sheet} = 110$
6	Global	$T_{sheet} = 120$
7	Mix	$T_{tool} = 80 – T_{sheet} = 60$
8	Mix	$T_{tool} = 100 – T_{sheet} = 60$
9	Mix	$T_{tool} = 110 – T_{sheet} = 60$

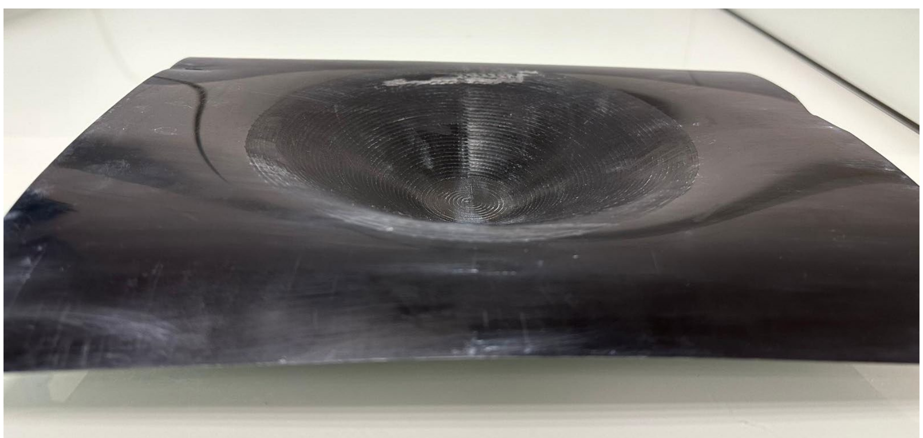

Fig. 4 – Final part for test 3 (local heating, 120°C)

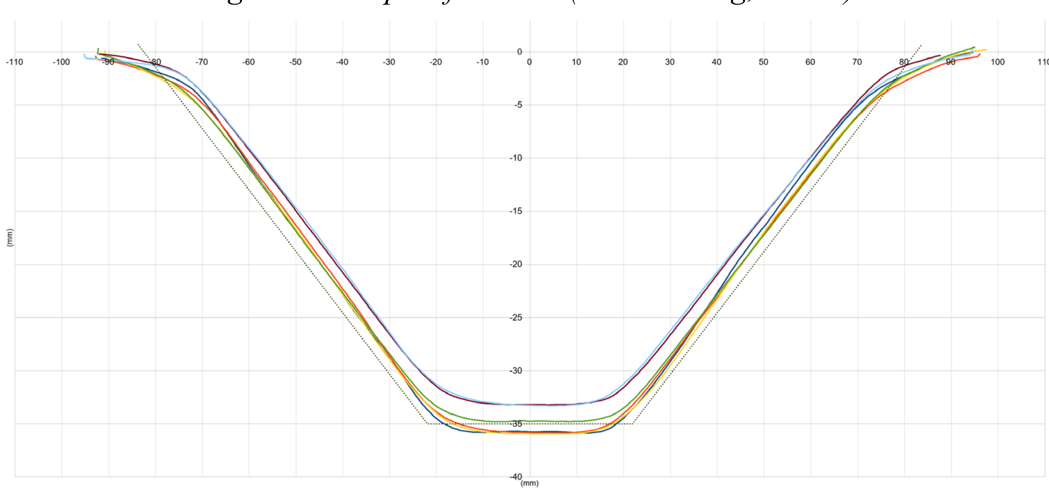

Fig. 5 – Comparison between experimental and theoretical profile for the different cases

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It can be observed that an error exists between the experimental and theoretical profile that neither the heating method nor the heating parameter can correct showing the necessity of optimizing the tool path.

Finite element simulation

The FEM simulation of single point incremental sheet forming of polymer sheet was performed with ABAQUS code using dynamic-temperature explicit solver. In this simulation multi-linear isotropic elasticity and bilinear isotropic hardening strain material model is used to model High Impact Polystyrene sheet blank. The blank is modeled by coupled displacement-temperature 8-node linear hexahedra finite element with Reduced Integration. Elastic and plastic material properties of the High Impact Polystyrene at each temperature were obtained by uniaxial tensile test given in Fig. 6. Other mechanical and thermal properties were obtained using literature review [3].

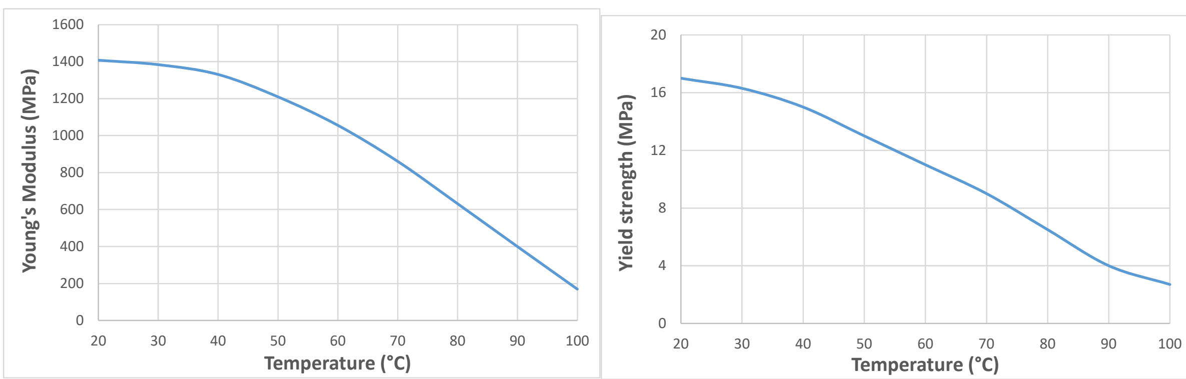

Fig. 6 – Uniaxial tensile properties of high impact polystyrene at different temperatures

The experimental tool path was used for the numerical simulation. Fig. 7 presents the final numerical profile obtained with a local heating of 100°C (with the same experimental condition as the test 1). This profile obtained numerically (Fig. 8) seems closed of the experimental and theoretical profiles. However, since the damage was not taken into account in the numerical model, the numerical simulation of the process with a global heating system was not able to predict the appearance of cracks and this result cannot be exploited at present. Further improvements of the numerical simulation are necessary to model thermal and mechanical effects as shearing due to the contact.

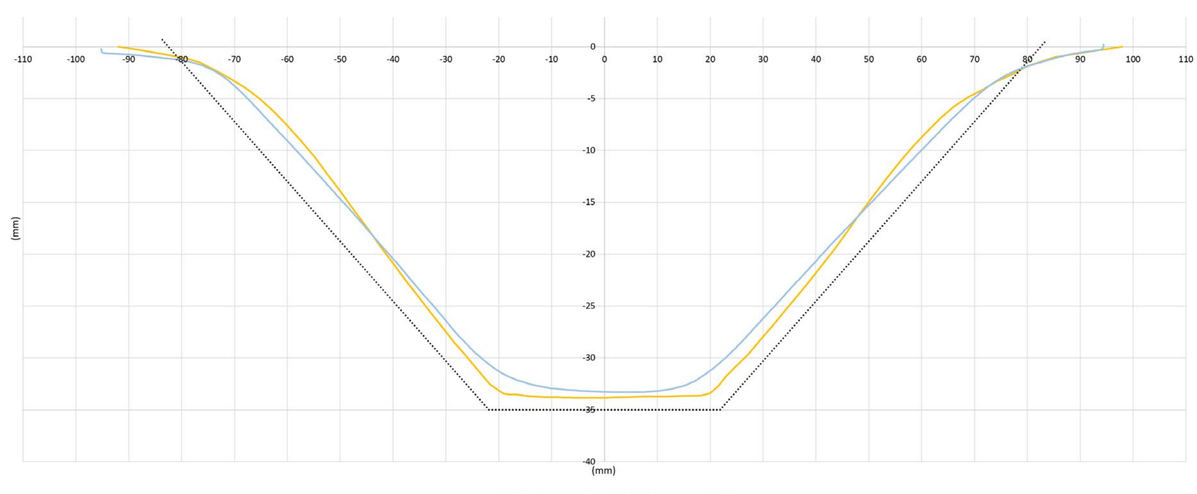

Fig. 7 – Predicted profile compared with the desired shape

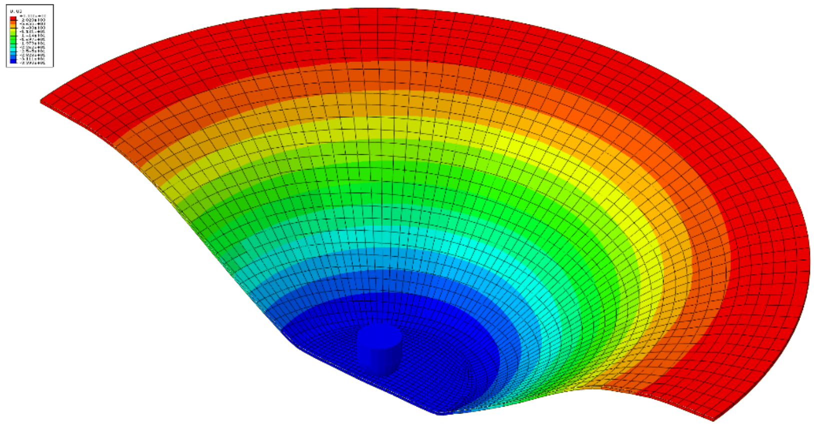

Fig. 8 – Final predicted forming part obtained with local heating at 100°C

Conclusion

The results of the experiment and numerical study of the warm robotized incremental forming of high impact polystyrene show that the heating system is a parameter having important impact on the final geometry. However, the desired final shape could not be achieved. The experimental results showed that an optimization of the tool path is necessary. Further research is also needed to improve the numerical model and obtain a more predictive tool.

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