

# Investigation of the Single Point Heating Tool for the Robotised Incremental Polymer Sheet Forming Process

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## 1. Introduction

Incremental sheet forming (ISF) technology is a suitable and flexible solution to create complex 3D geometries of the sheet. A sheet is gradually formed into the desired shape with a forming tool usually attached to a CNC machine or robot. Small deformations are made on the blank each time the position of the tool incrementally downgrades. This process is valid with metal as well as with polymer sheets. Incremental sheet forming has a vast potential in rapid prototyping and small-batch manufacturing [1]. CNC or manipulator can be easily reprogrammable to execute a different program for different geometry of the blank. It is essential to mention that this process does not require any stamps and dies, which makes ISF economically attractive as a solution. As the demand for custom orders and prototyping requirements increase, incremental sheet forming becomes a relevant technology that expands the possibilities of traditional sheet forming technologies and applications. As technologies advance, the automotive industry requires more complex and high-precision geometries of sheet products [2]. Incremental sheet forming technology can manufacture lightweight asymmetric products that are ideal for automotive applications. Reducing the mass of the components leads to a decrease in energy consumption and CO<sub>2</sub> reduction [3]. ISF has the potential to reduce costs, manufacturing time and increase the flexibility of geometries in aircraft and aerospace industries [4]. Biomedicine is another industry where incremental sheet forming has tremendous potential. Implants and prostheses require high geometrical accuracy and are mostly customized for small batch production in the biomedicine field [5]. The main application of ISF technology can be components such as ankle prostheses, cranial implants, knee prostheses, and various biomedical devices [6].

However, the inaccuracy of geometry and occurring process errors in previously discussed industries prove the novelty of the technology. Previous investigations [1] confirm that ISF is still hardly employed in manufacturing sectors due to the lack of understanding of the process and knowledge on improving precision and reducing surface roughness. Most researches focus on parameters such as spindle feed rate, tool diameter, and step size to find a dependency between the values and output of the forming [1]

without considering heating as a friction-reducing and formability increase solution. The automotive industry requires various wall angles, thickness of walls, accuracy, and forming limits. Research with different materials, sheet thickness, and forms was examined to achieve valid parameters [2], again, without considering tool influence and local heating to reveal stresses. Recent works show the formation of polymer aircraft parts where the tool's rotation speed and toolpath were investigated. Results [4] revealed that surface quality and deviation of some samples were in the allowable range with specific parameters – however, a lack of ISF research limits applications in the aircraft industry. The novelty of incremental sheet forming and tool heating can be observed in research on process applicability for biomedicine. Published novel research [5] focuses on implant forming while investigating friction, forces, and toolpath dependence on geometry accuracy.

A tool and heating process play a tremendous role in the incremental sheet polymer forming. The quality and mechanical properties of the part depend on choosing the right tool and the critical temperature of processing. The most crucial parameter in heating polymer processing is Glass transition temperature. Applying this amount of heat increases mechanical properties and quality of part in post-process. Under the influence of this temperature, plastic changes its structure from solid to liquid or rubber.  $T_g$  temperature of every polymer depends on density, porosity, moisture, degree of crystallinity, the orientation of grades, size of molecules, and defects of the material [7]. Various methods are used to heat the polymer sheet and thus to reach the glass transition temperature: thermoplastic composite induction welding [8], radiation heating [9], infrared light and laser [10], etc. However, usage of most of them are complex to be used in incremental sheet forming process.

An experimental study, presented in [11] was conducted to investigate the influence of process factors on the performance of composite materials. The thermoplastic matrix reinforced by 15 % fiberglass was processed by adding an external heating source on the three-axis CNC milling machine. Paper [12] presents two procedures for predicting axial force in Single Point Incremental Sheet Forming (SPIF) of polymer sheets. Particularly, a numerical model based on the Finite Element Model, which considers a hyper

elastic-plastic constitutive equation, and a simple semi-analytical model that extends the known specific energy concept used in machining. In work [13] SPIF experimental tests using two different polymers biocompatible have been carried out following a Box-Behnken design for four factors and a survival analysis. The maximum forming force, surface roughness and maximum vertical displacement response achieved in the experiments has been statistically analysed and empirical models for each material have been obtained. In [14], a new method for forming glass-fibre reinforced polymers has been proposed. This method uses a single-point forming that assists in heating hot air and forms a thermoplastic matrix polyamide. A glass-fibre-reinforced polymer was placed between two layers of Teflon and of metal sheets. Teflon has been adapted to improve the formation behaviour of glass-fibre reinforced polymers. Sheet metal was used to protect glass-fibre reinforced polymers from friction by the forming tool and to reduce the flow of dissolved matrix polymer from the woven fibre. In most of the researches parameters of heating, such as heating time or temperature, or mechanical properties dependency from heating temperature are not investigated or presented. Moreover, heating process are quite complicated to be used or has low power efficiency.

In this research a novel single point heated toll with control system for incremental sheet forming process is proposed and investigated. Experimental research results reveals main heating parameters necessary for ISF and mechanical properties dependency from heating.

## 2. Single point incremental forming self-heating tool design

The concept of a single point incremental forming self-heating system is shown in Fig. 1 and wiring scheme of a heating control system is shown in Fig. 2.

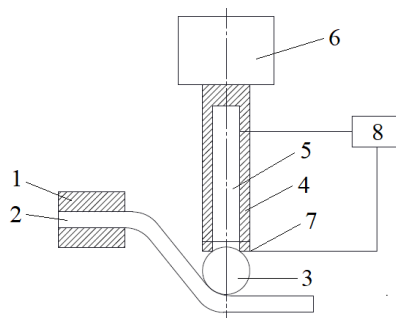


Fig. 1 The concept of SPIF self-heating tool: 1 – clamping, 2 – polymer sheet, 3 – forming ball, 4 – tool, 5 – heating element, 6 – 6-axis robot hand, 7 – thermal sensor, 8 – heat control system

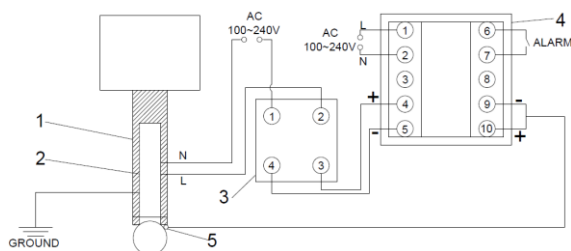


Fig. 2 Wiring scheme of a heating control system. 1 – Forming tool, 2 – 60W soldering-iron heat element, 3 – Solid-state relay (SSR), 4 – PID temperature controller, 5 – thermocouple

Heating element 2 attached to the tool 1 must be wired through a solid-state relay (SSR) 3. This electric switch device turns on and off the heating element when an external AC or DC voltage is applied. When thermocouple 5 senses the required temperature, it sends information to the PID temperature controller 4. PID temperature controller connected through SSR turns off the heating element or changes voltage depending on the situation. To indicate temperature drops or rises, an alarm can be used. This solution is presented for industry exploitation.

## 3. Heating process investigation

To use a 60 W soldering-iron heat element in the process, it is essential to know heating element and PVC polymer heating possibilities. An investigation of the heating element 's capabilities was held at room temperature and repeated three times with each temperature to increase the accuracy of the outcome. The scheme of the held experiment is shown in Fig. 3, a and the set-up view in Fig. 3, b.

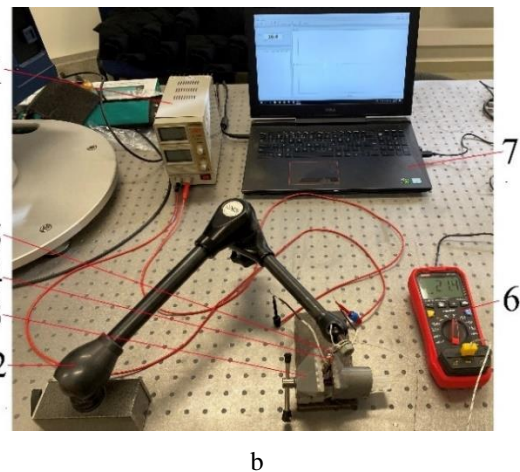
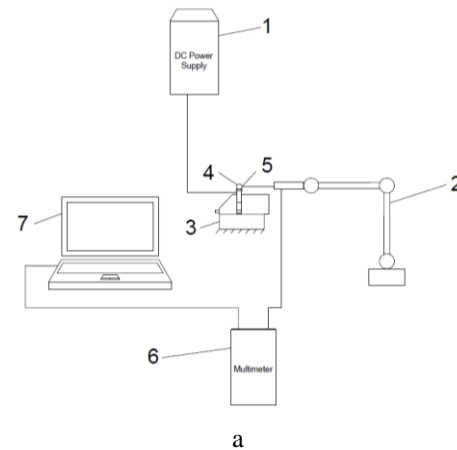


Fig. 3 The experimental calibration: a – scheme, b – set-up view. Here: 1 – DC Power Supply HY1803D (0-18V, 3A), 2 – Stand, 3 – Clamp, 4 – Heater with magnet and ball, 5 – Thermocouple, 6 – Digital Multimeter UNI-T UT161D, 7 – PC

The research was carried out by changing the current of the DC Power Supply HY1803D 1 and measuring the temperature on the forming ball 's 4 furthest point from the heating source. The ball was attached to the heater with a magnet. Since the heater has steel parts, magnetism ensures the rigidity of the construction while investigating. The temperature of the forming sphere 4 was indicated with

a thermocouple 5 stationary attached to stand 2. A heater is fixed in the clamp 3. Thermocouple 5 sends information to the multimeter UNI-T UT161D 6 and the PC 7. To prevent heat losses and inaccurate results due to the conduction, textolite STAF-1 plates were used in the contact regions of the heating element and clamps. Experiment was held with Ø12,5 mm forming ball and four different powers: 0,3 W, 0,675 W, 1,2 W and 2,7 W. The results of the investigation are shown in Fig. 4.

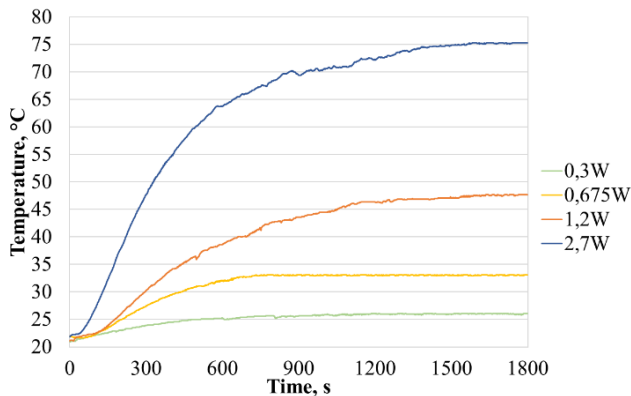


Fig. 4 Temperature values of Ø12,5 mm sphere under different power versus time

Results of the experiment revealed that different temperatures are reached with different supplied power: at 0,3 W heater reaches a peak of 26,1°C, at 0,675 W – 33,1°C, at 1,2 W – 47,7°C, and 2,7 W – 75,3°C. Also, it was noticed that the forming ball's temperature settles down over different time frames: 26,1°C in ~600 s (10 min), 33,1°C in ~900 (15 min), 47,7°C in ~1500 s (25 min), and 75,3°C in ~1800 s, (30 min).

To evaluate thermal losses in the polymer material, ensure the heater's feasibility and approach forming temperature of the sphere another experimental research was carried out. One of the aims of this approach was to find polymer sheet temperature in contact with different ball's temperature. Another one – to find forming sphere's temperature which reaches  $T_g$  temperature in polymer sheet. The experiment was held at room temperature and repeated three times with every temperature to increase the accuracy of the results. The scheme of the experiment is shown in Fig. 5, a, and the set-up view in Fig. 5, b.

During this experiment, a 3 mm thickness polymer sheet 6 with drilled 0,5 mm, 1 mm, 1,5 mm, 2 mm, and 2.5 mm depth and 2 mm diameter holes were heated. The sample was attached to stand 4 to reduce displacements and loss of contact. As in the previous investigation, a forming ball with the heater 8 was clamped with textolite STAF-1 plates. Two multimeters were used in this experiment: digital multimeter UNI-T UT161D 9, which indicated the temperature of the polymer sample on the other side of the heating surface, and another digital multimeter CHY 24CS LCR 3 was used to track the temperature of the forming ball. Thermocouple of the first multimeter was attached to stand 2 and placed in drilled holes. Heating was generated with DC Power Supply HY1803D 1, and data from digital multimeter UNI-T UT161D was sent to the PC 7.

An experiment was held with a Ø12,5 mm forming ball and four different sphere temperatures: 50°C, 60°C, 75°C, and 100°C. When a forming ball 4 reached investigation temperature, sample 2 with a thermocouple at room

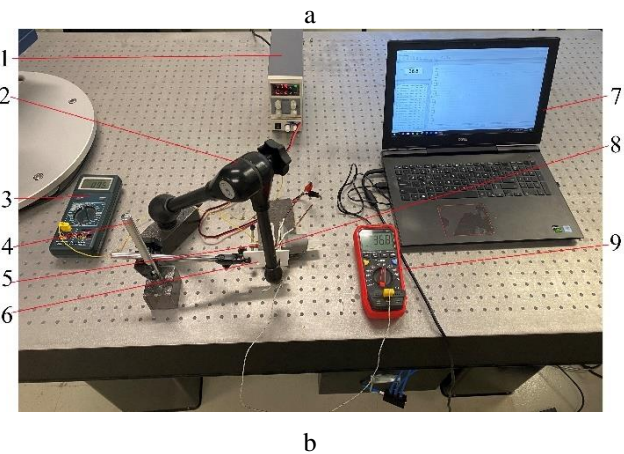
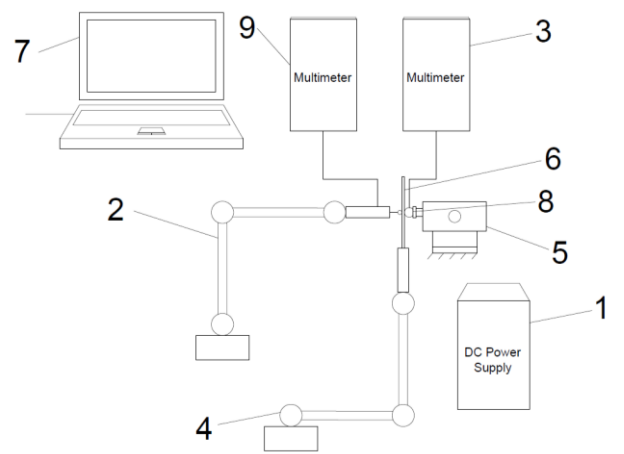


Fig. 5 Polymer's heating investigation: a – scheme, b – set-up view. Here: 1 – DC Power Supply HY1803D (0-18V, 3A), 2, 4 – Stands, 3 – Digital Multimeter CHY 24CS LCR METER, 4 – Heater with magnet and ball, 5 – Clamp, 6 – Sample, 7 – PC, 8 – Heating element, 9 – Digital Multimeter UNI-T UT161D

temperature 3 were touched to the sphere. Temperatures of different layers of material at different ball temperatures were indicated. The temperature versus time of the polymer heating process was also tracked. Only one temperature – 75°C of the forming sphere was analyzed from a time perspective since this amount of heat triggers  $T_g$  temperature in PVC plastics. Results of the investigation are shown in Figs. 6 and 7.

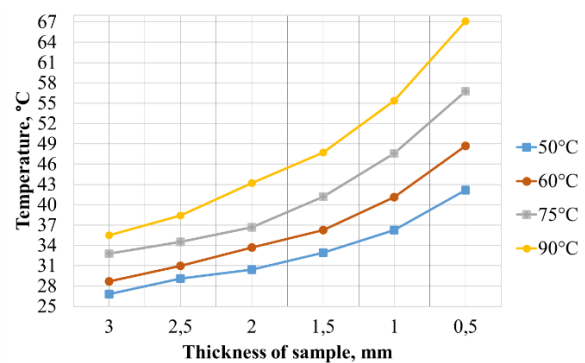


Fig. 6 Temperature values of sheet layers under different forming ball temperatures versus thickness of a sheet

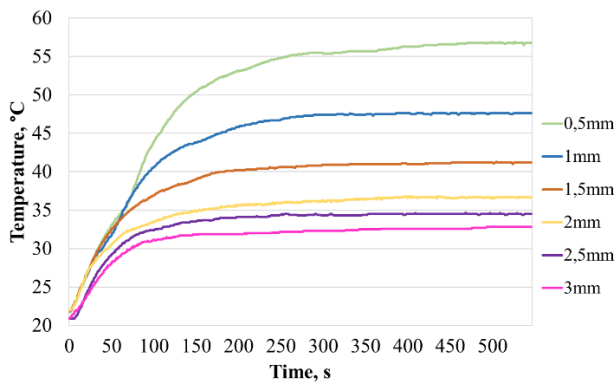


Fig. 7 Temperature values of sheet layers under 75°C forming ball temperature versus time

The results of carried experiments revealed that under 75°C sphere's temperature, polymer temperature in 0.5 mm thickness reached 56.8°C, and this temperature can be considered theoretical forming temperature to achieve the best results. However, 32% of generated heat at the 75°C temperature of forming ball was lost in the conduction process. Results showed that the temperature difference in 0.5 mm thickness and 3 mm thickness material is more than 20°C. Experiment revealed that deeper layers of material reach its highest temperature faster than closer layers to the heating element. An exponentially higher temperature of forming ball is needed to heat deeper layers. The investigation provided valuable information that it takes about 8 minutes of heating with a 75°C ball to reach optimal forming temperature in 0.5 thickness of the material.

#### 4. Experimental research of self-heating forming tool

The self-heating incremental process feasibility and efficiency can only be acquired through experimental research. Various experiments must be held to use a novel self-heating incremental forming tool in the production. Before using the tool in forming a blank, main parameters such as the temperature of the forming sphere and forming forces must be analyzed. Static and dynamic experiments must be conducted since the heat amount transferred to the forming sphere is different from the previous research. The static approach reveals novel tool's formability dependency on forming forces and temperature. A dynamic approach provides valuable information about polymer formability and process temperature boundaries in the dynamics. Obtained data is used in further simulating and experimental research to achieve the best quality of incremental sheet forming.

A static experiment approach of self-heating incremental formation tool can lead to a better understanding of temperature and forces contribution to the process quality. Studying static tool heating to the polymer sheet can reveal losses and distribution of heat and provide valuable information about surface quality. An experiment was held at room temperature and repeated three times to increase the accuracy of the outcome. As a result, average values are presented in the results. Two different spheres were used to understand the impact of forming pressure on the blank: Ø12,5 mm and Ø11 mm. The research was held with three different temperatures and three different forming forces. The schematic view of a held experiment is shown in Fig. 8, a and the set-up view in Fig. 8, b.

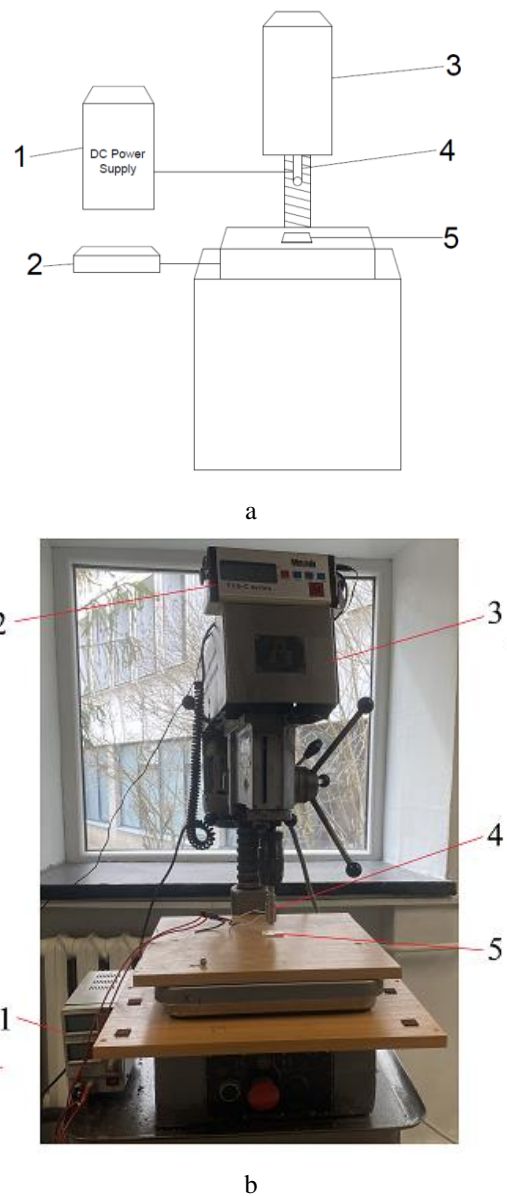


Fig. 8 Static self-heating forming tool experiment: a – scheme, b – setup view. Here: 1 – DC Power Supply HY1803D (Mastech Digital, Inc., USA), 2 – FCS-C series platform scales (UAB Mingeda, Lithuania), 3 – Praktika drilling machine TU2-024-2546-70, 4 – Designed SPIF self-heating tool, 5 – PVC ESA-D 3 mm thickness polymer sheet

During the experimental research, the forming tool 4 was heated by increasing the power of the heating element by changing the current and voltage of DC Power Supply HY1803D 1. PVC ESA-D 3mm thickness samples 5 aligned on the FCS-C platform scales 2. Forming tool was attached to the drilling machine Praktika TU2-024-2546-70 3. With each temperature, samples were affected by different forces. To track the temperature of the tool's sphere, multimeter UNI-T UT161D with a thermocouple was used. When the temperature of the contacting point of the sphere reaches and stays at the experimental temperature, the machine heats the polymer and stamps samples with the self-heating tool for 60 s with each specified constant force. Samples after the experiment are shown in Fig. 9.

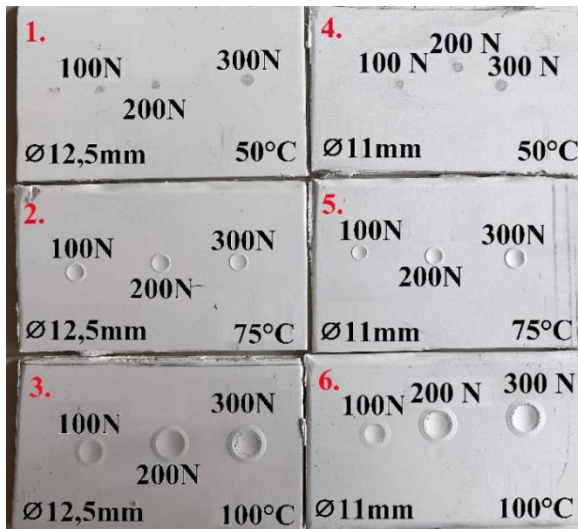


Fig. 9 Samples after the static experimental research: 1 – Sphere Ø12,5 mm, 50°C, 2 – Sphere Ø12,5 mm, 75°C, 3 – Sphere Ø12,5 mm, 100°C, 4 – Sphere Ø11 mm, 50°C, 5 – Sphere Ø11 mm, 75°C, 6 – Sphere Ø11 mm, 100°C

When the sample is affected by the machine, the mass of the pressing is shown in the platform scales. Mass of shown weight multiplied by standard gravity is equal to applied forces. Since the polymer is a plastic material, deformations can be noticed due to the force and heat – the value in the platform scales drops in time. The higher temperature and forces, the more significant decrease in the scales, and deeper prints are noticed in the samples. The principle of the process with variables is shown in Fig. 10.

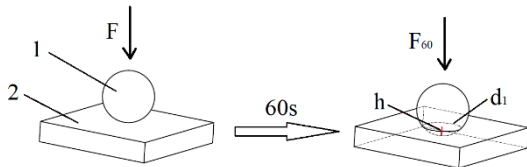


Fig. 10 The principle of the static experiment: 1 – hot sphere, 2 – sample,  $F$  – initial force,  $F_{60}$  – reduced force after 60 seconds of deformation,  $h$  – depth of the imprint,  $d_1$  – diameter of the imprint

Experimental research revealed that temperature, the force of press, and the sphere's diameter have a significant influence on the process. An accomplished experiment revealed that the sphere's diameter influences the depth of the imprint. Imprints' depth dependency on forming sphere diameter and temperatures are shown in Fig. 11.

The dependency graph revealed that the depth of the imprint is directly proportional to applied force under the same size forming ball. However, the perpendicularity of the line depends on the sphere's temperature. Forming with a smaller sphere creates a slightly deeper imprint than the bigger one. This phenomenon can be explained as a force applied perpendicular to the surface per unit area. The smaller diameter of the forming tool's sphere, the deeper imprint is achieved with a greater force. This observation can conclude that a smaller diameter sphere requires lower forming forces to achieve the same imprint depth as with a bigger diameter. However, visual analysis of samples showed that higher surface quality could be achieved with a bigger diameter sphere under the same conditions.

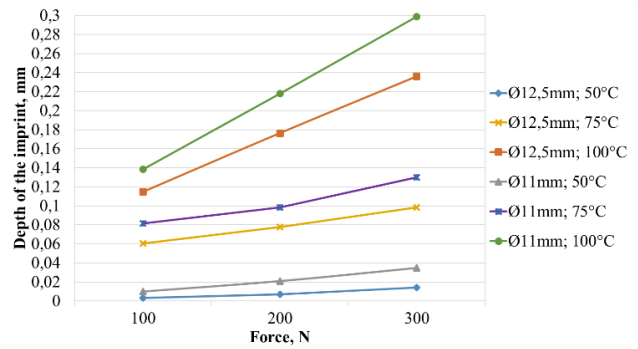


Fig. 11 Depth of imprint values under different forming ball diameters and temperatures versus applied forces

A dynamic experiment with a self-heating forming tool is a closer approach to the incremental sheet forming process. However, in this experiment, as in the static, the whole bottom of the sample is touching the stand's surface. Therefore, the tool makes a groove instead of performing an incremental step. Studying the movement of the tool on the surface can reveal the material's formability in dynamics at different temperatures and forces and provide valuable information about the surface quality. An experiment was held at room temperature and repeated three times to increase the accuracy of the outcome. As before, two different spheres were used to understand the impact of forming pressure on the blank: Ø12,5 mm and Ø11 mm. The research was held at four different temperatures. To investigate plastic under critical conditions, higher experimental temperatures are chosen. The amount of heat transferred to the polymer area depends on tool movement speed in this approach. To find the boundaries of heating that could be used in the incremental forming process, 50°C, 75°C, 100°C, and 120°C temperatures were analyzed. To find eligible force boundaries, 100 N, 200 N, 300 N, 400 N, and 500 N forces were determined. The schematic view of a held experiment is shown in Fig. 12.

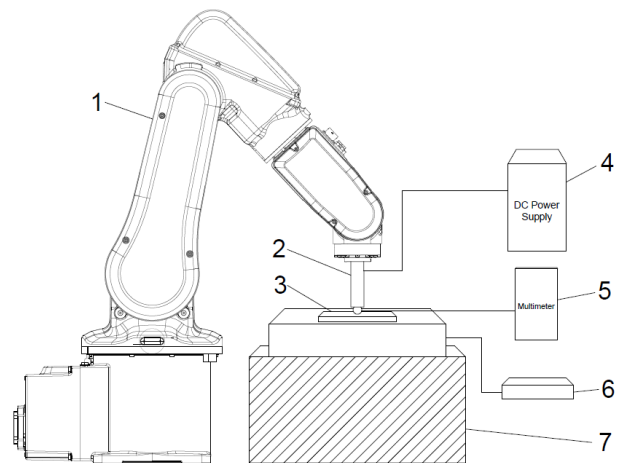


Fig. 12 Scheme of dynamic experiment with a self-heating forming tool. Here: 1 – Manipulator ABB IRB1200 (ABB Robotics & Discrete Automation, Västerås, Sweden), 2 – Designed SPIF self-heating tool, 3 – PVC ESA-D 3mm thickness polymer sheet, 4 – DC Power Supply HY1803D (Mastech Digital, Inc., USA), 5 – Digital Multimeter (Uni-Trend Technology Co., Ltd., China), 6 – FCS-C series platform scales (UAB Mingeda, Lithuania), 7 – Holding frame

As well as before, during the experimental research, the forming tool 2 was heated by increasing the power of the heating element by changing the current and voltage of DC Power Supply HY1803D 4. PVC ESA-D 3mm thickness sample 3 clamped on the FCS-C platform scales 6. During the experiment, it was essential to maintain a horizontal blank level. Wrongly set samples could increase or decrease forces and geometry inaccuracy of imprinted path. A level was used to determine the horizontal position of the blank. Samples with scales were clamped to the holding frame 7. Forming tool was attached to the ABB IRB1200 manipulator 1. With each temperature, samples were formed with a constant 6.33 mm/s speed and affected by 100 N, 200 N, 300 N, 400 N, and 500 N forces. Since the tool is moving and the amount of heat transferred to one unit of polymer volume is lower than in the static experiment, the assumption was made that more immense forces must be analyzed to maintain similar depth imprints as in the previous approach. To track the temperature of the tool's sphere, multimeter UNI-T UT161D 5 with a thermocouple was used. When the temperature of the contacting point of the sphere reaches and stays at the experimental temperature, the manipulator is operated to form a groove on the blank. When the tool interfaces with the sheet weight of pressing are shown in the platform scales. As in the previous experiment, mass multiplied by standard gravity equals applied forces. As in the static investigation, when the tool touches the sheet's surface, heat softens the blank, and deformations appear – the weight shown in the scales starts to drop. When the tool starts to move, forces start to grow again because one unit of material's volume gets less heat, and the material's hardness is higher than starting point's hardness. The higher temperatures and forces, the deeper groove can be noticed. The principle of the process with main variables is shown in Fig. 13.

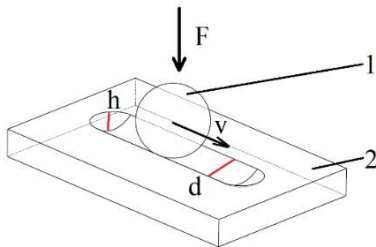


Fig. 13 The principle of the dynamic experiment: 1 – hot sphere, 2 – sample,  $F$  – initial force,  $h$  – speed of moving sphere,  $h$  – depth of the groove,  $d$  – width of the groove

Dynamic experimental research proved legitimate of static investigation results that temperature, forming force of press, and sphere diameter influences the forming process. Nevertheless, the dynamic experiment revealed that even under greater forces and higher temperatures, grooves are more trivial than static imprints. This observation leads to the statement that the temperature and forces of the forming tool should be changed depending on the movement speed of the tool. Grooves' depth dependency on forming sphere diameter and temperatures are shown in Fig. 14.

Results revealed that the depth of the groove is directly proportional to applied force under the same size forming ball. However, the perpendicularity of the line depends on the sphere's temperature. It was noticed that a

smaller sphere forms a deeper groove under the same conditions.

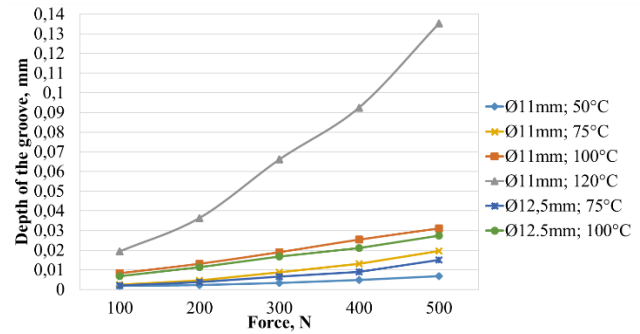


Fig. 14 Depth of groove values under different forming ball diameters and temperatures versus applied forces

#### 4. Conclusions

In this paper a novel single point heating tool for the robotized incremental polymer sheet forming is proposed and investigated. The tool has inserted 60 W heating element to provide heat to the forming sphere which heats polymer through conduction. Proposed tool has an automatic control system: a PID temperature controller with a solid-state relay and a thermocouple attached to the tool and power supply. Heating process investigation revealed supplied power dependency on the temperature and proved the heating capacity. Results showed that the forming ball's temperature used in further research (75°C) reaches 2.7 W power of the heating element. Experiments showed that under 75°C sphere's temperature, polymer temperature in 0.5 mm thickness reaches 56.8°C temperature close to optimal processing temperature.

Results of static and dynamic experiments revealed that the depth of the groove is directly proportional to applied force under the same size of forming ball – it varies from 0.002 mm with 11mm diameter sphere heated up to 50°C and loaded with 100N up to 0.135 mm deep imprint, heated up to 120°C and loaded with 500 N force. Noticed, that the smaller the forming sphere's diameter, the deeper the imprint is with a greater force. Results of the static experiment showed system's temperature influence on polymer formability. Obtained results showed that increasing temperature from 50°C to 75°C increases formability 3.72 times, and from 75°C to 100°C increases formability 2.3 times. Dynamic approaches with 75°C and 100°C forming temperatures showed that grooves are notable to the naked eye and have smooth surfaces – formability between these values increases by 63.3%. The paper presents the proof that in forming, the faster the tool moves, the less formable polymer is due to lower heat absorption in time.

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#### INVESTIGATION OF THE SINGLE POINT HEATING TOOL FOR THE ROBOTISED INCREMENTAL POLYMER SHEET FORMING PROCESS

#### S u m m a r y

Incremental sheet forming (ISF) technology is a suitable and flexible solution to create complex 3D geometries of the sheet. A sheet is gradually formed into the desired shape with a forming tool usually attached to a CNC machine or robot. This process is valid with metal as well as with polymer sheets. However, the inaccuracy of geometry and occurring process errors in previously discussed industries prove the novelty of the technology.

In this research a novel single point heated tool with control system for incremental sheet forming process is proposed and investigated. Experimental research results revealed main heating parameters necessary for ISF and mechanical properties dependency from heating.

**Keywords:** single point heating, heating parameters, polymer forming, incremental sheet forming, robotics.

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