

Article

Advanced FEM Insights into Pressure-Assisted Warm Single-Point Incremental Forming of Ti-6Al-4V Titanium Alloy Sheet Metal

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Abstract: This study employs the finite element (FE) method to analyze the Incremental Sheet Forming (ISF) process of Ti-6Al-4V titanium alloy. The numerical modeling of pressure-assisted warm forming of Ti-6Al-4V sheets with combined oil-heating and friction stir rotation-assisted heating of the workpiece is presented in this article. The thermo-mechanical FE-based numerical model took into account the characteristics of the mechanical properties of the sheet along with the temperature. The experimental conditions were replicated in FEM simulations conducted in Abaqus/Explicit, which incorporated boundary conditions and evaluated various mesh sizes for enhanced accuracy and efficiency. The simulation outcomes were compared with actual experimental results to validate the FE-based model's predictive capacity. The maximum temperature of the tool measured using infrared camera was approximately 326 °C. Different mesh sizes were considered. The results of FEM modeling were experimentally validated based on axial forming force and thickness distribution measured using the ARGUS optical measuring system for non-contact acquisition of deformations. The greatest agreement between FEM results and the experimental result of the axial component of forming force was obtained for finite elements with a size of 1 mm. The maximum values of the axial component of forming force determined experimentally and numerically differ by approximately 8%. The variations of the forming force components and thickness distribution predicted by FEM are in good agreement with experimental measurements. The numerical model overestimated the wall thickness with an error of approximately 5%. By focusing on the heating techniques applied to Ti-6Al-4V titanium alloy sheet, this comparative analysis underlines the adaptability and precision of numerical analysis applied in modeling advanced manufacturing processes.

Keywords: coefficient of friction; friction; incremental sheet forming; sheet metal forming; titanium



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1. Introduction

Titanium and titanium alloy sheets are characterized by low weight (density $\rho = 4.43 \div 4.85 \text{ g/cm}^3$) and high mechanical strength (from $R_m \approx 290 \text{ MPa}$ for commercially pure (CP) titanium Grade 1 to approximately 1750 MPa for heat-treated β titanium alloys) [1,2]. The combination of high mechanical strength, low density and corrosion resistance means that titanium sheets are used where the weight and strength of the structure are important (high-performance motor vehicles [3], aircrafts [4], sports equipment [5]). Titanium is a biocompatible material that does not cause allergic reactions and is not rejected by the

human body. Therefore, titanium products are often used in joint implants [6], bones [7] and teeth [8], as well as in other prosthetic elements [9].

Metal forming has a significant share in modern manufacturing techniques, as it allows the production of high-quality products with complex shapes at low production costs [10]. Sheet metal forming processes, mainly deep-drawing, enable the production of ready-made metal components. In addition to conventional forming processes, many types of single-point incremental forming (SPIF) processes have been developed in recent years. In the SPIF process, a rotating or non-rotating pin with a rounded tip moves along a programmed trajectory, and gradually sinks into the sheet. Usually, the edge of the workpiece is fixed. The forming process parameters (tool rotational speed, feed rate, step size) determine the degree of sheet metal deformation [11] and the surface topography of the SPIFed components [12]. The degree of sheet metal deformation is also limited by the material itself and its properties, part shape, the wall angle of the drawpiece [13], contact conditions [14] and the tool path strategy [15]. Sheet metals formed using the SPIF technology show higher limit deformations compared to conventional sheet forming methods. The forming forces in SPIF are much lower compared to conventional deep-drawing. In SPIF there is no need to produce profiled dies and punches adapted to the shape of the component being formed. Economical, technological and ecological aspects of SPIF versus conventional deep drawing were presented by Petek et al. [16] and Oleksik et al. [17]. The disadvantage of the SPIF process is the relatively large springback of the components after the forming process [18] and the pillow effect [19]. Behera and Ou [20] found that the stress-relieving heat treatment of titanium sheets affects the dimensional accuracy of parts formed using SPIF. The long processing time compared to conventional forming makes incremental forming methods suitable for small batch sheet metal forming operations [21]. SPIF can be performed under cold and hot conditions using heat blowers [22], frictional heat generated by tool rotation [23] and liquid heating [24].

Components made of titanium and its alloys encounter great difficulties, mainly due to the high tendency of this metal to adhere to the tool surface [25]. This phenomenon is more intense in SPIF due to the small contact surface area of the tool with the formed component. The adherence of the sheet material to the tool surface causes the deterioration of the surface quality of the drawpieces and changes in contact conditions due to greater heat generation. High temperatures reduce the lubricating properties of greases that are not adapted to high temperature conditions. For the above reasons, the SPIF process of titanium sheets requires the effective lubrication of the sheet surface [26] or the use of anti-adhesive coatings on the tools [27].

Numerical modeling is a tool supporting the experimental identification of deformations and parameters of the SPIF forming process. Over recent years, finite element modeling has been developed and has been the subject of many research works on forming titanium and its alloys. The main directions of research include the selection of forming strategies [28], the analysis of forming force components [29], thinning rate [30] and friction conditions [31], and the prediction of material fracture [32]. Particular attention should be paid to the following works related to the subject of this article. Sbayti et al. [33] analyzed the effect of the punch diameter and the forming temperature on the geometric accuracy of Ti-6Al-4V titanium alloy SPIF-ed hip prostheses. A three-dimensional thermo-mechanical model with thermally coupled brick finite elements was set up for the simulation of the SPIF process. Palumbo et al. [34] investigated the effects of both the draw angle and tool/pitch ratio on the material deformation in SPIF of Ti-6Al-4V sheets. The results of FE-based analyses were used in investigating the forming of an automotive component. Naranjo et al. [35] simulated the SPIF of Ti-6Al-4V sheets to study the effect of forming temperature on the sheet metal formability and SPIF process forces. Different mesh sizes were investigated for FEM modeling in order to optimize the computing time. Hadoush and van den Boogaard [36] investigated self-adaptive mesh techniques to reduce calculation efforts. Abdelkefi et al. [37] used a simple elastic-plastic material model to predict forming forces in the finite element modeling of SPIF process of T40 titanium alloy. It was found that the

accuracy of the calculated forces depends strongly on the constitutive material behavior of the workpiece. Saidi et al. [38] investigated the warm incremental process based on the use of heat cartridges. The effect of warm temperature on the forming force and thickness distribution of the truncated cone was investigated using FE-based Abaqus/Explicit software (version 2019). It was found that the finite element model gives accurate predictions. Honarpisheh et al. [39] analyzed the forming forces and thickness distribution in the electric hot SPIF of the Ti-6Al-4V sheets. The authors indicated the most important parameters in the forming process of truncated cones: step size, tool feed rate and current amperage. Kumar et al. [40] simulated the formability process of Ti-6Al-4V sculptured sheet metal parts produced using SPIF technology. They investigated the effects of forming parameters on the thickness distribution, effective stress distribution and forming depth. It was found that the thickness distribution and fracture depth increase with a decrease in the mesh size, whereas they decrease with the increase in the wall angle.

Taking into account what has been indicated above, the authors of the present work approach the numerical modeling of pressure-assisted warm-forming of Ti-6Al-4V sheets with combined oil-heating and friction stir rotation-assisted heating of the workpiece. An established numerical model has not been found in the literature to the best of our knowledge. A finite element-based numerical model build in Abaqus/Explicit took into account the experimental parameters presented in the authors' previous article [24]. This article focuses on the numerical analysis of deformations and forming forces for the optimal set of SPIF process parameters experimentally obtained in [24]. Section 2 presents the material properties, experimental setup and numerical model of the warm-forming of Ti-6Al-4V sheets. The mesh sensitivity analysis and comparison of numerical and experimental results, with a discussion, is presented in Section 3. Finally, conclusions are drawn in Section 4.

2. Materials and Methods

2.1. Material

The research material were annealed Ti-6Al-4V titanium alloy in sheet form with a thickness of 0.82 mm. The main alloying elements in this alloy are aluminum (5.5 wt. %) and vanadium (3.5 wt. %). The contents of other elements (wt. %) are Fe < 0.3, O < 0.2, N < 0.05, C < 0.09, H < 0.0015. The mechanical properties of the sheet at ambient temperature (20 °C) were determined in the three replicated runs using a uniaxial tensile test. A Zwick/Roell Z030 testing machine (Ulm, Germany) was used to determine the mechanical properties of sheets at ambient temperature. The mechanical properties of the sheet material at a temperature of 340 °C were also determined (maximum temperature observed in the contact zone of the tool with workpiece in warm SPIF). Additionally, tests were carried out for three intermediate temperatures: 104, 183 and 261 °C. Tests at temperatures of 104 and 183 °C were carried out using an Instron 8801 tensile testing machine (Norwood, MA, USA). Tests at temperatures of 261 and 340 °C were carried out using an Instron 5982 tensile testing machine. Tests at elevated temperature were carried out in accordance with the ASTM E21-20 standard [41]. The average values of basic mechanical properties are presented in Table 1.

Table 1. Basic mechanical properties of Ti-6Al-4V alloy.

Temperature, °C	Yield Stress $R_{p0.2}$, MPa	Ultimate Tensile Strength R_m , MPa	Elongation A, %
20	1082	1112	9.1
104	916	938	15.1
183	819	850	14.7
261	751	795	10.7
340	682	777	13.5

2.2. Experimental Setup

A varying wall angle conical frustum (VWACF) with circular generatrix (Figure 1) was produced. The experimental research presented in this work is limited to the production of a drawpiece under optimal parameters that were determined in the previous work [24]. The pressure-assisted warm forming of 0.82 mm-thick Ti-6Al-4V sheets with combined oil-heating and friction stir rotation-assisted heating was performed using a special forming die (Figure 2a,b). The forming die consisted of a housing, inside which there was oil at a temperature of 200 °C at a constant pressure of 0.4 MPa, adjusted by discharge valve and also verified with a pressure gauge. Constant oil pressure was ensured via a pressure valve. The forming die was mounted on the work table of a PS95 vertical CNC milling machine via a high-accuracy piezoelectric dynamometer. An insulation plate was used to limit heat exchange between the oil chamber and the table of the milling machine.

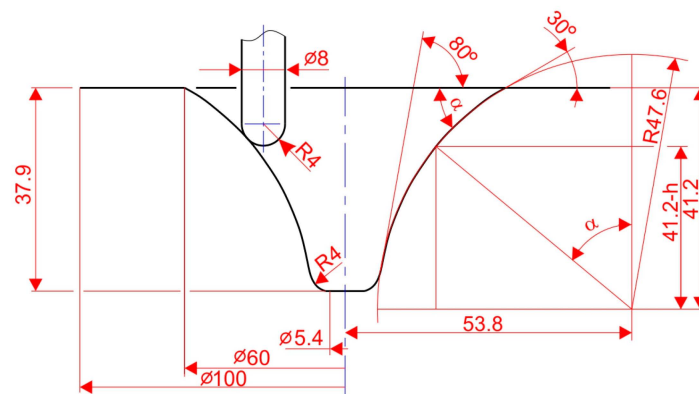


Figure 1. Geometry of VWACF (dimensions in mm).

Before the forming procedure, a measuring grid was marked with a laser engraving machine on the back side of the blank (where there is no contact between the tool and a workpiece, (Figure 3a). The grid's purpose was to measure the thickness distribution after sheet deformation using the ARGUS non-contact measuring system with a strain measuring accuracy up to 0.01% [42,43]. Dot size and pattern measurement was required as an input to compare with the deformed mesh (Figure 3b).

The oil was heated by electric heaters located in the base of the die. Workpieces in the form of discs with a diameter of 100 mm were positioned symmetrically relative to the axis of the forming die using screws located on the periphery of the housing. The forming tool was a tungsten carbide pin with a rounded tip with a radius of $r = 4$ mm mounted in the spindle of the milling machine. Warm SPIF requires the use of an appropriate lubricant adapted to the processing temperature and the grade of sheet metal being formed. Before the forming test, the sheet metal surfaces were degreased. Grease-free dry anti-friction spray containing MoS_2 was used, which is resistant to temperatures up to 400 °C. The VWACF drawpiece was formed with the following parameters: tool rotational speed 1000 rpm, step size 0.4 mm and feed rate 2000 mm/min. The spiral tool trajectory allowing for obtaining the drawpiece shown in Figure 1 was generated using Siemens NX CAM software (version 1938) based on the geometrical model of the drawpiece.

A high-accuracy piezoelectric dynamometer manufactured by Kistler Holding AG (Winterthur, Switzerland) (sample rate 200 kHz) mounted to the milling machine work-table was used to measure the axial component of forming force F_z and the horizontal components of forming force F_x and F_y . The in-plane force F_{xy} was determined according to Equation (1),

$$F_{xy} = \sqrt{F_x^2 + F_y^2} \quad (1)$$

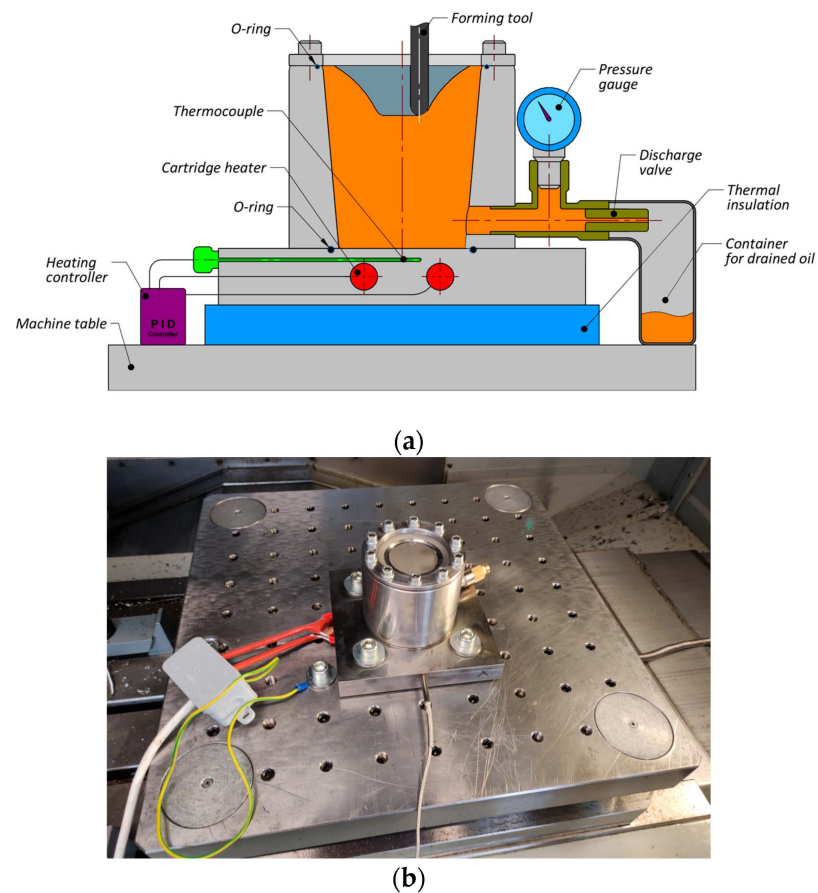


Figure 2. (a) Schematic diagram and (b) view of forming tool.

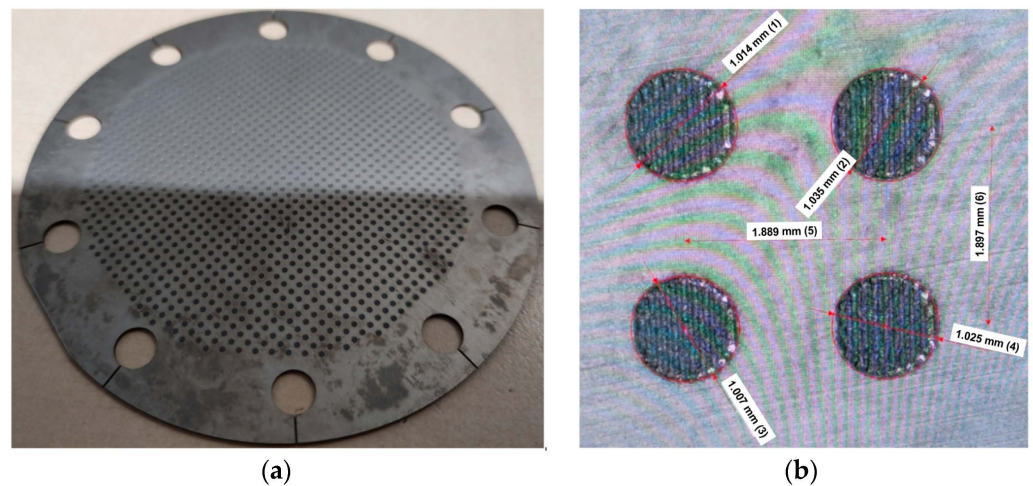


Figure 3. (a) Grid markings on the back side of the blank with (b) measurement (the measurement numbers are indicated in parentheses).

The resultant forming force is equal to

$$F_w = \sqrt{F_{xy}^2 + F_z^2} \quad (2)$$

As a result of the experimental forming, the VWACF with a maximum formable wall angle $\alpha = 66^\circ$ (Figure 4) was formed. The height of the drawpiece was 21.9 mm. The heights of drawpieces were measured using a height gauge.



Figure 4. Photograph of the varying wall angle conical frustum.

The drawpiece was located on a measuring table with reference cubes for the visual inspection GOM system. Then, the ARGUS measuring system was used to scan the initially located grid (Figure 5). Such a measurement allows for complex analyses, such as of the thickness distribution. Then scanned drawpiece was analyzed with Zeiss GOM Inspect software (version 2021 Hotfix 4, Rev. 146662 Build 2022-02-19), which allows one to create offline (without access to camera) measurement reports.

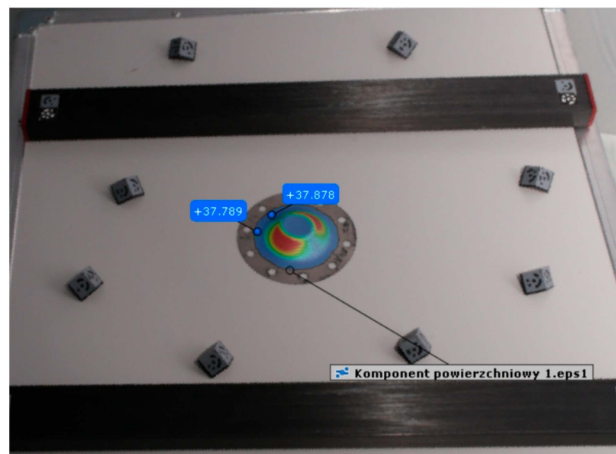


Figure 5. Measuring stand for ARGUS system.

2.3. Numerical Model

The numerical modeling of the warm-forming of Ti-6Al-4V sheets with combined oil-heating and friction stir rotation-assisted heating was carried out using the finite element method in the Abaqus/Explicit program (Dassault Systemès, Waltham, MA, USA). The pin and sheet model correspond to the geometric dimensions used in the experiments. To simplify the numerical model, isolated sheet metal was considered, without modeling the support used in experiments. The displacement and rotations of the outer ring of the sheet metal affected by the blankholder (Figure 6a) were defined as a boundary condition of the “fix support-type”. Both the displacement and boundary rotation on all the axes were restricted ($x = y = z = 0$, φ_x , φ_y , $\varphi_z = 0$). The tool moved along a continuous tool path exported from Siemens NX CAM software. The tool path started from the outside of the area of the sheet metal subjected to deformations towards the inner part, and incrementally traveled downwards in the Z-direction. A pressure of 0.4 MPa was applied to the bottom surface of the sheet (Figure 6b), which corresponds to the oil pressure in the experiments.

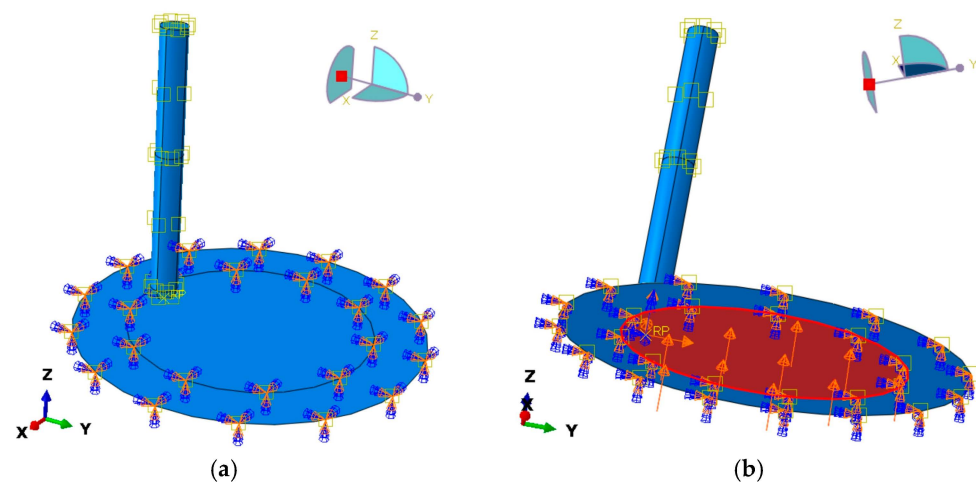


Figure 6. Numerical model of warm SPIF process of VWACF in (a) top and (b) bottom view.

A 3-node thermally coupled triangular shell, with finite membrane strain elements with bilinear temperature in the shell surface, were used to discretize the sheet material. The model of the forming tool was discretized using 14,813 4-node thermally coupled tetrahedrons with a coupled temperature-displacement strategy [44].

The sheet metal was modeled as an elastic–plastic material associated with the von Mises yield criterion. The isotropic material model was set based on the measurement of the thinning of the experimental drawpiece using the ARGUS non-contact measuring system. As is presented in the Section 3, uniform thinning of the sheet metal along the perimeter of the drawpiece was observed. This assumption was also the subject of research by other authors examining the SPIF of titanium and its alloys [45–47]. Models of flow curves (Figure 7a) at temperatures between 183 and 340 °C were prepared by approximating the experimental curves using the approach proposed by Naranjo et al. [35]. The temperature distribution during experimental forming was measured using an FLIR T400 infrared camera. The maximum temperature in the contact zone during combined oil-heating and friction stir rotation-assisted heating was equal to 326 °C (Figure 7b). Therefore, the simulation included flow curves determined in the temperature range 183–340 °C. The process parameters of experiments were adjusted so that the temperature at the interface did not exceed 500 °C. These conditions ensure the lack of oxidation of the titanium alloy [48]. The temperature of oil-heated workpiece (initial temperature) was $T \sim 200$ °C (Figure 8).

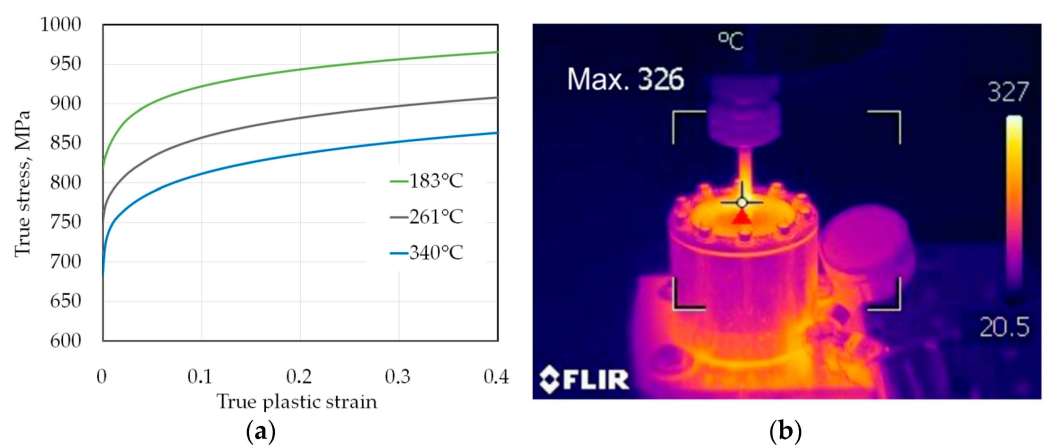


Figure 7. (a) Flow curves of Ti-6Al-4V and (b) maximum temperature registered in the contact zone (place where the highest temperature occurs is indicated by red triangle).

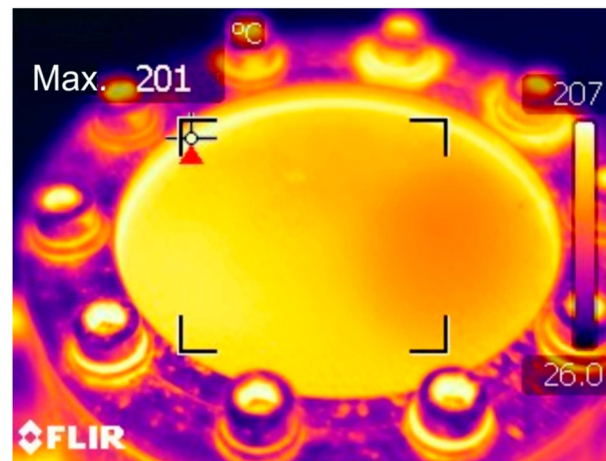


Figure 8. Temperature of the workpiece immediately before starting the forming process (place where the highest temperature occurs is indicated by red triangle).

The density and Poisson's ratio of the Ti-6Al-4V alloy in the analyzed temperature range were $\rho = 4430 \text{ kg/m}^3$ and $\nu = 0.31$, respectively. Heat transfer between the pin and the sheet metal and the environment was taken into account. The ambient temperature was set at 20°C . The values of the remaining thermo-mechanical parameters [39] are presented in Figure 9. The physico-mechanical parameters of the tungsten carbide pin material were as follows: density $\rho = 14,450 \text{ kg/m}^3$, Poisson's ratio $\nu = 0.31$, Young's modulus $E = 650 \text{ GPa}$, conductivity $h_c = 75 \text{ W/m/}^\circ\text{C}$ and specific heat $c_p = 280 \text{ J/kg/}^\circ\text{C}$.

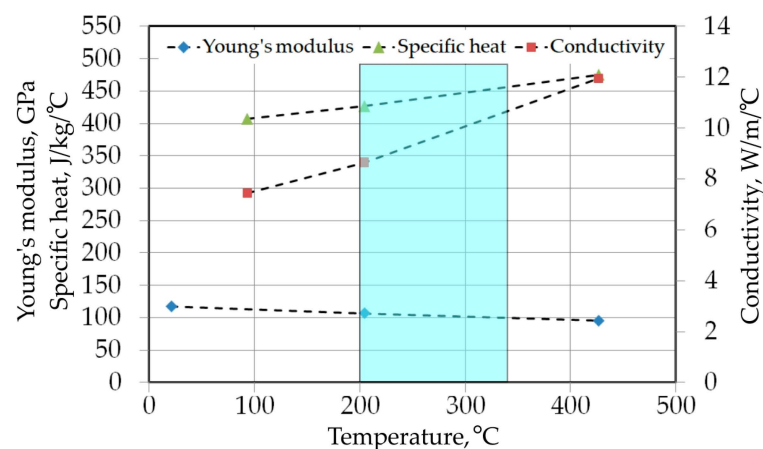


Figure 9. Effect of temperature on the selected thermo-mechanical parameters of Ti-6Al-4V titanium alloy (blue shaded rectangle indicates the temperature range considered in the numerical model).

There is one contact pair between the workpiece and the surface of the forming tool. This pair enables surface-to-surface contact and allows a small amount of sliding between the surfaces. The penalty contact method was used to formulate mechanical constraints. The frictional behavior of the contact pair is assumed to follow the Coulomb's model, which is commonly used to describe the phenomenon of friction in cold [49,50] and hot [33,51] SPIF. The heat generation ability was used to generate heat via frictional sliding. The value of the coefficient of friction was determined experimentally based on the methodology proposed by Decultot [52] and Saidi et al. [53]. In previous studies, for the same sheet and the same shape of the drawpiece, a stable course of changes in the coefficient of friction was obtained, which was presented in the authors' previous work [54]. The average value of the coefficient of friction when forming the drawpiece with the SPIF process parameters presented in this article was 0.15. This value of coefficient of friction is fully consistent with the coefficient of friction used by Sbayti et al. [51] for hot SPIF of Grade 5 titanium alloy.

The heat flux density generated due to frictional heat generated by the forming tool is determined using the Equation (3),

$$q_{hf} = \tau \varphi \frac{\Delta s}{\Delta t} \quad (3)$$

where t is the temperature and friction-dependent frictional stress, φ is the fraction of frictional work converted to heat, and Δs and Δt are incremental slip and incremental time, respectively.

The contact pair included thermal conductance at the tool–sheet interface. The heat flux due to conduction is defined as

$$q_k = \varepsilon(h, p, \bar{\theta}) \Delta \Theta \quad (4)$$

where ε is heat transfer coefficient, h is overclosure, p is contact pressure and $\bar{\theta}$ is average temperature on the surfaces on both sides of contact interface, $\Delta \Theta = \Theta_1 - \Theta_2$ (Θ_1 and Θ_2 are the temperatures of side 1 and side 2 of the interface, respectively).

3. Results and Discussion

It is generally accepted that numerical analyses should ensure the achievement of an appropriate level of accuracy in the shortest possible time. In this aspect, mesh sensitivity analysis is an important stage of analysis. The selection of an appropriate size of the finite element mesh is one of the most important issues of correctly performed FEM-based numerical modeling [55]. For FEM-based computational models, it is generally assumed that reducing the size of the finite element mesh leads to more accurate simulation results [56]. The density of the numerical mesh guarantees an increase in the accuracy of calculations by approximating the function on shorter sections; however, the time necessary to perform the calculations increases [55].

In the area of the sheet metal subjected to deformations resulting from coming into contact with the tool, a denser mesh of finite elements was assigned. The rest of the workpiece was simulated with a larger size of finite elements that were not subject to deformation. The following finite element sizes in the sheet metal deformation zone were considered: 0.5 mm (Figure 10a), 1 mm (Figure 10b), 2 mm (Figure 10c) and 4 mm (Figure 10d).

The forming force in SPIF is characterized by localized deformation that leads to high frictional forces. The prevailing force component is the axial component F_z of the forming force [57,58]. The selection of the finite element mesh was carried out based on the compliance of the axial component (F_z) of forming force with experimental data [37]. So, in this article, computation time was not the most important criterion. Greater importance was attached to the accuracy of reproducing experimental conditions. In SPIF, the pin with a rounded tip contacts the sheet metal over a very small area. Hence, the size of the elements is much more important in ensuring the accuracy of the results compared to conventional sheet metal forming methods.

Figure 11 shows a comparison of the values of the axial component F_z of the forming force for the analyzed mesh sizes. The greatest agreement between FEM results and the experimental result was obtained for finite elements with a size of 1 mm. Elements that are too large result in fewer mesh nodes being in contact with the tool at any given time. This causes the excessive overestimation of the force value. It is also visible that in the initial forming stage, the value of the axial force increases. In the initial stage of forming, the tool must overcome high resistance to deformation of the sheet metal, which causes a rapid increase in the axial force. After reaching a certain depth, the force tends to remain approximately constant. In the initial stage, the close proximity of the supporting backing plate imposes wiper bending, which is gradually transformed in the steady-state incremental forming regime [59]. The tool travels continuously inside the profile, and this

requires more force in pushing the material during forming [60]. High step size values increase the reactivity of the material, which increases the forming force [61].

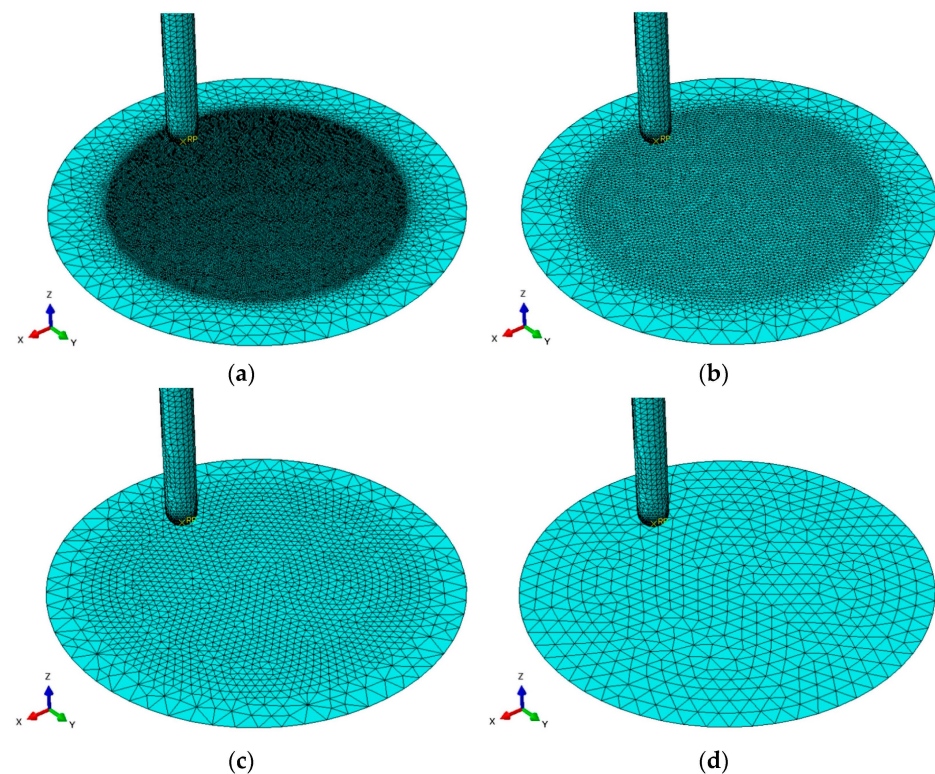


Figure 10. Finite element mesh of considered models with average sizes of elements of (a) 0.5 mm, (b) 1 mm, (c) 2 mm and (d) 4 mm (RP—reference point).

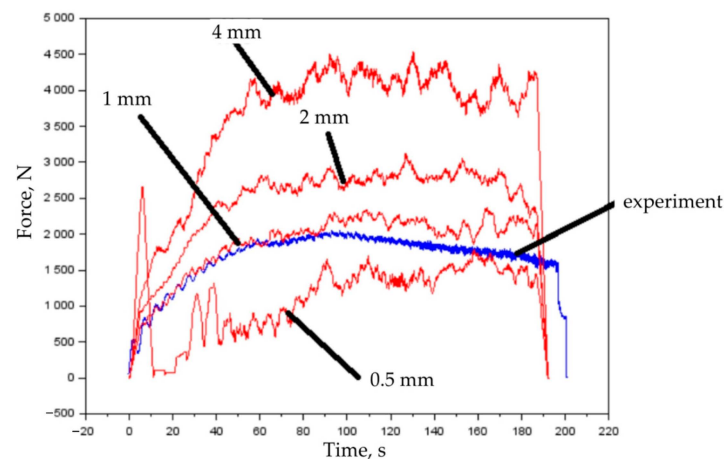


Figure 11. Comparison of the axial component of forming force F_z for different mesh sizes.

The parameters of the numerical calculations were recorded in 0.01 units of time. The oscillations of the total force (Figure 11) were due to the penalty method used to model contact [62]. The penalty method usually checks the contact at integration or nodal points. Therefore, for small tool radii, the sizes of finite elements are limited if a stable tool force is required [63]. To reduce the oscillation effect due to the contact interface, it is necessary to increase the number of integration points in the contact element. Oscillations are also related to instantaneous elastic deformations of the drawpiece walls that are not supported by the tool, and the associated numerical instabilities. For large element sizes, the force components become dependent on the relative position of the tool and on the points where

contact is evaluated. Due to numerical instabilities, a common method to present force variation is data filtering and the presentation of the averaged total force by combining the mean values [64].

The computational time of the simulations, taking into account different mesh densities, is presented in Table 2. It can be concluded that computation time is not directly proportional to the number of nodes. The calculation time for the selected mesh size of 1 mm is acceptable.

Table 2. Effect of the mesh size on the computation time.

Mesh Size, mm	Number of Elements	Number of Nodes	Computation Time
0.5	36,659	18,362	5 h 5 min
1	10,365	5215	1 h 47 min
2	3271	1168	42 min
4	1029	547	22 min

Predicting the components of the forming force is a fundamental task when optimizing the SPIF process and selecting the design of a forming tool. Figure 12 shows a comparison of the evolution of selected forming force components obtained experimentally and numerically (mesh size 1 mm) to improve our knowledge of the warm SPIF of Ti-6Al-4V VWACF. In the initial stage, the in-plane components (F_{xy}) of experimental forming force and axial force (F_z) increase until a certain depth of the drawpiece is reached. The in-plane force then tends to increase, but with lower intensity than in the initial stage. Meanwhile, the axial force (F_z) is reduced. This is caused by a reduction in deformation resistance by the more intense heating of the material. In the initial stage, the tool performs a circular motion along a trajectory with a large radius. Since the cone has a variable angle of inclination of its wall, as the depth of the extrusion increases, the tool contacts with the sheet metal more and more on the lateral surface. For this reason, the axial force F_z decreases (Figure 13) and the F_x and F_y components decrease, and consequently, according to Equation (1), the in-plane force F_{xy} increases (Figure 13).

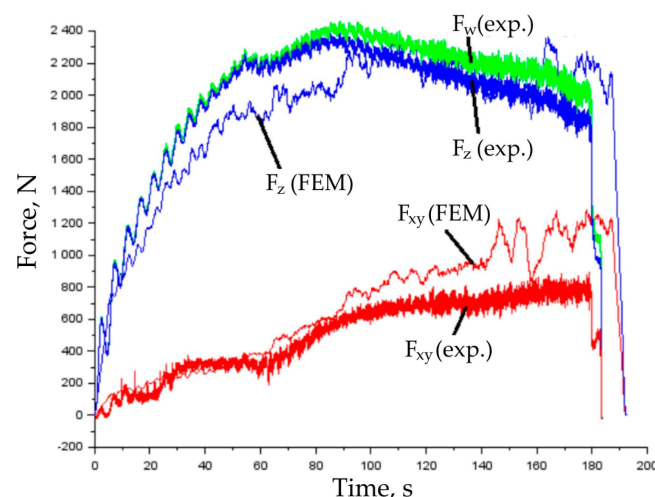


Figure 12. Variation of the forming force components (FEM vs. experiment).

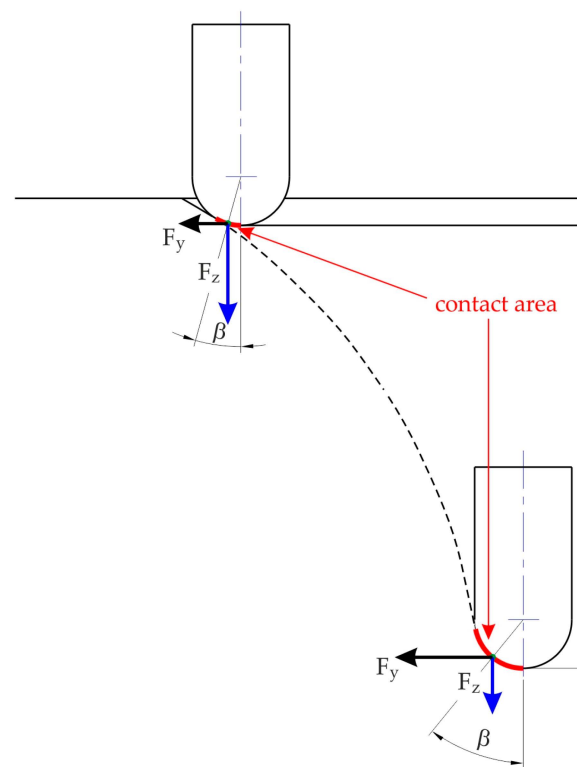


Figure 13. Variation of the F_y and F_z components of forming force along the generating line of VWACF drawpiece.

As the depth of the drawpiece increases, the trajectory during one axial revolution decreases. Meanwhile, the feed rate remains constant. In the final stage, both in-plane and axial components of the forming force predicted by the numerical model are overestimated. During the thermal imaging measurement, the maximum temperature of the tool was measured as approximately 326 °C. The temperature of the tool tip in the experimental conditions in the contact zone of the tool tip with the sheet metal could have been higher. However, it was impossible to measure the temperature in the contact zone during the forming process with the thermal imaging camera.

Figure 14 shows the distribution of the temperature at selected forming stages. As the forming time (drawpiece height) increases, the temperature accumulates in the area of contact of the tool tip with the workpiece (Figure 14c), which is associated with a decrease in the tool path radius and an intensification of frictional contact. The temperature increase as a result of friction stir rotation-assisted heating of the workpiece occurs only in the area of direct contact between the tool tip and the drawpiece. After passing the tool, the temperature gradually decreases. However, part of the thermal energy is transferred to the surroundings and to the remaining area of the drawpiece, which is heated with oil to a temperature of 200 °C.

The maximum values of the axial force F_z determined experimentally and numerically differ by approximately 8% (Figure 12). With respect to the in-plane force F_{xy} at the drawpiece depth of up to 9 mm, the experimental and numerical values of this force are in high agreement. After exceeding this depth, the numerically predicted in-plane force is approximately 23% greater. The numerical prediction of the forming force components allows for determining the stiffness of the tooling and the multiaxial load on the tool head at the design stage of the technological process [60].

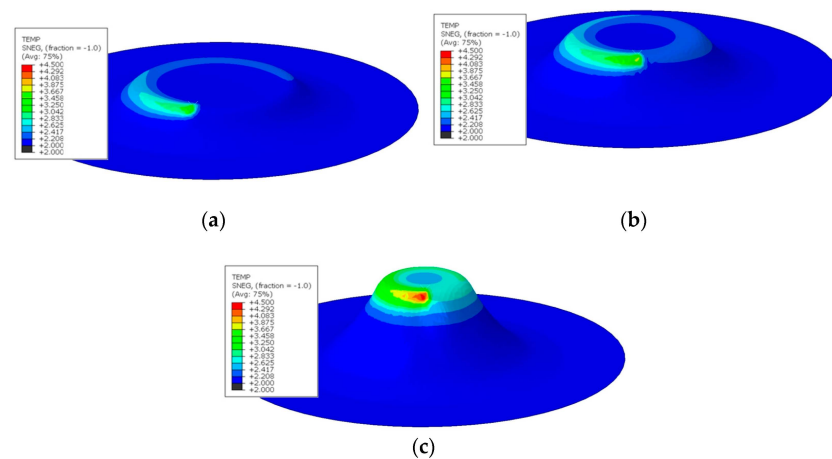


Figure 14. Distribution of the temperature for drawpieces with heights of (a) 7 mm, (b) 11 mm and (c) 21 mm (all values $\times 10^2$).

Figure 15 shows the evolution of equivalent plastic strain during the SPIF of the VWACF. In SPIF, the workpiece is formed mainly by thinning the side wall material. At this stage, the side wall is significantly loaded and the flow of material from the upper zone of the bottom to the side wall is limited. As the height of the drawpiece increases, the material undergoes strain-hardening. This phenomenon has a smaller effect to that seen during cold forming. However, this effect on material behavior in the warm-forming of Ti-6Al-4V titanium alloy is far from being negligible. It was also deduced by He et al. [65] that the strain path changes and the resulting accumulated equivalent strain could influence the work-hardening behavior of the material during the SPIF process. The bending and unbending behaviors remind us that, at a lower level, strains are imposed on the conventional sheet metal forming process.

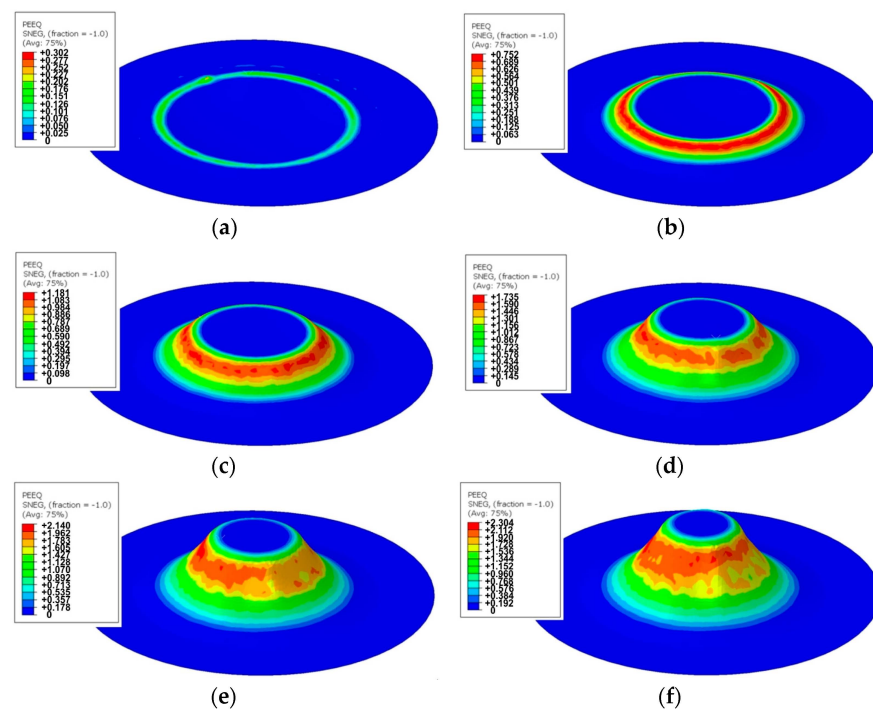


Figure 15. Distribution of the equivalent plastic strain for drawpieces with heights of (a) 1 mm, (b) 5.3 mm, (c) 9.9 mm, (d) 13.8 mm, (e) 17.5 mm and (f) 21.9 mm.

Comparison of sheet thickness distribution of the final drawpiece obtained using the finite element method, and the optical measuring system ARGUS (Figure 16) confirms the reliability of the developed FE-based model of the pressure-assisted warm-forming of Ti-6Al-4V sheets with the combined oil-heating and friction stir rotation-assisted heating of the workpiece. The smallest wall thickness predicted by the numerical model is 0.368 mm. Meanwhile, the smallest wall thickness of the experimentally formed drawpiece is 0.35 mm. The error is about 5%.

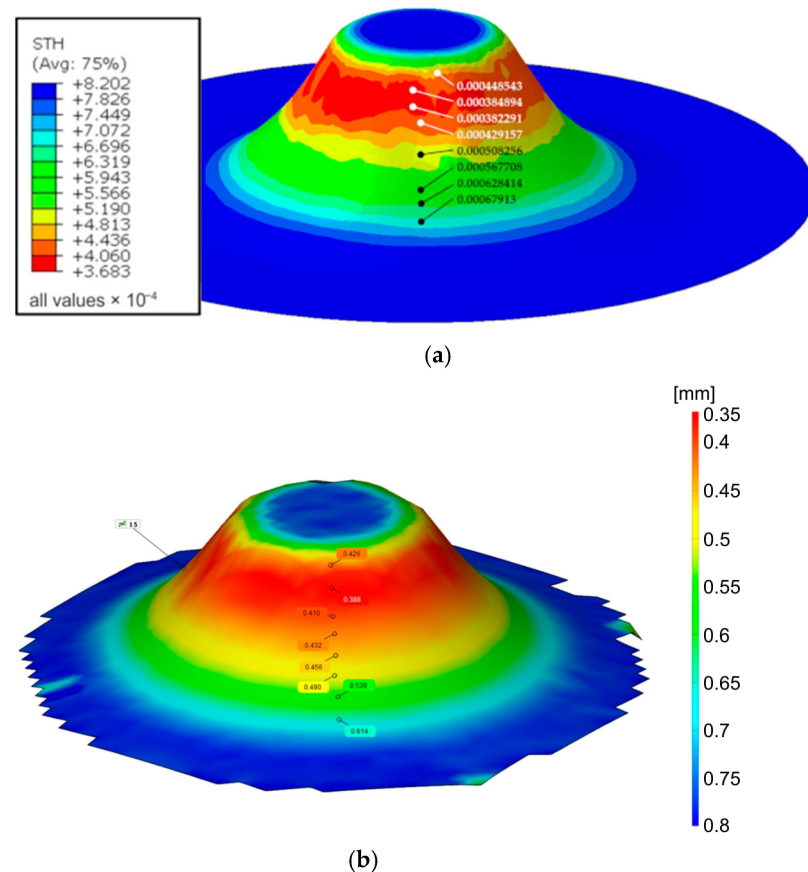


Figure 16. Comparison of sheet thickness distribution of final drawpiece obtained using (a) the finite element method and (b) the optical measuring system ARGUS.

4. Conclusions

This article presents the results of the numerical modeling of the pressure-assisted warm-forming of 0.82 mm-thick Ti-6Al-4V titanium alloy sheets with the combined oil-heating and friction stir rotation-assisted heating of the workpiece. Numerical studies were performed on the pressure-assisted warm SPIF process parameters, ensuring that we obtained the Ti-6Al-4V titanium alloy VWACF drawpiece with the greatest height, as specified in the authors' previous article [24]. The results of FE-based numerical simulations were validated on the basis of values of the axial forming force determined in a real SPIF process and the sheet thickness distribution determined using the ARGUS non-contact measuring system. Based on the obtained results, the following conclusions can be drawn:

- The greatest agreement between the FEM results and the experimental result of the axial component of forming force was obtained for finite elements with a size of 1 mm;
- The maximum values of the axial component (F_z) of forming force determined experimentally and numerically differ by approximately 8%;
- The numerically determined variation of the in-plane component (F_{xy}) of forming force is in high agreement with experimental results for a drawpiece depth range up

to 9 mm. After exceeding this depth, the FE-based model overestimates the value of in-plane force;

- As a result of friction stir rotation-assisted heating, with increases in the drawpiece depth, the temperature accumulates in the area of contact of the tool tip with the workpiece, which is associated with a decrease in the tool path radius and the intensification of frictional contact;
- The temperature increase as a result of friction stir rotation-assisted heating of the workpiece occurs only in the area of direct contact between the tool tip and the drawpiece. After passing the tool, the temperature gradually decreases. However, part of the thermal energy is transferred to the surroundings and to the remaining area of the drawpiece, which is heated with oil to a temperature of 200 °C;
- The comparison of sheet thickness distribution of the final drawpiece obtained using the experiment and finite element method confirms the reliability of the developed numerical model of pressure-assisted warm-forming with combined oil-heating and friction stir rotation-assisted heating of the workpiece. The error between numerically predicted and experimentally measured values of the minimum wall thickness of a Ti-6Al-4V drawpiece is about 5%.

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