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ANALYSIS OF THE INFLUENCE OF TOOL MODIFICATIONS ON THE SINGLE-POINT INCREMENTAL FORMING PROCESS OF CP-Ti Gr 2 AND Ti-6Al-4V TITANIUM SHEETS

This study focuses on the influence of modifications of the material and geometry of the forming tool on the process of single-point incremental forming of titanium sheets CP-Ti Gr 2 and Ti-6Al-4V. The aim of the research was to analyze the influence of variants of the tool material and modifications of the geometry in the form of grooves with different arrangements on the forming process and the quality of the obtained drawpieces. Additionally, the influence of lubricant type and the heating method on the efficiency of the process was examined. Forming CP-Ti Gr 2 sheets using lubrication grooves on the tools did not contribute to the surface roughness and deformation improvement of the drawpieces. The most favorable results for CP-Ti Gr 2 sheet were obtained using a tool made of Al_2O_3 ceramics reinforced with SiC whiskers, warming with heating oil and lubrication with rape-seed oil. In the case of Ti-6Al-4V sheets, it was found that the uncoated carbide tool allowed for the greatest deformation of the drawpiece compared to the tools coated with different coatings and whisker-reinforced ceramics. The use of coatings did not have a positive effect on the process in terms of the coefficient of friction, tool wear and the drawpiece deformation. The conducted studies allow for a better understanding of the relationship between tool modification and the efficiency of the single-point forming process of titanium sheets and the quality of the obtained drawpieces.

Keywords: Contact conditions; incremental sheet forming; titanium; tool material

1. Introduction

Single-point incremental forming (SPIF) is a type of sheet metal forming process that involves incremental deformation of a sheet metal using a tool moving along an appropriate trajectory. The advantage of SPIF is the possibility of obtaining greater plastic deformations of the sheet metal compared to conventional deep-drawing processes. This high formability is beneficial, but SPIF causes the formation of high residual stresses [1]. High residual stress values significantly increase the geometric deviations of the components after forming [2]. There are many methods for minimising or eliminating the springback phenomenon, by correcting the tool path, multi-stage forming or using two-point forming methods. Despite many advantages, the main disadvantage of SPIF is the long processing time associated with the gradual forming of the drawpieces. Nevertheless, SPIF is perfectly suited for manufacturing products in single-unit and small-series processing applications. Incremental forming can take place in cold plastic forming conditions or at elevated temperatures. The techniques for heating the charge, apart from friction stir rotation-assisted heating as a result of the cooperation of the tool with sheet metal, are analogous to those in conventional deep-drawing processes. Currently, SPIF applications encountered in the literature focus on the production of medical implants, aircraft components and automotive parts.

Optimal incremental forming requires the selection of appropriate parameters of the forming process, i.e., tool rotational speed, tool feed rate, forming strategy, step size, friction conditions, tool geometry and tool dimensions [3]. Forming parameters should be appropriately adapted to SPIF-ed part geometry (shape, inclination angle, and depth). The shape of ~~the~~ drawpiece determines the value of the forming limit strains. The optimal selection of these parameters is extremely difficult and requires time-consuming tests, often conducted by trial and error techniques [4]. The analysis of the literature indicates that the basic method of planning SPIF experiments is the Taguchi method using an orthogonal array experiments [5,6]. Due to many factors that simultaneously synergistically affect the SPIF

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process, authors often focus on the optimisation of a selected parameter, such as the surface roughness of the inner or outer surface of drawpiece [7], the tool path [8] or the geometric accuracy of parts manufactured by SPIF [9].

Contact phenomena occurring at the interface between tool surface and deformed sheet metal in SPIF technologies are more complex than in conventional sheet metal forming processes. A small contact zone between tool and semi-finished product causes the occurrence of large contact pressures, which increase resistance to friction. Friction in SPIF methods is difficult to analyse qualitatively and quantitatively due to the occurrence of severe mechanical interactions of the cooperating surfaces, one of which (the sheet metal) has much lower strength and hardness than the tool. This intensifies the phenomena of adhesive wear and mechanical flattening of surface asperities, directly affecting the surface quality of drawpieces. The basic method of reducing friction is the use of lubrication, application of anti-wear coatings on tools or texturing of working surfaces of tools [10,11]. In cold SPIF forming, analogous lubricants intended for conventional sheet metal forming are used. In plastic forming at elevated temperature, practically regardless of the material being formed, molybdenum disulfide (MoS_2) dominates [12,13].

The aim of the research, the results of which are presented in this article, was to determine the effect of tool material variants and anti-wear coatings, as well as tool geometry, on sheet metal formability and the quality of the obtained drawpieces. The SPIF tests were carried out for CP-Ti Gr 2 titanium and Ti-6Al-4V titanium alloy sheets. CP-Ti Gr 2 titanium sheets were formed using two methods: friction stir rotation-assisted SPIF and oil-based heating of workpiece. Meanwhile, titanium alloy sheets were formed under combined oil-based and friction stir rotation-assisted heating conditions.

2. Materials and methods

The incremental forming tests of drawpieces were carried out for 0.4-mm-thick CP-Ti Gr 2 titanium sheet and 0.8-mm-thick Ti-6Al-4V titanium sheet. Basic mechanical parameters of the test materials were determined in a uniaxial tensile test according to ENISO6892-1-2019 standard. The average values of the basic mechanical parameters were determined based on three repetitions. The yield strength (YS), ultimate tensile strength (UTS) and elongation (A) values for the CP-Ti Gr 2 sheet were 463.3 MPa, 616.7 MPa and 21.7%, respectively. The values of these parameters for the Ti-6Al-4V sheet were YS = 1013.7 MPa, UTS = 1072.3 MPa and A = 11.2%. The topographies of sheet metals in as-received state were measured using Bruker Contour GT 3D profilometer, in accordance with ENISO25178-2016. The values of basic surface roughness parameters Sa, Sz, Sp and Sv were determined. The CP-Ti Gr 2 sheet was characterised by the following values of these parameters: Sa = 0.458 µm, Sz = 4.63 µm, Sp = 2.17 µm and Sv = 2.46 µm. The surface of the Ti-6Al-4V sheet was characterised by the following parameters: Sa = 0.564 µm, Sz = 6.64 µm, Sp = 3.38 µm and Sv = 3.26 µm.

The device used in the tests (Fig. 1a)) consists of a body integrated with the base by means of a seal made of a material resistant to high temperature. The base contains heaters to heat the Jasol TERMOIL 6 oil, the temperature of which was dynamically set using a temperature controller. Before forming provess the temperature of workpiece in the forming area was elevated as a result of heat transfer from working oil. A valve with a pressure gauge is used to set the pressure of the working oil. Workpieces in the form of sheet metal discs were placed coaxially on the upper surface of the body and pressed by screws. The intermediate element between workpiece and upper surface

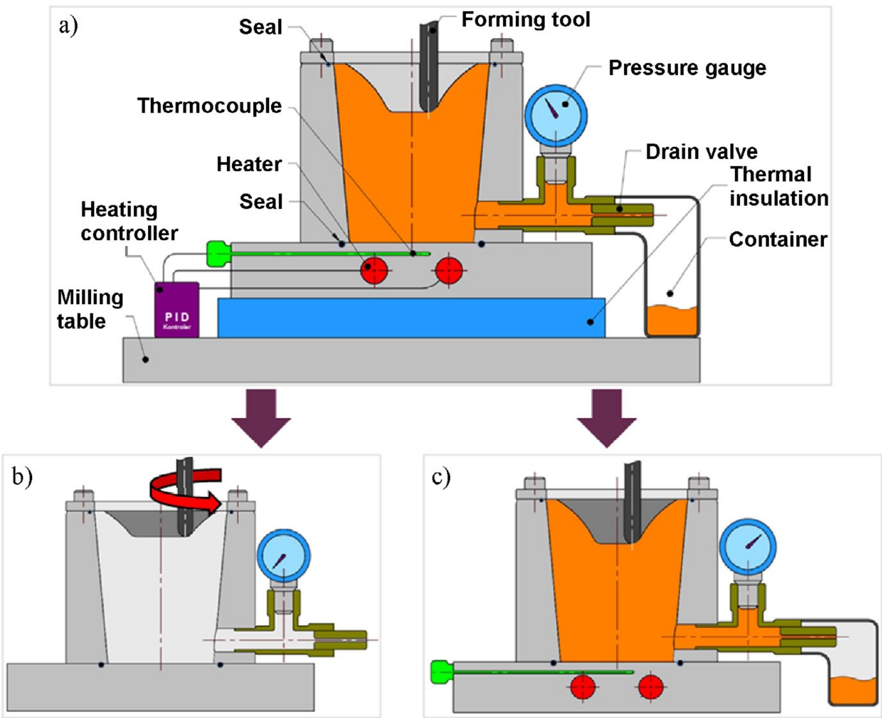

Fig. 1. a) model of the SPIF device in the configuration intended for forming b) CP-Ti Gr 2 and c) Ti-6Al-4V sheets

of the body is an annular seal. After removing the heating oil, the device (Fig. 1(b)) was used to carry out SPIF process with friction stir rotation-assisted heating of CP-Ti Gr 2 workpiece.

The test device was mounted on the table of a 3-axis vertical CNC milling machine Makino PS95 (Fig. 2). A Kistler piezoelectric plate type 9366C was also used to record the F_x, F_y and F_z components of the forming force. The formability of the sheets in SPIF was discussed in the authors' earlier works [14,15], where the geometry of the formed drawpieces was also explained.

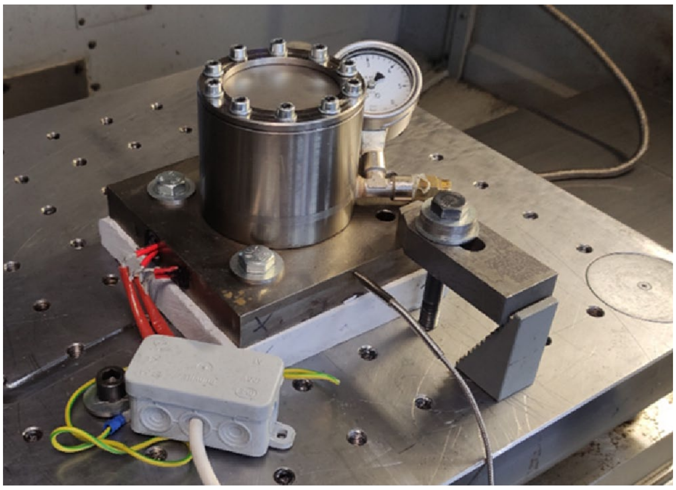

Fig. 2. Photograph of the research stand

(Fig. 3). The measured output parameters of the process were defined as forming force components (axial force and in-plane force) and surface roughness parameters of the inner surface of drawpiece. Selected surface roughness parameters (*Sa*, *Sz*, *Ssk*, *Sku*, *Sdq*) were measured using an Alicona Infinite Focus G4 microscope. As a result of searching for tool solutions for SPIF of CP-Ti Gr 2 titanium sheets, 20 tests were carried out successively (TABLE 2) according to the experimental input parameters presented in TABLE 1.

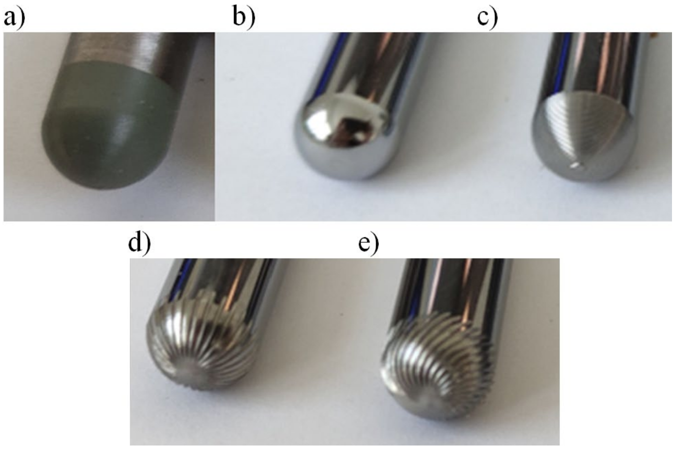

Fig. 3. Tool variants for testing: a) Al_2O_3 ceramics reinforced with SiC whiskers, b) cemented carbide tool, smooth tip; c) cemented carbide tool, spiral grooves with a pitch of 0.5 mm; d) cemented carbide tool, longitudinal grooves; e) cemented carbide tool, spiral grooves at an angle of 45°

3. Results and discussion

3.1. CP-Ti Gr 2 titanium sheet forming

After determining the optimal parameters according to the given criteria [15], additional studies were carried out on the possibilities of improving the SPIF process. An experimental plan was built according to three input factors: lubricant, tool type and heating method (TABLE 1).

For each of the tests, it was planned to use the previously obtained optimal forming parameters, whereby in the case when workpiece was oil-based heated, the tool rotation was turned off and the tool was allowed to roll freely on sheet metal surface during forming. The heating oil was heated to 200°C and maintained at a pressure of 4 bar. For friction stir rotation-assisted tests, the oil container was emptied and the heaters were turned off. As the second factor of the experiment, two types of lubricant were selected: environmentally friendly rape-seed oil and solid MoS_2 grease. Five variants of tool geometry were selected

The result of the 20 experimental tests carried out with the optimal parameters determined in [15], 10 drawpieces were successfully formed, while the remaining 10 drawpieces were prematurely damaged (TABLE 3). It can be observed that the grooves on tool surface, which were supposed to contribute to the improvement of lubrication, worsened the surface quality of the obtained drawpieces. For frictional heating, it was not possible to successfully perform any test using tools with grooves. In the variant when the workpiece was heated with oil, only one type of tool with grooves (test no. 17 and 18) was able to successfully form the drawpieces with the intended height.

It was observed that the use of Al_2O_3 ceramics reinforced with SiC(w) whiskers, oil-based heating together with lubrication with rape-seed oil contribute to the best quality of inner surface of drawpiece in terms of the Sa parameter in relation to other tests (Figs. 4-6). The lowest surface roughness parameter Sz was obtained for tests realised with a carbide tool with a smooth tip

TABLE 1

Experiment input parameters

Factor	Name	Level 1	Level 2	Level 3	Level 4	Level 5
A	lubricant	Rapeseed oil	MoS_2	—	—	—
B	tool type	Al_2O_3 ceramics reinforced with SiC whiskers	cemented carbide tool, smooth tip	cemented carbide tool, longitudinal grooves	cemented carbide tool, spiral grooves at an angle of 45°	cemented carbide tool, spiral grooves with a pitch of 0.5 mm
C	heating method	friction-based heating	oil-based heating	—	—	—

TABLE 2

Experiment plan for tool modification

Trial no.	Factor 1 A: Lubrication	Factor 2 B: Tool type	Factor 3 C: Heating method
1	rapeseed oil	Al_2O_3 ceramics reinforced with SiC whiskers	friction-based heating
2	MoS_2		
3	rapeseed oil	cemented carbide tool, smooth tip	
4	MoS_2		
5	rapeseed oil	cemented carbide tool, longitudinal grooves	
6	MoS_2		
7	rapeseed oil	cemented carbide tool, spiral grooves at an angle of 45°	
8	MoS_2		
9	rapeseed oil	cemented carbide tool, spiral grooves with a pitch of 0.5 mm	
10	MoS_2		
11	rapeseed oil	Al_2O_3 ceramics reinforced with SiC whiskers	oil-based heating
12	MoS_2		
13	rapeseed oil	cemented carbide tool, smooth tip	
14	MoS_2		
15	rapeseed oil	cemented carbide tool, longitudinal grooves	
16	MoS_2		
17	rapeseed oil	cemented carbide tool, spiral grooves at an angle of 45°	
18	MoS_2		
19	rapeseed oil	cemented carbide tool, spiral grooves with a pitch of 0.5 mm	
20	MoS_2		

TABLE 3

Results of experimental studies on the formation of CP-Ti Gr 2 titanium drawpieces

Trial no.	Response 1 In-plane force, N	Response 2 Thrust force, N	Response 3 *Sa*, µm	Response 4 *Sz*, µm	Response 5 *Ssk*	Response 6 *Sku*	Response 7 *Sdq*
1	376	584	2.0428	48.1239	0.452	4.199	0.2336
2	335	607	4.1529	114.284	0.728	10.5454	0.5424
3	403	578	2.4133	26.782	0.3881	3.4459	0.2685
4	340	608	3.5403	95.7812	1.0384	7.4427	0.4059
5	damage of the drawpiece						
6	damage of the drawpiece						
7	damage of the drawpiece						
8	damage of the drawpiece						
9	damage of the drawpiece						
10	damage of the drawpiece						
11	503	616	1.0327	34.8175	–1.3321	7.626	0.1722
12	301	661	2.0977	23.7304	–0.7423	3.4515	0.3172
13	514	628	1.1045	19.8124	–1.2664	5.9015	0.166
14	331	718	1.9691	40.8025	–0.164	4.6367	0.2908
15	damage of the drawpiece						
16	damage of the drawpiece						
17	452	608	4.1132	118.7419	2.0153	16.6731	0.5702
18	407	637	3.8838	80.6284	1.3021	10.9218	0.5408
19	damage of the drawpiece						
20	damage of the drawpiece						

and using rape-seed oil for both variants of workpiece heating. The lowest value of thrust force and in-plane force was achieved for tool with a tip made of SiC(w)-reinforced Al_2O_3 ceramic tool.

The use of oil heating is more labor-intensive and energy-intensive compared to friction stir rotation-assisted heating. This approach requires appropriate adjustment of the valve, heating of device and workpiece to set temperature. The advantage is better surface quality of the drawpiece for all of the tests, with the same other process factors. For incorrectly selected process parameters, when the sheet metal is damaged (Fig. 6b), heating oil escapes due to the pressure in the container and may pose a threat to the operator or cause damage to machine. In addition, during the change of workpiece, heated oil volatilise into the atmosphere. During forming with a spiral-groove carbide

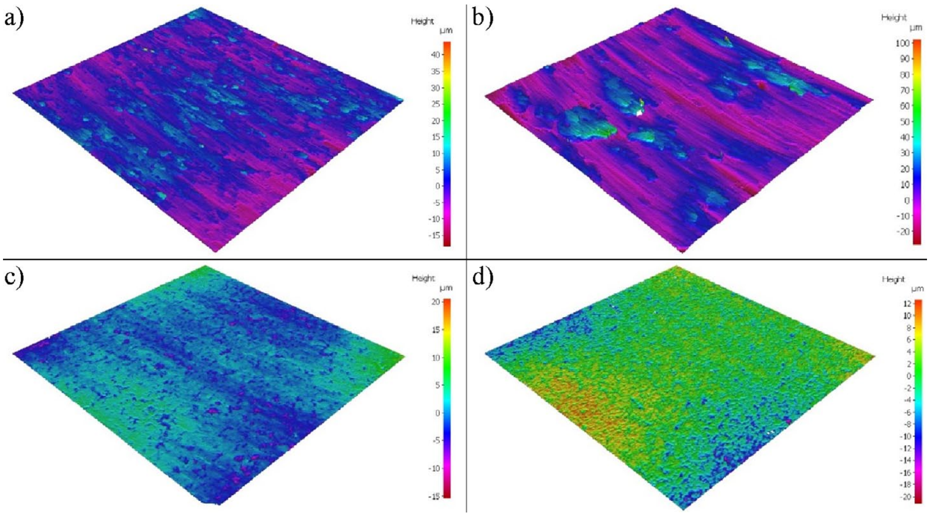

Fig. 4. Topography of the inner surface of drawpieces made with a tool with a Al_2O_3 + SiC(w) tip: a) friction-based heating + rape-seed oil, b) friction-based heating + rape-seed oil + MoS_2, c) oil-based heating + rape-seed oil and d) oil-based heating + MoS_2

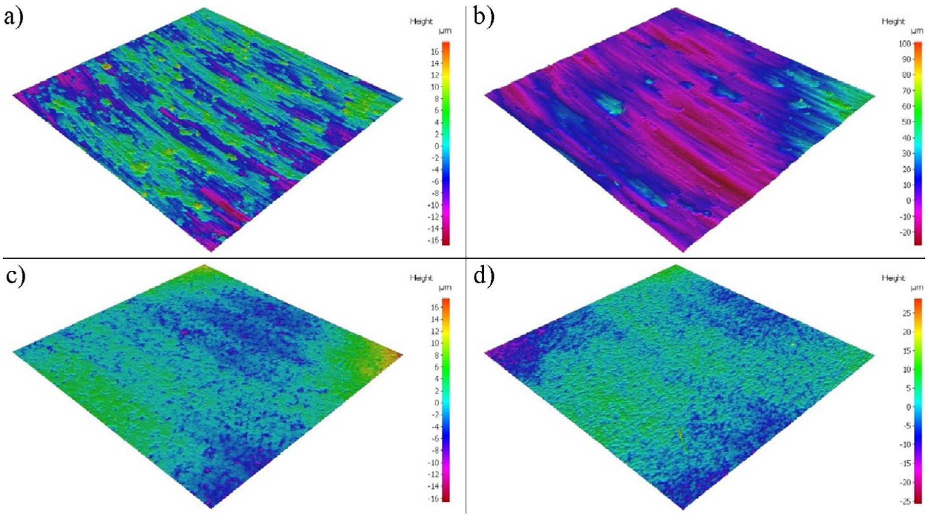

Fig. 5. Topography of the inner surface of drawpieces made with a cemented carbide tool with smooth surface: a) friction-based heating + rape-seed oil, b) friction-based heating + rape-seed oil + MoS_2, c) oil-based heating + rape-seed oil and d) oil-based heating + MoS_2

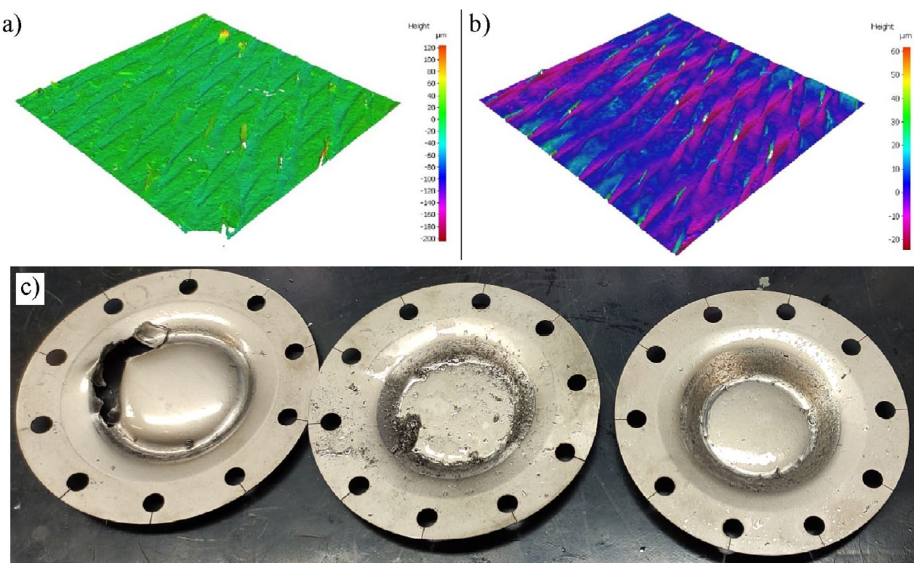

Fig. 6. Topography of the inner surface of drawpieces formed with a cemented carbide tool with a spiral grooves: a) oil-based heating + rape-seed oil, b) oil-based heating + MoS_2 and c) damaged drawpieces due to the use of tools with lubrication grooves

tool under friction stir rotation-assisted heating conditions, the drawpieces were damaged. The topographies of the drawpieces formed with a spiral-groove tool during oil-based heating are shown in Figs. 6(a) and 6(b).

3.2. Ti-6Al-4V titanium alloy drawpieces

The experiments were carried out using a factorial design, which allows for the evaluation of influence of two independent variables – tool rotational speed and type of tool material – on the formability and surface quality of drawpieces. The remaining parameters such as feed rate of 500 mm/min, step size 0.5 mm, oil-based heating temperature of 200°C and oil pressure of 4 bar were set constant [14]. Ten different combinations of tool material and tool rotational speed were used to create an experimental plan (TABLE 4). The measured value in the experiment was the maximum formable wall angle, which is a key parameter in assessing the obtained material deformation. This angle was measured for each combination of tool rotational speed and tool material in order to assess the effect of these factors on the change in drawpiece geometry. In addition, the type and amount of tool wear were assessed by using a Zoller genius 3s measuring machine.

Physical vapour deposition (PVD) coatings were selected based on the manufacturers' recommendations (SHM s.r.o., Oerlikon Balzers Coating Poland Sp. z o.o., ION Galenica Sp. z o.o.) for the plastic forming of titanium and its alloys. Additionally, whisker-reinforced ceramic tool from Greenleaf Corporation, intended for use at elevated temperatures, was also used.

In the context of the incremental forming process for titanium or its alloys, one of the key challenges is to ensure high shape and dimensional accuracy and high surface quality of the final components. The selection and application of tools, both coated, uncoated and whisker-reinforced ceramics, is crucial to achieve the desired results. As a result of the conducted forming tests using different variants of tool material, two dominant tool wear criteria were defined: catastrophic wear with a rupture of the sheet material after exceeding the tool rotational speed value of 1000 rpm and wear due to the formation of a built-up edge as a result of frictional interaction of tool surface and sheet metal surface. Adhesion of the sheet metal material on tool surface can lead to significant problems with dimensional accuracy, because the built-up edge changes tool shape. Moreover, the built-up edge has a strong effect on the surface roughness of the inner surface of drawpiece.

Tool coatings play a key role in protecting tools from accelerated wear, especially at elevated temperatures. Coatings based on titanium nitride (TiN) or aluminium nitride (AlN) are commonly used to improve tool wear resistance and reduce friction between the tool and workpiece. As observed by Li et al. [16], PVD coatings can effectively protect against high temperatures and aggressive environments. Whisker-reinforced Al_2O_3 ceramics are another innovative alternative for tools, offering exceptional resistance to wear and high temperatures. Whiskers can significantly improve the mechanical properties of ceramics, increasing their strength and fracture toughness [17].

The SPIF process of the varying wall angle conical frustums was carried out for different tool materials and for the two tool

TABLE 4

Independent input variables of the experimental studies

Factor	Name	Unit	Type	Minimum	Maximum
A	tool rotational speed (n)	rpm	numerical	100	1000
B	tool material	—	categorical	cemented carbide (CC), CC + AlCrN, CC + TiSiXN, CC + ZrN, Al_2O_3 ceramics reinforced with SiC whiskers	

TABLE 5

Results of tests aimed at selecting the most advantageous tool variant

Trial no.	Factor 1	Factor 2	Response 1	Response 2
	A: Tool rotational speed (*n*), rpm	**B: Tool material**	**The maximum formable wall angle α_m, °**	**Tool build-up b_u, µm**
1	100	Cemented carbide (CC)	55	7.7
2	1000	CC	65	
3	100	CC + AlCrN	51	126.6
4	1000	CC + AlCrN	63	
5	100	CC + TiSiXN	52	11.6
6	1000	CC + TiSiXN	61	
7	100	CC + ZrN	51	13.1
8	1000	CC + ZrN	60	
9	100	Al_2O_3 ceramics reinforced with SiC whiskers	50	damage of the tool during trial no. 10
10	1000	Al_2O_3 ceramics reinforced with SiC whiskers	60	

rotational speeds, that is, 100 rpm and 1000 rpm. The remaining parameters of the SPIF process, i.e. oil pressure (4 bar), tool feed rate (2000 mm/min) and step size (0.5 mm) were considered constant.

In order to select the most advantageous tool for SPIF process of Ti-6Al-4V sheet, the varying wall angle conical frustums and tool build-up were merasured. The results of initial tests aimed at selecting the most advantageous tools for further analysis of SPIF process are presented in TABLE 5.

By analysing the heights of obtained drawpieces and converting them into the angle of the wall according to Eq. (1), it is possible to assess which of the tools allowed for obtaining a greater deformation (Fig. 7) [18,19].

$$\alpha_m = \arccos\frac{41.2 - h_w}{47.6} \tag{1}$$

where h_w is height of drawpiece.

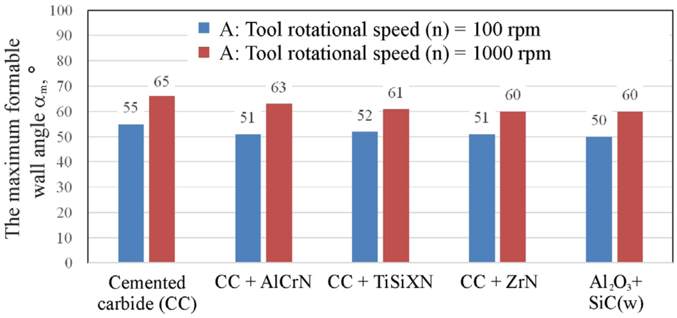

Fig. 7. The maximum formable wall angles of drawpieces obtained for two tool rotational speeds and five tool material variants

It can be clearly stated that both for the low tool rotation speed of 100 rpm and the high speed of 1000 rpm, the largest wall angle of drawpiece was obtained for the uncoated tool made of cemented carbide. This suggests that the use of coatings or ceramic tool does not improve the forming conditions in the SPIF of the Ti-6Al-4V drawpieces. A positive effect of increasing the tool rotation speed on improving the formability of sheet material can be observed. This results from the creation of a higher temperature at the tool-sheet metal interface, which favours the sheet material to experience greater plastic deformations without the risk of rupture. The tool geometry was measured before the forming tests (Fig. 8) and then they were measured again taking into account their wear after SPIF tests (Fig. 9).

The basic symptom of tool wear observed was the build-up on the tip of forming tool. Its amount was assessed and compared between the tool variants considered (Fig. 10). The observations show that the uncoated cemented carbide tool achieved the lowest amount of build-up.

Analysis of the variation of forming force components and calculation of the coefficient of friction for the selected tools did not show any significant discrepancies (Fig. 11). This means that the use of coatings or changing the tool material does not contribute any significant features to improving the forming process of Ti-6Al-4V sheets in terms of friction. This may be due to the adhesion of the formed sheet to the tool and build-up, as a result of which there is no real contact between tool substrate material and deformed sheet. Taking into account the obtained deformation of the drawpieces using several tool variants, their type and amount of wear and lack of influence of tool type on the coefficient of friction, an uncoated tool made of cemented carbide should be proposed for SPIF forming of Ti-6Al-4V titanium alloy sheets.

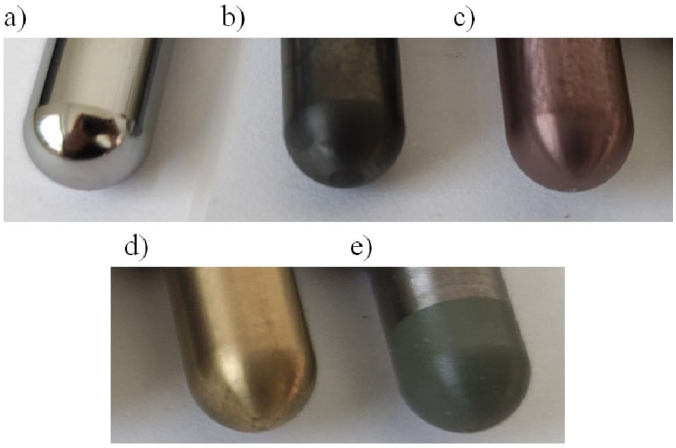

Fig. 8. View of tool tips before testing, tool variants: a) cemented carbide (CC), b) CC + AlCrN, c) CC + TiSiXN, d) CC + ZrN, e) Al_2O_3 ceramics reinforced with SiC whiskers

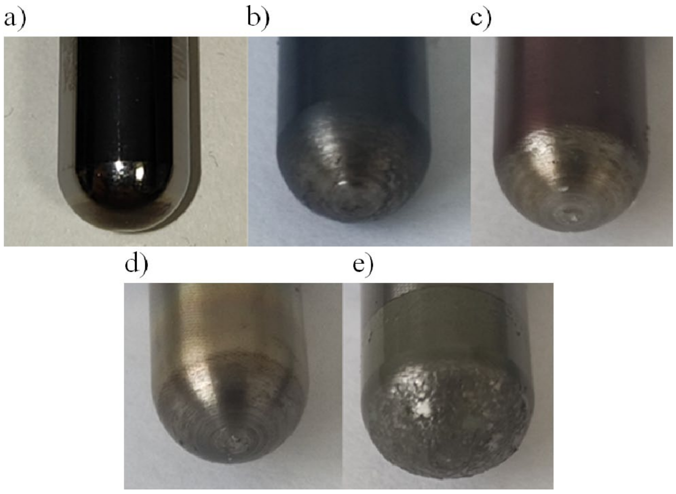

Fig. 9. View of tool tips after forming, tool variants: a) cemented carbide (CC), b) CC + AlCrN, c) CC + TiSiXN, d) CC + ZrN, e) Al_2O_3 ceramics reinforced with SiC whiskers

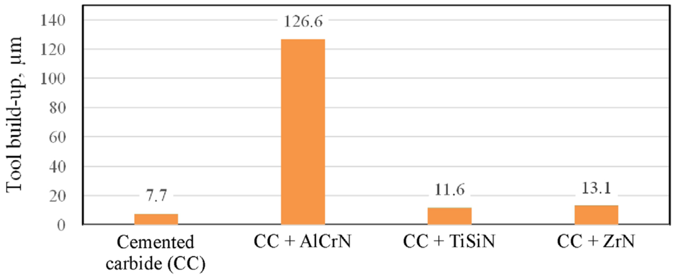

Fig. 10. Measured amount of build-up on tested tool variants (after tests)

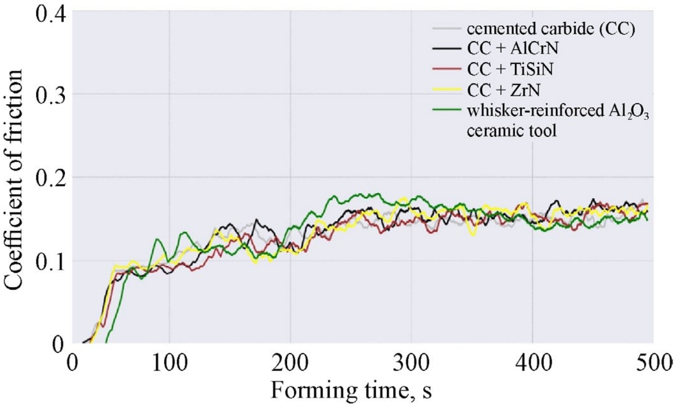

Fig. 11. Variation of the coefficient of friction during SPIF process for a tool rotational speed of 1000 rpm

4. Conclusions

Based on the conducted experimental investigations of the effect of tool type on formability of titanium sheet metals, the quality of the inner surface of drawpieces and the tool wear, the following conclusions can be drawn:

1. During the forming of CP-Ti Gr 2 sheets, rape-seed oil reduces the surface roughness parameters (*Sa*, *Sz*), while increasing the in-plane component of forming forces, compared to lubrication with the MoS_2 grease.
2. Friction stir rotation-assisted heating of CP-Ti Gr 2 sheets results in higher surface roughness parameters *Sa* and *Sz* compared to oil-based heating.
3. When forming CP-Ti Gr 2 sheets, the Al_2O_3 ceramic tool generates lower forming forces compared to the cemented carbide tool, regardless of the heating method. In addition, the whisker-reinforced ceramic tool provides better surface quality of the formed CP-Ti Gr 2 drawpieces.
4. The use of an uncoated cemented carbide tool contributed to achieving the highest deformation of Ti-6Al-4V titanium alloy drawpieces.
5. The use of several variants of PVD coatings contributed to the increased build-up on cemented carbide tools during the forming of Ti-6Al-4V sheets, which may result in shape errors of drawpiece and a lower quality of its inner surface.
6. The reason for the similar coefficient of friction for the tested tools was the adhesion of the sheet metal material to the tool surface.
7. Taking into account the quality of the inner surface of drawpiece, the amount of built-up edge and the surface quality of tool after forming, an uncoated cemented carbide tool made of cemented carbide was the most suitable for SPIF of Ti-6Al-4V sheet.

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