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Investigating the Impact of Tool Velocity on the Process Conditions in Incremental Forming of Titanium Sheets

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Abstract

This paper deals with a study focused on the single point incremental forming (SPIF) of titanium Grade 2 sheets. The direct impact of the sliding velocity of the forming tool on mechanical and thermal process loads was experimentally investigated. A wide range of spindle speeds and feed rates were examined at different forming conditions. The developed profiles of the mechanical and thermal demands during the SPIF of titanium sheets are presented and discussed. Forming temperature and force were directly related to the tool rotation speed, higher temperatures and lower reactional forces correspond to higher speeds. At very high rotation, failure conditions occurred and the ability to shape a CP Grade 2 sheet is decreased; these failures were mainly due to extreme heating, leading to termination of the tests concerned. The main objective of the study is to gain a better understanding of the combined effects that the varied relative motions at the tool/sheet contact zone have on the process conditions.

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Keywords: Incremental sheet forming; Themomechanical demands; Titanium Grade2

1. Introduction

Titanium Grade 2 also known as CP Grade 2 is usually selected as the sheet material because of its outstanding corrosion resistance, particularly in applications where high strength is not required (given that its tensile strength is < 340 MPa). Forming temperature is a decisive factor affecting the processing of titanium alloys and is responsible for the phase changes in its microstructure. During the metal forming operation, the surface of the forming tool and

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of the deforming material are in direct contact with each other, and the friction at their interface plays a major role. Localised temperature gradient and deformation generate microstructural changes along the forming path of the workpiece [1]. As a result, non-uniform material properties can be produced over the workpiece, which in turn impacts on the quality and performance of the produced component.

In state-of-the-art of SPIF, it is particularly the mechanical forces and their dependency on process variables that have widely been researched. A limited attention has, however, been applied to the process thermal conditions [2]. According to some publications [3–5], it is presumed that the upper limit of a practical forming rate is governed by the maximum feed rate achievable by the CNC machine. Hussain et al.[6] studied the formability of CP Grade 2 in SPIF by running different forming strategies; they observed a significant rise in titanium temperature with increased feed rate, although they did not present details on the order of these temperatures. Furthermore they reported a decrease in the formability of titanium with an increase in the forming feed rate. It has to be stated, however, that their CNC machine was subjected to some constraints during testing, and accordingly experiments were performed using a non-rotating forming tool; this may have affected friction conditions at tool/sheet interface. Ambrogio et al. [4] investigated the effect of extreme feed rates on the CP Grade 2 and Ti6Al4V alloys. Instead of a conventional milling machine, they used a novel technique, mounting experimental apparatus on a CNC lathe to allow increased feasible speeds up to 600 m/min. They used a tool holder incorporating bearings to allow free tool rotation, with the workpiece clamped in the lathe spindle. They concluded that increasing the feed rate has a negligible effect on both the microstructure and the hardness of CP Grade 2. In their discussion the authors mentioned that there were signs of high forming temperatures, but they did not provide any details on the magnitude of these temperatures.

As summarised in the preceding discussion, the forming conditions (the non-rotating tool and the lathe machine with a rolling tool) described and implemented by Ambrogio et al. and Hussain et al. [4,6] deviate slightly from a standard SPIF process done typically on a milling machine. But to the knowledge of the authors of this paper, little information on the thermal demands of the SPIF process has been published, and there is even less information on the SPIF process involving titanium sheets. Quantitative knowledge of frictional heat and the forces at the tool/sheet interface is crucial for adequate design of the SPIF of CP Grade 2. The work presented in this paper fits into a broader study and series of experimental campaigns that have been directed toward understanding the correlation between the key design factors in SPIF and the process outcomes. The ultimate goal is to establish a process map for the SPIF of CP Grade 2 [7]. In this paper an experimental study has been performed in order to investigate the influences of the tool rotation, ω_t and feed rate, f_r on the thermo-mechanical loads in the SPIF of CP Grade 2 sheets.

2. Experimental setup and design

A summary of the experimental setup and process settings that have been used in the tool speed tests is given in this section. Figure 1(a) depicts a fixture developed to be attached to a force dynamometer and bolt-mounted onto the CNC table.

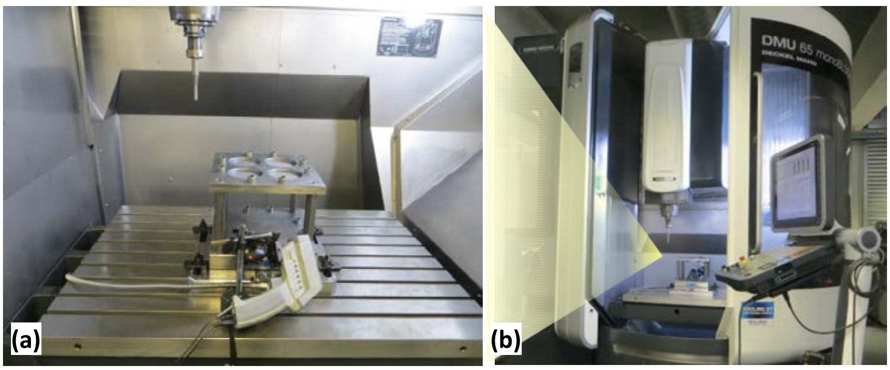


Figure 1: Depiction of the test platform: (a) the fixture, the dynamometer, and the IR-camera (b) the CNC machine

The experimental work was performed at the facilities of the Stellenbosch Technology Centre - Laboratory for Advanced Manufacturing (STC-LAM). The DMU 65 FD monoBlock 3-axis CNC machine (see Figure 1(b)), equipped with stationary table was employed. A commercial CAD/CAM Package from Delcam, PowerSHAPE and PowerMILL were respectively used to generate the benchmark geometry and the toolpath. A varying wall angle conical frustum (VWACF) was identified as the test benchmark. The CAD model of the VWACF shown in Figure 2, has maximum inner diameter of 56 mm and a height of 25 mm. The model drawing angle starts from $\theta_i = 30°$ at the sample opening and extends to $\theta_{max} = 75°$ at the bottom of the cone. All the test parts (samples) were produced using a 3D spiral, out-to-in toolpath, with a fixed step-down, Δ_z value of 0.3 mm.

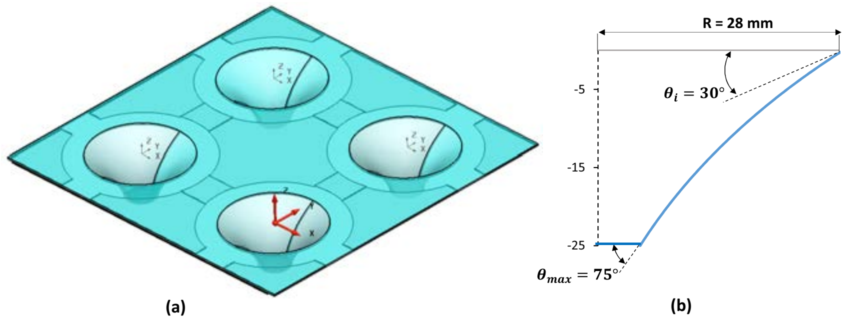


Figure 2: Illustration of the varying wall angle conical frustum benchmark; (a) the CAD model, (b) the geometrical details.

Data acquisition was facilitated through an IR camera for measuring the forming temperature and a Kistler dynamometer to pick up the forming forces. All test specimens were CP Grade 2, in the form of 0.8 mm thick sheeting. The specimens had overall dimensions of 190 mm × 190 mm, and were fitted symmetrically over the four working spaces. To intensify pyrometer (IR camera) readings of the forming temperature, the underside of the specimens was spray-painted to enhance and unify the emissivity of the titanium specimens. The forming tool has a hemispherical tool-tip with a 10 mm diameter stem made of tool steel 2312 and heat-treated using the TUFFRIDE process. Molybdenum disulphide (98.5% pure MoS_2) powder was used as a lubricant during the forming operations.

3. Experimental results and discussion

In Table 1, a summary of the setting of the variables, as well as the obtained response data from the two types of one factor at a time (OFAT) experiment are presented. In cases where a sheet fractured, or extreme heating occurred during the experiments, the test run was immediately stopped, otherwise the test continued until the design depth of 25 mm was reached. In Sections 3.1 and 3.2 the results for temperature, forming forces and formability for each test respectively, are presented.

Table 1: The layout of SPIF experiments and the obtained responses

Run	*Sheet*	*Feed*	*Tool*	*Step*	*Speed*	*Temperature*		*Force*		*Formability*	
No	t_0	f_t	d_t	Δ_z	ω_t	T_{max}	T_{ref}	F_z	F_x	Depth	Angle
	mm	mm/min	mm	mm	rpm	°C	°C	N	N	mm	deg
C39	0.8	625	10	0.30	**450**	90	42	603	600	18.5	63
C40	0.8	625	10	0.30	**900**	117	49	560	500	17.8	62
C41	0.8	625	10	0.30	**1500**	152	67	508	420	16.2	59
C42	0.8	625	10	0.30	**2500**	177	84	483	380	14.9	57
C43	0.8	625	10	0.30	**4000**	372	183	226	250	16.4	59
C44	0.8	625	10	0.30	**5500**	335	245	124	170	7.9	44
C45	0.8	625	10	0.30	**7500**	343	342	94	94	6.8	42
C46	0.8	625	10	0.30	**15000**	----	296	53	63	1.7	33
C51	0.8	**1200**	10	0.30	1940	195		544	410	14.9	56
C52	0.8	**2000**	10	0.30	1940	242		526	400	14.7	56
C53	0.8	**4000**	10	0.30	1940	181		546	500	15.1	57
C54	0.8	**10000**	10	0.30	1940	186		594	550	15.7	58

3.1. Effect of tool rotational speed

The tool rotational rate, ω_t ranged from 450 rpm to 15 000 rpm, while all the other process settings were kept at their reference values as shown in Table 1. The profiles of the measured temperatures verses forming time, are illustrated in Figure 3. To obtain a sensible comparison between the eight runs, a reference temperature reading was taken for each run at the same cycle time of 360 s, being a common point for the temperature profiles.

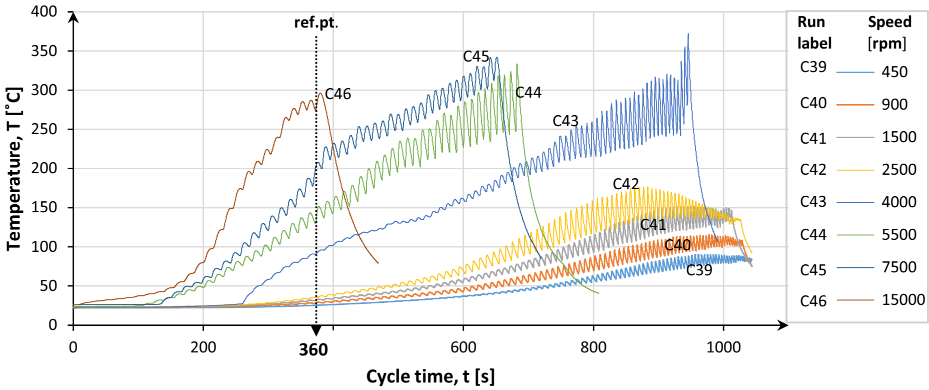
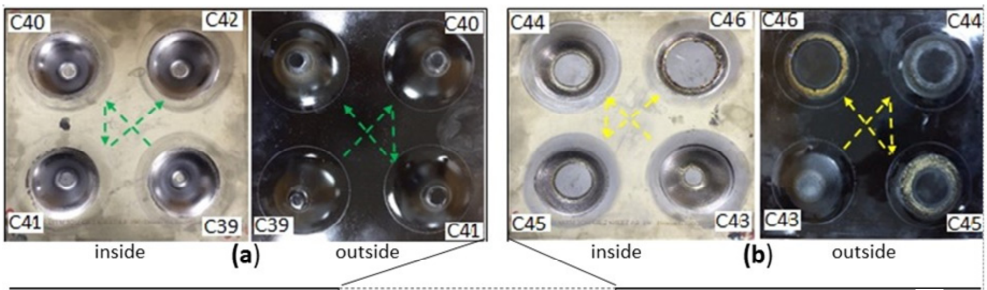


Figure 3: Illustration of temperature gradients at different spindle speeds

As it can be seen at the reference point (dotted line in Figure 3), the temperature profiles are directly related to the spindle speeds; following the order of run labels, higher temperatures correspond to higher speeds. Figure 4, depicts the eight formed samples. The dashed arrows show the sequence of the runs, so that they can easily be matched with their settings in Table 1 and temperature profiles in Figure 3. On the inside of the samples shown in Figure 4(a) an improvement of surface quality in terms of a reduced waviness effect in direction of tool feed was observed at increased speed. On the external surface though, following the direction of the arrow, there is slight decrease in quality manifested by a defect which is known in sheet forming as the orange peel (OP) phenomena; this is particularly apparent on the last two runs.

Regarding the second test run depicted in Figure 4(b), it is evident that there are speed effects on both surfaces of the produced samples. In this test, even at 4000 rpm, a rough surface occurred on the inner side due to the removal of titanium material, while on the outer surface a coarse OP effect developed. Also, following the same order as indicated by the arrows in the second test, there is obvious deterioration of the inner surfaces, together with evidence of material removal which increased at higher tool rotations.



C39	C40	C41	C42	Run label	C43	C44	C45	C46
450	900	1500	2500	Tool speed, ω_t [rpm]	4000	5500	7500	15000
35	43	53	65	Temperature, T_{-ref} [°C]	152	246	294	325
63	62	59	57	Forming angle θ_{max} [deg.]	59	44	42	33

Figure 4: Depiction of titanium samples formed in the rpm test (note that inside and outside views are mirror images): (a) large formed depth at relatively low rpm; (b) rise of thermal defects and failure with increased rpm

Of more concern was the reduction of the forming angle (see Figure 4) obtained at speeds above 4000 rpm; these test runs were stopped early because of manifestation of overheating conditions. The increased temperature caused glowing of the forming tool, and sparking of titanium particles at the tool-tip/sheet interface. This finding is in contrast to the observations of some researchers [3,8,9] which reported that the formability of aluminium sheets was improved with higher tool rotation.

Figure 5 highlights the relationship between the forming forces and the reference temperature (T-ref) at different tool rotational speeds. Both the axial force, F_z and in-plane force, F_x decreased with an increase in tool rotation.

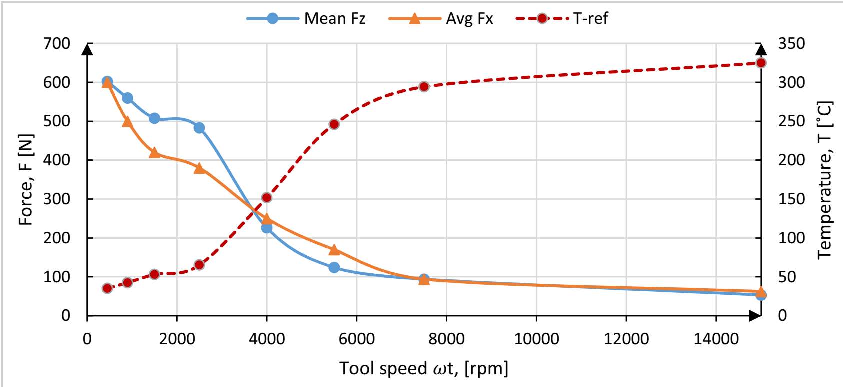


Figure 5: Illustration of the relationships between tool rotation and process thermal and mechanical loads

In the first two runs with lower spindle speeds, the drop in the forces is attributed to the decreased sliding friction, and not to softening of the titanium material because the maximum temperature did not exceeded 120°C. As the rotational speed of tool was stepped up, forces were determined by the combined effect of the reduced friction and the evolving heat. The heat effect was dominant for the last four runs with higher rotation contributing to the softening of the titanium workpieces and significantly reduced force; temperatures surpassed 330°C.

3.2. Effects of the tool feed rate

In this work, tool feed rates were experimentally examined over a wide range, starting at a low speed of 1200 mm/min, which was increased up to 10000 mm/min, while keeping the other process variables at their reference values as listed in Table 1. Figure 6 is a graphical illustration of the measured temperature during the feed speed test.

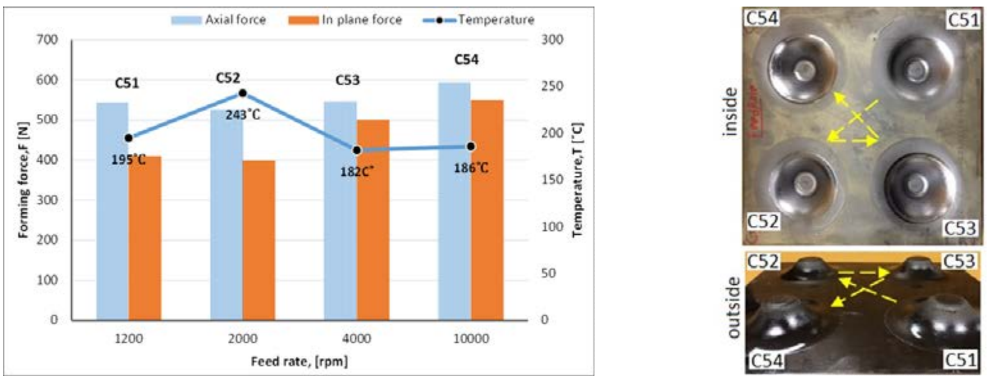


Figure 6: An illustration of the influences of the feed speed in SPIF: (left) on the process demands; (right) on the obtained titanium samples

From the temperature diagram in Figure 6, and considering the investigated range of SPIF variables, it can be stated that the variation in the tool feed rate has a marginal impact on the heat generated at the forming zone. Large feed rates slightly increase the forces, in particular the in-plane force.

There is minor reduction in the temperature at the large feed rates. This can be linked to a lesser opportunity for the localised heating of material to build up at high feed speeds, as the heat source (tool) rolls faster over the workspace surface and heat is more dissipated than it accumulated in a specific zone. The exception was found in the run with a feed of 2000 mm/min, in which a temperature of 242℃ occurred; interaction between this particular feed level and the applied tool rotation is suspected for the increase in temperature. Further investigation of these phenomena is envisaged in line with data obtained from a multifactor design of experiment.

Consistent with cited references [3,10], the test results shown in Table 1 revealed no significant change due to the feed rate in the formability of CP Grade 2 between the four formed samples (maximum wall angle was 57˚ ± 1˚). However, this angle remains far below the formability angle (65˚) that was obtained in another experiment at the same settings, but with a reduced feed rate of 625 mm/min.

4. Conclusion

This paper investigates the influence of the tool rotation and feed rate on the thermomechanical loads in SPIF of titanium Grade 2 sheets. Within the wide range of speed factors investigated, and with particular reference to the SPIF process as applied to titanium, the information acquired can be outlined as follows:

- Of the two speed mechanisms investigated, the rotating tool is the dominant factor that drives the thermomechanical effects. Both the rise in the forming temperature and the reduction in the forming forces, are directly associated with an increase in the applied tool turning speed.
- Tool rotations up to 2500 rpm are conducive in that forming forces are reduced and deformation is eased.
- Increasing tool rotation above 4000 rpm yields no gain in formability. On the contrary, the CP Grade 2 forming angle was substantially decreased due to emergence of two kinds of surface defect, both at tool/sheet interface and on the non-contact side; the escalated rate of material removal led to workpiece failure. With very high speeds there seems to be no possibility of successful forming; instead failure tends to occur at initiation of forming.
- Unlike changes in the tool rotation speed, changes in the feed rate do not materially impact either on the heat generated, or on the formability; an increase in the feed rate does however, slightly increase the forces, in particular the in-plane component.
- Future work involves the study of the interaction between the two speed factors to assess their non-linear behaviour on the thermomechanical demands in the SPIF process.

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