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Investigation on the fracture behavior of titanium grade 2 sheets by using the single point incremental forming process

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ABSTRACT

The objective of the present research work is to study the fracture behaviour (void coalescence) of titanium grade 2 sheets using the Single Point Incremental Forming (SPIF) process and its dependence on various process parameters. The importance of tool diameter on the fracture behavior of the titanium grade 2 was investigated and it was found that the maximum deformation fracture strain was observed for the highest (12 mm) tool diameter. The Forming Limit Diagram (FLD) is plotted for each speed of titanium grade 2 sheets. The variation of fracture behaviour with respect to speed was examined and it showed that this was the maximum for higher speed of 600 rpm spindle speed. The void coalescence analysis was carried out using AutoCAD software, and the strain triaxiality was determined. The Energy Dispersive X-ray Spectroscopy (EDS) analysis was investigated to confirm the elemental composition of titanium grade 2 sheets.

1. Introduction

Titanium is the most widely used material in the aircraft, marine, orthopedic and dental applications because of its high strength to weight ratio and good resistance to corrosion as compared to aluminum and steel [1]. Ti–6Al–4V is the most popular universally used titanium grade 5 (alpha–beta) alloy; its usage is nearly 80% of the entire titanium used in the USA. Ti–6Al–4V has low formability as compared to titanium grade 2 and commercially available pure titanium at room temperature [2]. Single Point Incremental Forming (SPIF) is a new sheet metal forming technique, which is used to deform the sheet metal into different shapes namely straight groove, cup and cone shaped parts with different variable wall angles. This is a die-less forming process that enables the development of miniature batches and modified products at a comparatively lower cost. SPIF is an advanced technological process and is progressively developing in the direction of industrial and manufacturing applications mainly in the aerospace and automobile sectors [3–5]. Belhassen et al. [6] was studied stamping of aluminum sheet metal with soft punch is simulated, and also discussed the effect of various process parameters namely hardness of rubber, type of rubber on the variation of the thickness, the spring back and damage of aluminum sheet metal are investigated by using Finite Element Analysis (FEA). Ben Said et al. [7] studies on numerical investigation of damage mechanism during the Single Point Incremental Forming (SPIF) of a part with conical shape, and also to find a Finite Element Model (FEM) was developed to simulate the SPIF process of truncated cones manufactured from an aluminum alloy sheet metal. Belhassen et al. [8] focused on to study numerically the “elastomer-assisted compression beading process” (EACB) and the results was validated with experimentally and analytically. Wali et al. [9] attempted to find an easy integration algorithm for a non-associated anisotropic plasticity, with comprehensive quadratic functions for plastic potential, yield criterion and nonlinear isotropic hardening is proposed. Ben Said et al. [10] developed finite element model based on Hill’ 48 yield criterion, isotropic hardening behavior and simulation of SPIF process and also compared four tool path strategies on SPIF process of a square box. Shakir et al. [11] published a detailed review on the current state of incremental sheet forming processes with a focus on the effect of various parameters on incremental sheet forming. The methodical quantitative analysis and literature review was under taken to analyze the effect of various parameters, namely tool shape and type, material thickness, spindle speed and rotation direction, feed rate, tool diameter, step down and a few other parameters [12]. Ambrogio et al. [13] investigated and compared two lightweight alloys, a titanium alloy (Ti-6Al-4V) and an aluminum alloy (AA5754) subjected to a high speed incremental forming process. Behera et al. [14] elucidated the shape and accuracy of titanium medical implants during an incremental forming process. An application was developed to produce a customized medical product, such as an ankle support, by using an incremental forming (IF) process. This process was selected to develop sheet

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exalting and profiling, when complicated shapes are to be produced [15]. Jewet et al. [16] studied in detail the manufacturing of variety of asymmetric complex shapes with SPIF. In this work, two processes, the single point and multi point IF processes were used, the single point process was for forming and the latter was applied for partial die fill up. Hussain et al. [17–19] attempted to find suitable tools and lubricants by using different combinations of tools for forming pure titanium sheet by negative incremental forming. This is a new method to lubricate sheet metal. The effect of various material properties on SPIF was analyzed. The correlation between formability and the mechanical properties was examined in this investigation. The author also analyzed experimentally the formability of commercially pure titanium sheets by varying the process parameters.

Ti-6Al-4 V can be formed excellently by electric hot incremental forming [20–22]. If proper lubrication, temperature range, and lubrication method are adopted, the forming process can be highly efficient. For example, nitride disulfide, a self-lubricant, is suitable for forming at high temperatures. The proposed electric hot incremental forming is a novel technique to form Ti-6Al-4V sheets, which are in general considered to be difficult-to form, but controlling the geometric accuracy is major obstacle. A novel technique was also introduced, the single sided electric hot incremental forming to study the mechanical properties, viz. hardness, tensile strength and microstructural properties of the Ti-6Al-4V sheets. Palumbo et al. [23] introduced an economical technique for forming titanium alloy sheets by increasing the temperature used with a combination of electric static heating and high tool speed rotations. Ambrogio et al [24] studied the microstructure of titanium grade-2and Ti-6Al-4V in the as received conditions. To overcome the slow progress in SPIF, high speed incremental forming was introduced. Tensile test was carried out using copper foils of different grain sizes; experimental tests were carried out on blanks of different grain sizes by using two forming methods, as explained clearly by Ben et al. [25]. A detailed over view of the incremental sheet forming process used to form sandwich panels was presented by Jackson et al. [26].The ability of incremental forming processes to from hole-flanges by single stage incremental forming. Borrego et al. [27] experimentally studied the Al-7075-O alloy and measured the surface roughness and forming force.

Narayanasamy et al. [28–30] elucidated the forming behavior in terms of the forming limit, fracture limit and wrinkling limit diagram by using sheets of different thicknesses. They clearly explained the void coalescence and length to width (L/W) ratio for different sheets and associated these properties with shear strains and material parameters. Vigneshwaran et al. [31] correlated the void coalescence and fracture limit to strain triaxiality by using different aluminum alloy grades AA5083, AA6061 and CP-Al.

Most of the research on SPIF is focused on aluminum, steel and copper and its alloys [28–32]. Limited information is available on the SPIF of titanium grade 2. Titanium grade 2 and Ti–6Al–4Vare the most widely used titanium alloys in aerospace applications and medical implants. However, titanium grade-5 (Ti-6Al-4V) has poor stretchability at room temperature and needs to be hot formed for work hardening at lower temperatures. Moreover, there is a lack of literature on titanium grade 2. The objective of the current research is to study the fracture behavior of titanium grade 2 sheets using the single point incremental forming technique by varying different parameters such as the tool diameter, speed with a feed rate of 300 mm/min and vertical step depth. The fracture behavior was analyzed by using AutoCAD software through void coalescence analysis and inters crystalline separation with respect to strain triaxiality.

2. Experimental

2.1. Material's microstructure and X-ray diffraction (XRD)

The work material selected for the current study is a 1 mm thickness of titanium grade 2 sheets (as received condition). Titanium grade 2 was selected for its excellent corrosion resistance and formability at elevated temperatures. The chemical composition of the titanium grade-2 sheet (as received condition) was N-0.03%, C-0.08%, H-0.014%, Fe-0.2%, O-0.17% and Ti-balance. All the values are in terms of wt. %. X-ray diffraction (XRD) analysis of the base sheet material was carried out on a Rigaku Ultima III diffractometer using Cu-kα radiation with a wavelength of 1.5406 Aº. A sample coupon for analyzing the microstructure was cut from the sheet blank. By following standard metallographic procedure, the microstructure of titanium grade 2 was observed using an optical microscope. Krolls's reagent (2 mL HF, 6 mL HNO_3 and 92 mL H_2O) was used as the etchant to reveal the microstructure of the samples.

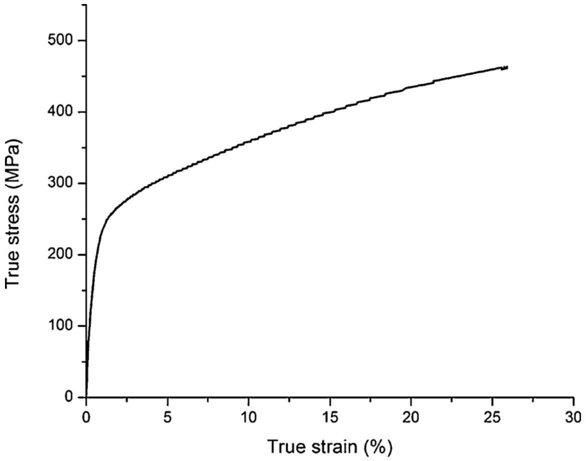

Fig. 1. Represents the true stress versus true strain curve for titanium grade 2.

Table 1
Mechanical properties of titanium grade 2.

S. No.	Properties	Values
1	Strength coefficient, K	495 MPa
2	Strain hardening exponent, n	0.17
3	Ultimate Tensile strength	420 Mpa
4	Yield strength	284 Mpa

The tensile test specimens were cut using Wire cut Electrical Discharge Machining (WEDM) according to the ASTM E-8 standard with a gauge length of 30 mm. Tensile test on the samples were carried out using an automatic computerized electronic Tinius Olsen Universal Testing Machine (UTM) (H50KL-TINIUS OLSEN, Concord Pvt. Ltd., Bangalore, India) at a constant strain rate of 1 mm/min with a 50 kN load cell at room temperature. From Load versus extension curve were obtained from the tensile tests and using these, the true stress and true strain values were calculated and the plot as shown in Fig. 1.

The following equations were used to transform the engineering stress and the engineering strain into a true stress and a true strain value

$$e = \ln (k+1) \tag{1}$$

Where e is the true strain, and k is the engineering strain

$$s = p\ (k+1) \tag{2}$$

Where s is the true stress, and p is the engineering stress.

From the true stress and true strain plot, the mechanical properties were analyzed and listed in Table 1. The fractured titanium grade 2 tensile specimens were also observed using a Scanning Electron Microscope (JEOL-JSM 7500F).