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Influence of Tooling and Lubrication on Surface Integrity of Titanium Grade 5 Sheets Formed By Single Point Incremental Forming

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Abstract* - The current work focusses on extensive experimental parametric study on surface integrity in terms of roughness, topography, induced surface residual stresses and corresponding surface corrosion of Titanium Grade 5 alloy formed sheet employing single point incremental forming (SPIF). Titanium and its alloys are widely used in biomedical, automotive, and aerospace applications. Titanium alloys are utilized extensively in many different sectors because of their strength to weight ratio and resistance to corrosion. SPIF is a die-less forming process, where a sheet metal is plastically deformed to a desired shape in small increments according to a given tool path on a computer numeric controlled (CNC) machine or robotic platform. SPIF process for sheet metal is well established and has enabled flexibility in creation of symmetric, asymmetric and random shapes. SPIF also provides flexibility to tailor the surface characteristics and appearance of the formed sheet according to the application due to parametric flexibility. In the study, effect of incremental forming tooling parameters viz: tool rotational speed; tool feed rate; tool diameter and lubrication on the surface integrity has been presented considering varied levels. The results have indicated substantial bearing and variance in all the surface aspects at varied forming parameters and levels. The study shall provide a comprehensive overview regarding the selection of tooling parametric levels to obtain the desired surface characteristics of the formed Ti-Grade 5 sheet.

***Keywords* - Incremental forming; surface; corrosion; residual stresses; Titanium Grade 5.**

INTRODUCTION

Single point incremental forming employs computer numerical control (CNC) for sheet metal forming, that can efficiently create precisely shaped thin-walled workpieces without the need for a particular set of dies and mold. Advanced products, such as tiny surgical instruments, medical implants, and structural components and compact housing in consumer goods, require thin sheet metal components. A sophisticated metal forming method called single point incremental forming (SPIF) makes it simple to shape extremely thin (micro level) objects without a high concentration of stress. SPIF offers more promise products when it comes to small batch production and quick prototype manufacturing [1]. A revolving or non-spinning pin with a rounded tip travels along a predetermined path and progressively sinks into the sheet while going through the SPIF process [2]. While evaluating the possible use of the ISF technique and ensuring formation accuracy, a number of parameters are taken into account. These consist of technical factors (such as tool diameter, step size, tool rotational speed, and friction conditions), product design elements such as sheet thickness (fig. 1).

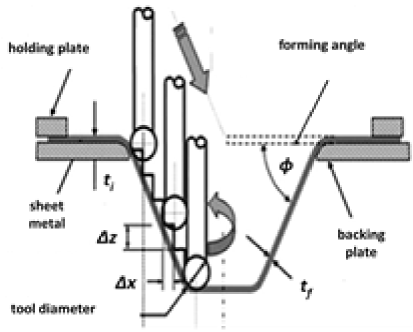

Fig. 1 Schematic of single point incremental forming [2]

Ti-6Al-4V (Ti grade 5) is utilized in medical applications such as customized hip and knee replacements, pacemakers, and dental implants. Due to their superior resistance to corrosion and great strength, titanium alloys are widely employed in aerospace, automotive, orthopaedic, and dentistry applications [3]. Out of all the metals used in engineering, titanium alloys have the highest strength-to-weight ratio. An additional benefit of titanium in medical applications is its biocompatibility, particularly in spite of postoperative difficulties when employing implants and surgical tools made of materials that sensitize patients [4]. Titanium alloy's superior mechanical qualities have led to its widespread application in the aircraft industry. Titanium alloy has several potential uses in lightweight applications because of its high specific strength and corrosion resistance. Grade 5 titanium alloys fall under the α-β alloys family, which offers significant formability and strong tensile strength [5]. The microstructural characteristics, formability, and mechanical qualities of implant-grade titanium are greatly impacted by the optimization of step size and tool diameter in SPIF [6]. Strength, ductility, fracture toughness, high-temperature strength, creep properties, weldability, workability, and thermal processing ability are all well-balanced in the Ti-6Al-4V alloy [7]. Grain size is unaffected by tool rotation, while grain orientation and elongation follow incremental step depth. Due to strain hardening during SPMIF, greater tensile strength and hardness were seen at higher spindle rotating speeds [8]. Titanium is frequently employed in designs to provide dependable, affordable, and long-lasting systems. There are different titanium grades available but the most common alloy is Ti-6Al-4V. Compared to other titanium alloys, pure titanium is less durable and formable. Ti-6Al-4V has reliable machinability and outstanding mechanical qualities [9]. Titanium and its alloys have intrinsic qualities that must be taken into consideration when selecting cutting tools for CNC machining processes in order to minimize machining challenges [10].

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Corrosion testing is necessary to ensure the service life and efficiency of titanium sheets in a variety of applications. Electrochemical Impedance Spectroscopy (EIS), salt Spray Test (ASTM B117), Potentiodynamic Polarization Testing, Cyclic Polarization Testing, Crevice Corrosion Testing, etc. are multiple methods for corrosion testing [11]. One of the main obstacles to progressing the SPIF process to the next level in terms of proficiency is the accurate assessment and analysis of the surface roughness of the SPIF components. In order to select appropriate parameter values to improve the surface quality, a number of factors have been considered, including step size, feed rate, tool rotation speed and direction, tool material, tool route, and wall angle [12]. Among many other surface characteristics, surface roughness is one of the most important factors for implant success. Biocompatibility is influenced by an implant material's physical properties in addition to its surface features and the nature of core and surface residual stresses generated in the product during the processing. Because of its physical properties and strength-to-weight ratio that is comparable to that of natural bone, Ti and Ti alloys are very popular biological implant materials in biomedical engineering and industry [13]. The machining performance of machined parts is significantly impacted by both sub-surface characteristics like residual stress, granular plastic flow direction, and surface defects (porosity, microcracks, etc.) and surface features like surface polish and shape. Analogous to machining, surface properties can be tailored in incremental forming subject to parametric variation very easily.

Therefore, the endeavor of this study is to find the quality, extent, magnitude and nature of the surface generated by SPIF on the formed Ti grade 5 sheets in terms of surface roughness, residual stresses and corrosion rates. Apart from the geometrical parameters in forming, tooling parameters viz. tool speed, feed, diameter and lubrication methods while forming play a critical role in determining the surface quality. This work studies the effect of all the tooling and lubricating parameters in SPIF on the surface quality of the formed sheets.

METHODOLOGY

Sample Preparation

Firstly, Ti grade 5 sheet metal blanks of sizes 70 mm × 70 mm were cut to be used as raw material. Thereafter, sheet metal sample formation at different parameters and levels was conducted on a 3 axis CNC machine (Make: STM, Model: VL850 CNC). For SPIF of sheet metal, a fixture was designed and manufactured considering the load requirements. It consists of a holding plate i.e. top plate and a backing plate with through hole of 50 mm diameter, with the sheet metal to be formed sandwiched in between. The fixture was held securely on the machine table with proper alignment with respect to the Cartesian directions of the machine (Fig. 2a). Fig 2(b) and 2(c) depicts the sliding single point spherical tooling employed in the sample preparation and formed sample respectively.

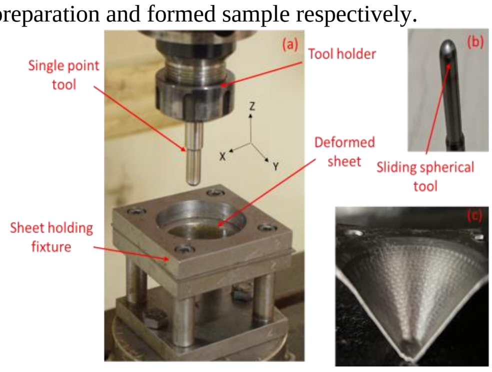

Fig. 2(a) Incremental forming fixture and tooling mounted on the CNC machine; 2(b) single point spherical tool; 2(c) formed sheet

Experimental Plan

Table 1 depicts the fixed experimental level of incremental forming parameters and dimensional attributes of the sheet. Table 2 depicts the variable levels of SPIF tooling and lubricating attributes for which various formed surface attributes were quantified and analysed. For example, the variation in surface attributes with change in tool speed was obtained by keeping all the parameters constant to the level given in table 1 except for the tool speed levels.

Table 1. Fixed levels of incremental forming parameters and geometrical attributes

	Parameters	Value
Incremental Forming	Tool rotational speed (m/min)	1.5
	Feed Rate (mm/min)	100
	Tool Diameter ‘*d*’ (mm)	6
	Forming angle ‘*ø*’ (º)	45
	Incremental depth ‘*Δz*’ (mm)	0.5
	Lubrication	Mobil Oil (15W-40)
Geometrical Attributes	Sheet Thickness ‘*t*’ (mm)	0.511 (24 gauge) ≈ 0.5
	Sheet exposed cone diameter (mm)	50

Table 2. Variable Levels of incremental forming parameters and geometrical attributes

Parameters	Value
Tool rotational speed (m/min)	1.5, 3, 6
Feed Rate (mm/min)	100, 200, 400
Tool Diameter ‘*d*’ (mm)	6, 8, 10
Lubrication	Mobil Oil (15W-40), Grease (Lithium Soap), Dry (without lubrication)

Surface roughness measurement and imaging

Surface roughness of all the samples were measured and graphs were recorded using Surf test SJ-400 Series (Make: Mitutoyo) detector uses interchangeable nosepieces that allow skid and skid less measurements to suit the type of measurement required. The average roughness (R_a) value was measured across the depth of the formed sheet and across the feed direction of the tool. Minimum three reading of each sample were taken and averaged out in the results. Surface microscopic images at different magnifaction were acquired using Scope A1 microscope (Make: Carl Zeiss).

Surface residual stress measurement

Surface residual stresses in formed AZ31 were evaluated employing nano-indentation technique, commonly used in case of thin film or substrate evaluations. The mechanical properties viz. hardness, young’s modulus by measuring contact area were estimated according to Oliver- Pharr method [14]. For the compressive residual stresses the contact load are larger in comparision to the unstressed (reference) samples. Whereas, for tensile residual stresses the contact loads are lesser in comparison d to the unstressed (reference) samples (Fig.3a) [15].

Surface corrosion measurement

The surface corrosion tests were conducted employing the Gamry electrochemical measurement system (DC105; Gamry Instruments Inc., Warminster, PA) based on DC potentiodynamic testing. Table 4 depicts the corrosion testing parameters for an Ti alloy. Corrosion rate is determined by an equilibrium current between positive and negative electrochemical reactions (Fig. 3b). The curved line is the sum of the anodic and cathodic currents. Tafel equation determines the theoretical current by curve fitting [16]. The equilibrium potential is called the Open Circuit Potential (*Eoc*) or Corrosion Potential. The current value measured at *Eoc* is called the Corrosion Current (*Icorr*). The corrosion rate (CR) is directly proportional to the corrosion current (*Icorr*). The current flow is related to mass flow and equivalent weight in an electrochemical through Faraday's Law.

$$CR = Icorr \cdot k.EW. / d\,A \qquad (1)$$

where,

CR = the corrosion rate, Icorr = the corrosion current in amps, *K* = corrosion rate constant (mm/year or mils/year), *EW* = the equivalent weight in grams/equivalent, d = density in grams/cm^3, *A* = sample area in cm^2

Table 4. Testing parameters in Gamry Corrosion Test

Electro-lyte	Area of sample	Density of sample	Conditioning Time	Stabilizing Time	Current convention
Simulated body fluid	1.65 cm^2	1.8 gm/cm^3	86400 s	900 s	Anodic

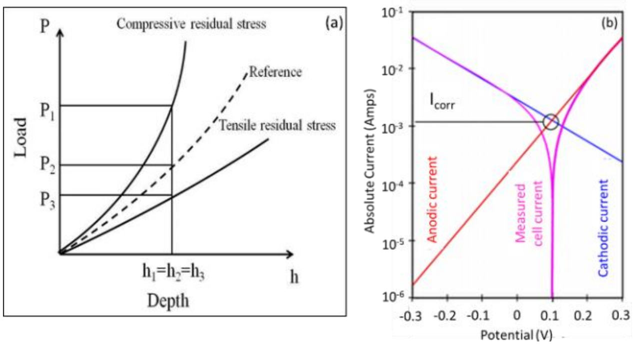

Fig. 3(a) Load v/s depth comparison for compressive and tensile residual stresses in nano-indentation; (b) V-I characteristics depicting anodic and cathodic current components during Gamry corrosion test

RESULTS AND DISCUSSION

Influence of tool rotational speed

Surface Roughness: According to the images and plots in Fig. 4, it can be inferred that the formed surface quality has slightly improved with the increase tool tangential speed along the sheet circumferential (tool feed) direction and along the depth. The primary reason for such trends is excessive tool sliding remarks chipping (i.e. material removal in small grits) during forming at lower tool speeds. At increased tool speeds, although there is chipping (i.e. material removal in small grits) observed which should deteriorate the formed surface quality. But, these chipped debris remain attached to the formed surface due to increased temperature at elevated tool rotational speeds. Hence, filling the pits generated due to surface ploughing and delamination, thereby improve the surface finish, though marginally.

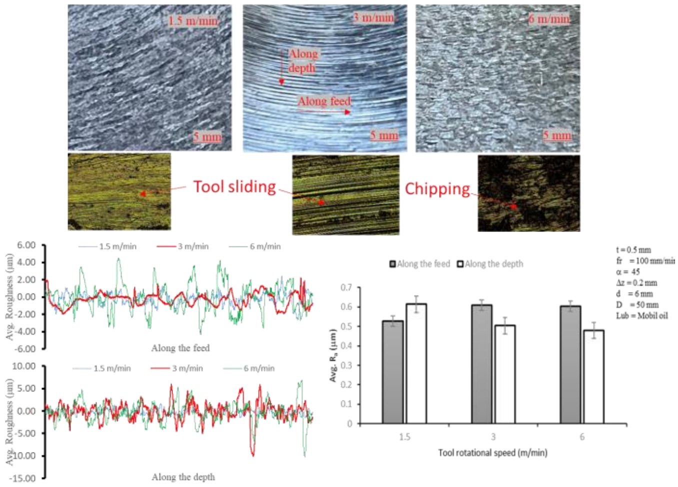

Fig. 4 Surface imagery of the formed sheet with varying tool rotational speeds; roughness profiles; average roughness values

Surface residual stresses and corrosion: The surface residual stresses on formed Ti grade 5 sheets with varying tool rotational speeds transit from compressive stresses at lower speeds of 1.5 m/min to tensile at higher speeds at 4.5 m/min. It can be inferred from reduced indentation load with respect to reference raw sample at higher tool speeds (Fig. 5a). This is because of increased strain hardening on the formed surfaces in comparison to the raw (unformed) sample, resulting from material churning at surface due to increased tool-sheet static friction at lower speeds. At relatively higher speeds, increased tool-sheet interface temperature during forming, softens the surfaces and induces primarily tensile residual stresses [17]. Surface corrosion rates primarily depends upon the surface quality in terms of surface roughness. Corrosion rate reduces with increase in tool speed (Fig. 5b), attributing mainly to poorer surface finish at lower tool rotational speeds.

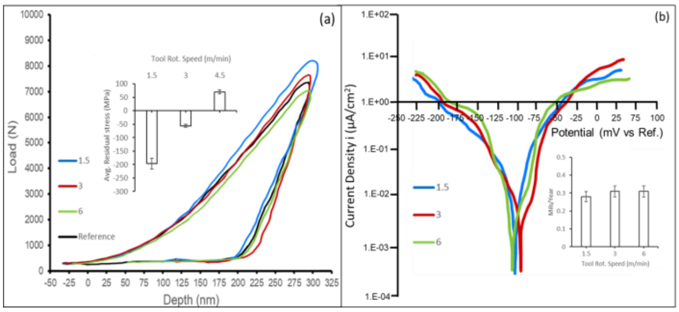

Fig. 5(a) Nano-indentation load-depth curves and surface residual stresses at varying tool rotational speeds; 5(b) Electro-chemical test results and corrosion values at varying tool rotational speeds

INFLUENCE OF TOOL FEED RATE

Surface Roughness: From the images and plots in fig. 6, it can be inferred that the formed surface quality along the tool feed (sheet circumference) direction has improved with the increase tool feed rate. This is mainly because of less instantaneous tool interaction with sheet surface (at particular point) with increasing tool feed rate. At higher feeds, the tool merely grazes past a point on the circumference of the forming region of the sheet, thereby making smooth sliding marks as against comparatively deep burnishing marks because of significant material churning at lower feed rates. The surface roughness, however vary insignificantly along the depth of formed sheet. The influence of tool feed is primarily along the circumference similar to tool tangential speed, therefore have negligible bearing on the roughness along the depth.

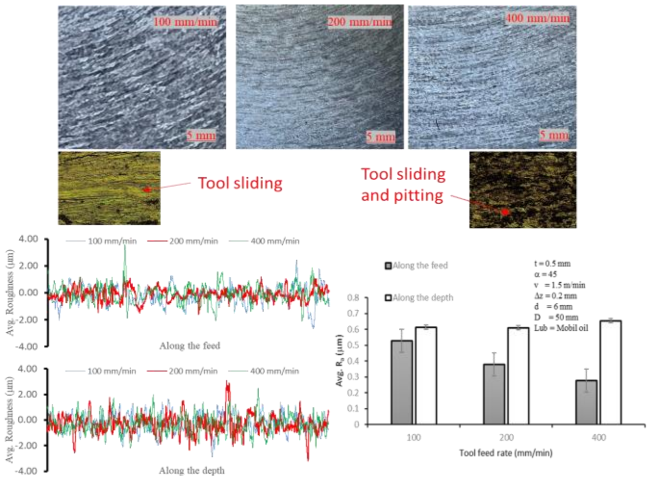

Fig. 6 Surface imagery of the formed sheet with varying tool feed rates; roughness profiles; average roughness values

Surface residual stresses and corrosion: The surface residual stresses induced on the formed sheet with varying tool feed rates are compressive in nature, with minor increase in the magnitude with increase in tool feed rates (fig. 7a). At lower feed rates, increased mechanical loading is countered by increased frictional temperature. At higher feed rates, less mechanical load along with less frictional temperature. Tool feed rates also have influence on surface corrosion rate proportional to the surface roughness (fig. 7b).

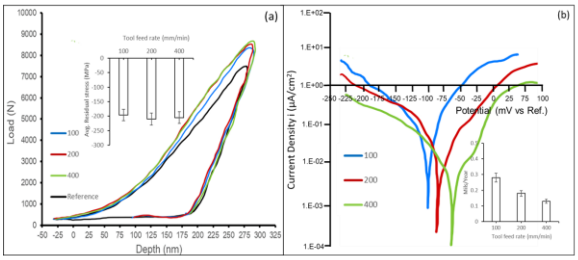

Fig. 7(a) Nano-indentation load-depth curves and surface residual stresses at varying tool feed rates; 7(b) Electro-chemical test results and corrosion values at varying tool feed rates

Influence of Tool Diameter

Surface Roughness: From the images and plots in fig. 8, it can be inferred that the formed surface quality has improved significantly with the increase tool diameter. The main reason behind these results is increased tool surface contact and overlapping in subsequent increments, resulting in lapping finish as against deep sliding remarks at lower tool diameter.

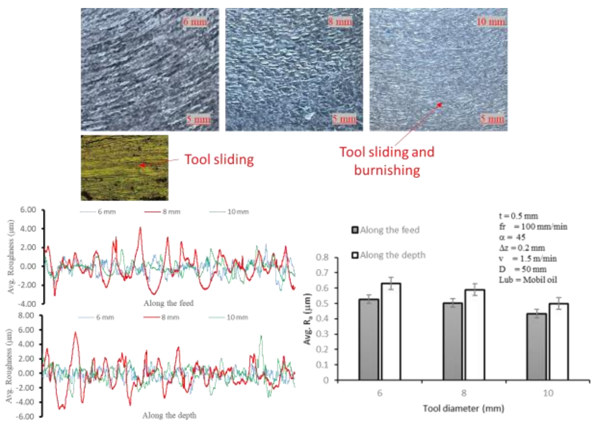

Fig. 8 Surface imagery of the formed sheet with varying tool feed rates; roughness profiles; average roughness values

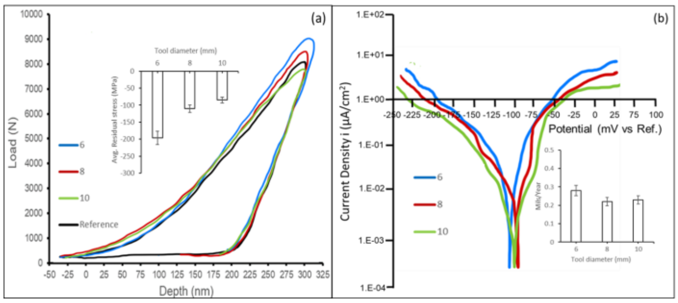

Fig. 9(a) Nano-indentation load-depth curves and surface residual stresses at varying tool sizes; 9(b) Electro-chemical test results and corrosion values at varying tool sizes

INFLUENCE OF LUBRICATION

Surface Roughness: From the images and plots in fig. 10, it can be inferred that the formed surface quality along the depth in particular and tool feed (sheet circumference) direction has deteriorated considerably with the change in lubricating conditions from the use of Mobil oil-15W-40 to Grease (lithium soap) to no lubrication- dry forming. In case of forming without lubrication, the formed sheet surface is extreme rugged, full of cracks with extensive signs of deep ploughing. The surface quality of the formed sheet with use of mobil oil had smooth sliding marks and with grease there were signs of mild pitting, ploughing. Dry forming resulted in deep ploughing along with sever delamination of the formed surface.

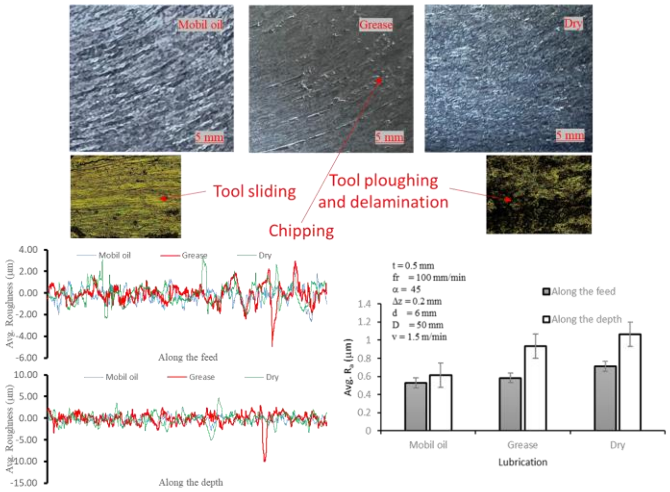

Fig. 10 Surface imagery of the formed sheet with varying lubricating conditions; roughness profiles; average roughness values

Surface residual stresses and corrosion: In case of mobil oil and grease the surface residual stresses are compressive in nature, but for dry lubrication the stresses are tensile. It can be inferred from the load-depth curves of nano-indentation, that average curve for dry lubrication has fallen below the reference raw material curve (fig. 11a) indicated the onset of tensile residual stresses. The primary reason is the increased frictional condition and consequently increased forming temperatures at the tool sheet interface. For grease, the stresses are tensile though of lower magnitude. Surface corrosion rate for dry samples is significantly higher in comparison to lubricated samples with mobil oil and grease (fig. 11b). Such results are primarily owed to the poor surface quality of the formed sheet generated without lubrication.

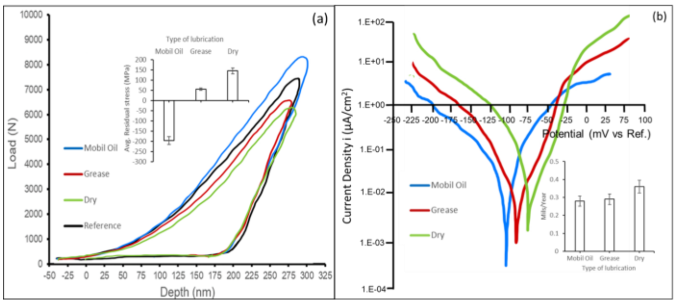

Fig. 11(a) Nano-indentation load-depth curves and surface residual stresses at varying lubricating conditions; 11(b) Electro-chemical test results and corrosion values at varying lubricating conditions

CONCLUSIONS

In the present work, influence of tooling parametric evaluation on surface integrity in terms of surface roughness, residual stresses and corrosion rate of Titanium grade 5 sheets, a commercial alloy, formed by single point incremental forming, has been presented. The results depicted that the tool tangential speed and lubricating were the most influential parameters impacting surface integrity and quality of the formed sheet. For most of the parametric levels the induced surface residual stresses were compressive in nature. The work has established that the formed surface texture can be tailored easily, as per the application by tweaking the forming parameters easily. The future work in this direction shall go into exploration and behaviour of different materials, and also in generation of customized surface texture employing the process of incremental forming.

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