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On the high-speed Single Point Incremental Forming of titanium alloys

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ABSTRACT

Single Point Incremental Forming processes show some limitations related to both dimensional accuracy and process slowness. The process slowness is here overcome by introducing the high speed forming, which allows a reduction to less than 1 min of execution time of target components made in Titanium alloys. The paper is aimed at analyzing the influence of the feed increasing on the material quality in order to investigate if the development of high speed machines could be a suitable solution to implement more extensively the Single Point Incremental Forming technique in practice.

All the results are discussed in the paper.

1. Introduction

The Incremental Forming process was patented in 1967 [1], well before its actual implementation and was named Incremental Dieless Forming. However, the first experimental studies on the process were carried out in the first years of nineties.

During the last 20 years, many papers have been published focusing on different aspects of Incremental Forming processes. In 2005, a very cited keynote paper titled “Asymmetric Single Point Incremental Forming of Sheet Metal” [2] was proposed at the CIRP General Assembly by Jeswiet et al. It fixed the state of the art about the process, highlighting the main aspects related to the process mechanics, formability, accuracy, and possible applications. The Authors claimed in the summary that “The process has tremendous potential and there are many future possibilities where it can be used”. After 8 years this potential has not resulted in large industrial applications, mainly due to the two main drawbacks of the Single Point Incremental Forming (SPIF) applied to sheet metals, namely the process inherent geometrical inaccuracy and the process slowness.

Looking at the scientific literature, many papers are related to the understanding of the process mechanics and, in particular, to the analysis of formability as compared to traditional stamping process. In 2008 Ambrogio et al. [3] published a paper on the formability of deep geometries not obtainable by the traditional stamping process; in 2009 Jackson and Allwood [4] gave a convincing explanation of the process mechanics and the role of the stress tensor for the formability enhancement.

Another cluster of papers is related to the processing of new materials, in particular lightweight alloys. Ji and Park in 2008 [5] carried out an investigation on the Single Point Incremental Forming of magnesium alloys; Franzen et al. in 2009 [6] presented a study on the Single Point Incremental Forming of PVC showing how it is possible to work also polymers using such a technology.

As far as the process drawbacks are regarded, different studies were published showing how to increase the process accuracy. Hirt et al. [7] in 2004 proposed a suitable way to design the tool trajectory taking into account the material springback during processing. Three years later, Micari et al. [8] discussed the different methodologies to correct the material deviation with respect to the desired shape. In fact, SPIF generates a geometrical inaccuracy as a consequence of the reduced material constraints during processing.

However, up to 2010, the issue of the process slowness was not deeply investigated by the researchers, probably because the machines used for the Single Point Incremental Forming implement the same concepts developed for the milling machines. In 2010 Hamilton and Jeswiet [9] proposed a study on the forming of AA3003-H14 alloy at high feed rates and rotational speeds, investigating the impact on the material surface and structure. According to their plan of experiments, Hamilton and Jeswiet applied a maximum feed rate equal to 9 m/min, nevertheless they introduced a new approach based on the use of high speed for reducing the lack of productivity of SPIF compared to traditional stamping processes.

The motivation of this work derives from the above sentence: the Authors tend to demonstrate that the competitiveness of SPIF is related to the development of proper high-speed machines and they show how it is possible to obtain a workpiece with a processing time of the order of few seconds. Therefore, the goal of this work is to investigate the effects that the increase of the working speed has on the quality of parts produced by SPIF. Recently, this issue was partially discussed considering some Aluminum alloys [10]. Here, the study is extended to Titanium alloys, in particular to the commercially pure Titanium (grade 2) and the Ti6Al4V (grade 5).

In its first part, the paper will present the novel experimental apparatus used for the SPIF experiments at high speed and the experimental conditions applied to the two Titanium grades; then, the obtained results will be discussed in terms of part quality and execution time, as well as in terms of part microstructural features

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and micro-hardness values. It will be demonstrated that the increase of the process speed does not alter either the material microstructure or the micro-hardness, thus proving the possibility to carry out SPIF processes at a rate of two orders of magnitude higher than the one currently imposed.

2. Experimental tests

This section presents the main characteristics of the two Titanium alloys utilized in the study, the experimental apparatus set-up to carry out SPIF tests at high speed, and the experimental plan for both the alloys.

2.1. Materials

The sheet materials used in the present investigation are the commercially pure Titanium ASTM grade 2 and the α–β alloy Ti6Al4V ASTM grade 5. The commercially pure Titanium grade 2 is usually selected for its excellent corrosion resistance, especially in applications where high strength is not required (being its tensile strength not higher than 340 MPa). The Ti6Al4V is the most utilized titanium alloy, containing 6 wt% Al and 4 wt% V; it presents an excellent combination of strength and toughness (tensile strength up to 1000 MPa and elongation at fracture up to 13%) together with a good corrosion resistance. While commercially pure Titanium can be cold formed to a limited extend, the cold forming of Ti6Al4V would generally result in reduced formability and excessive springback, thus requiring the forming at elevated temperatures.

The commercially pure Titanium grade 2 and the Ti6Al4V were provided in sheets of 1.0 mm thickness. Their microstructures in the as-delivered condition are shown in Fig. 1: the Titanium grade 2 presents recrystallized grains of primary α phase and transformed β phase containing acicular α, while the Ti6Al4V structure consists of elongated grains of α phase (light) and intergranular β phase (gray).

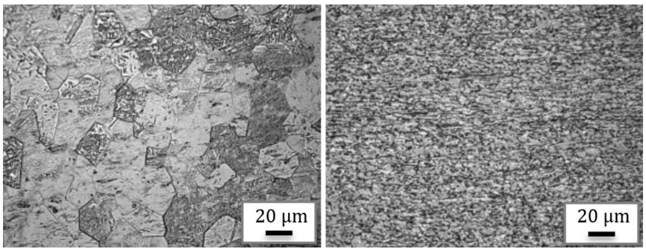


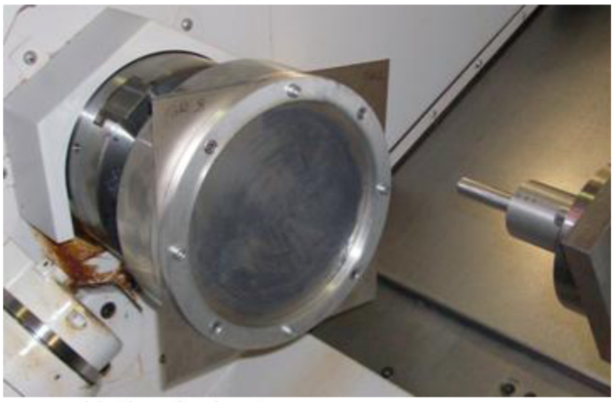
Fig. 1. Microstructure of the Titanium grade 2 (left) and Ti6Al4V (right) in the as-delivered condition.

2.2. Experimental apparatus

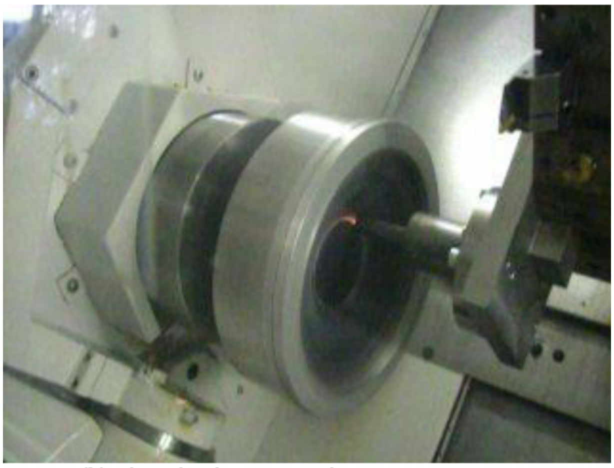
A high strain rate in the material is reached if the punch used to deform the blank is moved at high velocities. Accordingly, the experimental campaign was carried out by means of a Mazak™ Q-Turn 1000 CNC lathe. Tests at two different orders of magnitude of feed rate were performed, thus enlarging the investigated speed ranges in order to clearly investigate the strain rate influence on the material structure.

The machine spindle allows a rotating speed up to 4500 rpm, with a theoretical relative velocity between the sheet and punch, of about 2500 m/min for the investigated geometry. A traditional milling machine allows transverse speeds of the order of 2000 inches per minute (i.p.m.), which corresponds to about 50 m/min. This fully justifies the choice of the CNC lathe as a Single Point Incremental Forming machine to increase the process speed.

Because of the machine peculiarities, just axisymmetric shapes were analyzed. The latter is a restriction due to the machine characteristics, but does not affect the quality of the analysis since only a lack of flexibility in forming more complex shapes is shown.



(a). The utilized equipment.



(b). The utilized equipment during processing.

Fig. 2. (a) The utilized equipment. (b) The utilized equipment during processing.

In the proposed research, a frustum of cone with the major base of 180 mm and the minor base of 42 mm was manufactured. A proper clamping equipment was utilized (Fig. 2(a) and (b)), with two circular rings that were used to lock square sheets (240 mm × 240 mm) to a framework by means of bolts; the frame, in turn, was mounted to the lathe spindle.

A hemispherical punch of 15 mm diameter was used as forming tool. A properly designed holder with three bearings allowing the punch rotation was built. As far as lubrication is concerned, the molykote lubricant (MoS_2) was sprayed on the sheet to reduce friction. Finally, proper ISO functions were written in the CNC part program to link the spindle rotation to the coil pitch, generating the desired conical trajectory.

2.3. Experimental plan

Concerning the process parameters, a deep attention was paid to investigate the role of the speed at the interface between the punch and sheet and the one of the pitch. Preliminary studies suggested neglecting the role of thickness.

What is more, the wall inclination angle was selected according to safe conditions since the issue of material formability is not of interest in this paper [11].

As far as the tool speed is concerned, it ranged between 6 and 600 m/min for the Titanium grade 2 and between 5 and 500 m/min for the Ti6Al4V. It is worth to note that SPIF processes are normally run at a speed of the order of 1 m/min.

The tool pitch ranged between 0.1 mm and 1.0 mm during the whole investigation.

All the experimental conditions for both the grades are summarized in Table 1. The lower values imposed to feed and tool pitch during the experiments carried out on the Ti6Al4V sheets are justified by both the higher material strength and the machine technological limits, in terms of spindle power.