Induction Heating and Cryogenic Cooling in Single Point Incremental Forming of Ti-6Al-4V: Process Set Up and Evolution of Microstructure and Mechanical Properties

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Abstract. Hot Single Point Incremental Forming (SPIF) with induction heating and cryogenic cooling has been applied to form the Ti-6Al-4V sheets. The influence of both the forming temperature and the cooling rate after deformation, on microstructure evolution and microhardness of Ti-6Al-4V sheets, has been extensively studied. We propose the use and development of a new system of heating by induction. The system is composed of a medium-high frequency generator and, a continuously water cooled heating head, which is placed under the sheet and linked axially to the punch movement, heating the material locally by generating eddy current within the material. Furthermore, a cooling system integrated with the movement of the forming punch allows us to apply a cryogenic fluid to the recently deformed sheet metal. Both localized heating and cooling systems are particularly suitable for such a process as SPIF, whose primary characteristic is the incremental forming of localized sheet zones. The meta-dynamic and static recrystallization processes have been suppressed in the sheet material, evident by the final microstructure and mechanical properties. Finally, a comparison between parts is made, both with and without cooling during hot-SPIF.

Keywords: Hot SPIF, Induction Heating, Cryogenic Cooling, Ti-6Al-4V, Microstructure, Hardness.

Introduction

The SPIF technology is a flexible numerically controlled process that can form various materials from sheets into complex shapes. A blank sheet is clamped peripherally and deformed locally by a spherical head punch, which can be attached to a CNC machine or a robot arm, following a contour for shaping the desired part. SPIF has been investigated in several papers throughout past 20 years, with a significant focus on the process characteristic. In 2002, Filice et al. [1] analyzed issues related to material formability highlighting the fact that SPIF is characterized by a local stretching mechanism. The SPIF deformation mechanism has been further investigated and it was concluded that strain is driven by stretching and shear combination [2]. However, various process parameters affect the material formability, i.e. material type, sheet thickness, coil pitch, tool size, etc., and must be taken into account to accurately determine the SPIF forming limits [3]. Considering these process parameters, Xu et al. [4] have proven that material formability enhances with increased tool rotation speed, due to a combination effect of friction and heat. Centeno et al. [5] have considered SPIF's failure to take into account the influence of process parameters on sheet formability. They have determined that the enhancement of formability above the material forming limit curve in SPIF cannot only be ascribed to the bending effect induced by the punch radius. This effect plays an important role but is not the sole factor that allows for consistently stable deformations. In 2004, Hirt et al. [6] focused on forming strategies to overcome two relevant process limits, namely the maximum achievable wall angle and the geometrical accuracy of the manufactured parts. SPIF variants such as multi-pass incremental sheet forming [7] and double sided incremental forming [8] have been developed to increase material formability.

Jeswiet et al. [9] highlighted the remarkable potential of SPIF in 2005. In this work, guidelines related to several process parameters were established and discussed. Moreover, low process speed and limited geometrical accuracy of the final part were determined to be the primary drawbacks. They suggested that overcoming these limitations is essential in order to consider SPIF as a valuable alternative to stamping.

The potential for increasing forming speeds of incremental forming processes has been analyzed for several alloys [10]. The influence of an increasing feed rate on forming forces, temperature and formability has been thoroughly investigated in detail. Ambrogio et al. [11] have shown that the tool feed, increased up to two orders of magnitude higher than those traditionally applied, does not affect the material microstructure and properties.

The reduced geometrical accuracy of existing incremental sheet forming configurations has significantly diminished industrial interest in the process. Allwood et al. [12] have cut slots and tabs to form a partially cut-out blank hoping that this strategy could improve accuracy. They concluded that partial cut-outs do not significantly improve the geometrical accuracy of the product when compared to the use of backing plates.

In recent years, manufacturing lightweight sheet metal using SPIF has been under investigation. Hussain et al. [13] studied the formability of commercial pure titanium sheet at room temperature by SPIF using various processing parameters. They have confirmed that formability of titanium alloys is low at room temperature, resulting in severe limitations for industrial manufacturing. Forming at elevated temperature not only increases the material formability but also reduces the required forming forces and spring-back, providing a possible solution to the poor geometrical accuracy of the final product. The SPIF process at elevated temperatures has been described in the following section.

Hot Single Point Incremental Forming

Application of lightweight components, for both economic and ecological reasons, is a common challenge in modern transportation engineering [14]. Formability, which is typically low for alloys with hexagonal crystal structure, can be increased by raising the forming temperatures. Various hot SPIF methods have been developed consisting of local heating; focusing heat on a specific forming zone [15], or global heating; in which the entire sheet is heated at once [16]. The enhancement of incremental sheet forming has also been achieved by combining static heating with high tool rotation speed [17]; here, a combination of local and global heating has been utilized. An overview of the several different hot SPIF processes has been recently summarized by Xu et al. [18]. They have classified the heating systems as:

- *Convection:* taking advantage of heat convection by using hot air blowers on the entire sheet [19];
- *Conduction:* heater bands, mounted on the external surface of the fixture, heating the entire sheet during the forming process [20];
- *Radiation:* a laser light follows the punch trajectory heating the sheet locally [21-22];
- *Friction:* frictional forces between the rotating tool and the static sheet are used to heat the material [23-24];
- *Electric:* electric current supplied by a DC power source is used to heat the sheet metal locally. In detail, a closed circuit is built through the forming tool and the blank sheet [25-26].

Each heating system is characterized by its own strengths and weaknesses. The local heating systems are more suitable for SPIF taking into account the process characteristics due to the localized forming sequence. In fact, by using these systems, the material is heated just before forming to avoid keeping the entire sheet at working temperature for an extended period of time. This approach provides the most optimal conditions for heating the material immediately prior to deformation and therefore decreasing overall process time. Among the local heating systems, radiation allows for a well-controlled heating zone geometry and temperature, but at a higher cost. The complex and expensive equipment needed is a considerable process drawback, which must be taken into account for SPIF, which is promoted as a low cost technology. Inversely, the friction system does not require additional equipment. However, temperature control is extremely difficult depending on component geometry and process variables (e.g., lubricants and sheet material). Finally, the electric system stands in between its two alternatives: heating is achieved more efficiently than the friction method by adjusting the input current [27] and it is less expensive than the radiation system because of low costs associated with the necessary equipment. The energy control in the electric method is more complicated than the laser source because geometrical parameters such as the punch diameter and the wall angle must be considered to determine the arc of contact through which the current passes. This is especially important to prevent the material from burning [26].

The proposed work has been carried out by testing an innovative local heating system, which can be used by SPIF for hot forming of numerous alloys. In particular, the heating system is composed of an induction coil, placed under the sheet and coupled axially with the punch (Fig. 1). Therefore, a new alternative heating approach, related to induction, has been proposed and its feasibility investigated. Induction heating can be utilized as a less expensive alternative to the laser source, and at the same time, allows for a more effective and controllable temperature setting than friction and electric methods can provide. The cost of the required equipment, discussed in the next section, is less than one order of magnitude when compared to a laser source used for hot SPIF. The desired temperature can be reached by accurately setting:

1) Coils shape and distance from the sheet

2) Punch velocity

3) Supplied electric current

No geometrical variables need to be considered, allowing for easier temperature control. Therefore, the potential benefits are attainable if the process is developed properly. To test this theory, the feasibility of SPIF by induction heating has been experimentally investigated at different temperatures using the titanium alloy Ti-6Al-4V (Grade 5) a lightweight alloy widely utilized in industrial applications,. Moreover, the new SPIF method has been equipped with a cryogenic cooling system, which can be utilized to quench the sheet. This is useful for suppressing the meta-dynamic and static recrystallization, which, depending on process conditions and properties of the worked material, can affect the final properties of the hot worked sheet.

The induction coil instantaneously heats the material bringing it to a desired temperature starting from a sheet zone, which can be:

1) At room temperature (first punch passage)

2) Heated by a previous coil passage

3) At a cryogenic temperature

The sheets can either be air cooled or cooled in an accelerated way by spraying liquid nitrogen on them. In order to achieve this, a cryogenic system will be activated at specific intervals. Therefore, if the punch velocity, coil shape and distance from the sheet are constant for a single test, the electric current must be supplied according to the necessary temperature variation. The aim of the reported project was to test the effectiveness of the proposed heating system for SPIF. We have selected a titanium alloy for this purpose, as titanium and its alloys are nonmagnetic and, therefore, are more difficult to heat by induction when compared to magnetic materials such steels, due to the magnetic hysteresis [28]. Magnetic materials are naturally resistance to the rapid change of the magnetic fields close to the inductor; the resulting friction produces its own additional heat from the hysteresis that is added to the material generated by the eddy currents. Hence, the process feasibility for Ti-6Al-4V validates the SPIF variant applicability to other materials such as steels.

The influence of working temperature and different cooling rates on the Ti-6Al-4V microstructure and micro-hardness have also been analyzed. The hot forming temperature range for Ti-6Al-4V is between 600-700°C [29], which is below the beta transus temperature (~ 900°C).

Material and Procedures

This section has been divided into three parts. The analyzed titanium alloy is introduced along with its primary mechanical properties. Subsequently, the experimental equipment is described highlighting the unique aspects of the heating and cooling systems. Finally, the experimental plan is presented.

Ti-6Al-4V

The Ti-6Al-4V belongs to the alpha-beta class of the titanium alloys. In particular, it is composed of 6 wt. % aluminum, which is an alpha-stabilizing element and of 4 wt. % vanadium, which is a beta-stabilizing element. In the annealed condition, interstitial alloying elements, i.e. nitrogen, oxygen and hydrogen, generally increase alloy strength and decrease its ductility [29]. At room temperature, this alloy has approximately 90 vol. % alpha and, therefore, the alpha phase dominates its physical and mechanical properties. However, the microstructure depends on both processing history and heat treatment. In particular, metalworking operations tend to produce a preferred crystallographic orientation in alpha grains causing an anisotropic behavior. On the other hand, the Ti-6Al-4V is responsive to heat treatment because the beta phase can be adjusted, both in quantity and composition, for different working temperatures and cooling rates [29]. Ti-6Al-4V is typically hot deformed at ~650°C, allowing the material to deform more readily while simultaneously reducing the degree of spring-back. It is important not to exceed the beta transus temperature, otherwise the mechanical properties of the alloy will be affected. The threshold for Ti-6Al-4V hot working is around 900°C. The microstructure of the as-received sheet is presented in Fig.2 demonstrating the presence of the fine Beta phase in the Alpha matrix. Finally, its thermal properties at room temperature are reported in Table 1.

Experimental equipment

The experimental tests were performed using a customized CNC Cartesian robot with three screw driven axes movements. A schematic representation of the utilized equipment is shown in Fig. 3. The titanium sheets are firmly clamped onto a special frame made from low carbon steel, which is placed directly in the center of the working zone. A hemispherical punch 15 mm in diameter was used as a forming tool, while a passive spindle allowed for unconstrained punch rotation.

The sheets were heated locally by induction. More specifically, an induction coil was coupled axially to the punch and was then placed below the sheet on the opposite side of the forming tool. A precise crown made from a refractory material was then placed under the sheet to prevent current from spreading through the frame.

The generated magnetic flux crosses the sheet, which is heated by eddy currents. The coil is powered by a medium-high frequency generator with a working frequency of 150-220 kHz; this is driven by an integrated controller that manages the heating cycles. An optical sensor attached to the punch assembly was used to continuously measure the temperature in the area close to the tool–sheet interface. This sensor delivers the temperature value to the controller, which switches the generator on and off, depending on the discrepancy between the programmed and actual temperatures. The emissivity value, necessary to properly calibrate the optical detection system, has been set experimentally. In fact, thermocouples were used to check the optical measures; these validations were carried out at various temperatures and working conditions (i.e., using surface oxidizing lubricant).

Finally, an additional circuit was introduced into the equipment with the goal of using liquid nitrogen inside the working zone for cryogenic cooling. A working pressure of approximately 6 bar was guaranteed to the cryogenic fluid, which was sprayed onto the sheet using a circular nozzle placed axially around the punch. The forming time is divided into different phases and, at the conclusion of each one, the cryogenic medium was sprayed while the punch retraced from the last coil. A comprehensive illustration of the equipment used is shown in Figure 4.

Experimental Plan

We focused specifically on the process feasibility for different working conditions. In detail, two working temperatures were investigated, namely 600°C and 700°C; this range was chosen in accordance with industrial practices [29]. Regarding the cooling rate, the experimental tests have been divided in two different phases. In the first phase, the worked sheets were allowed to cool in air to room temperature. In the second phase, the material was cooled by spraying cryogenic fluid during the deformation process. The spraying frequency was fixed, cooling the sheet after a specific punch passage. In the presented research, the cryogenic cooling, important for suppressing microstructural changes within the sheet subjected to hot forming, is meant to increase the deformation temperature. This is important for understanding the process flexibility and its limitations. The tests were carried out and classified as cryogenic coolant "ON" or "OFF". As far as the lubrication is concerned, the Molybdenum Disulfide (MoS_2) was sprayed on the sheet to reduce friction where liquid nitrogen was not used (coolant OFF) because this cooling liquid is used also as lubricant in the "ON" configuration. Finally, other process parameters such as punch pitch and speed have been also considered. The experimental conditions for both phases are reported in Table 2.

1 mm thick Ti-6Al-4V sheets were processed to form a truncated cone with an initial diameter of 120 mm. The wall inclination angle was selected according to safe process conditions, namely 30°; the obtained specimens were formed up to 30mm in height. For the purpose of microstructure characterization and micro-hardness measurements, samples were sectioned from deformed parts. The focus was centered on the most deformed area after the transition bending phase. To satisfy these conditions, samples were ground and polished using standard metallography procedures. To reveal the microstructure by optical microscopy, the as-polished samples were subjected to immersion etching for seven seconds in Kroll's reagent composed of 3 mL HF, 6 mL HNO_3, and 100 mL H_2O.

For micro-hardness measurements, the samples were re-polished and a Leco® Micro-hardness Tester LM248AT was used under a load of 300 g with a dwell time of 13 s. The micro-hardness was measured along a line across the thickness on the most deformed area (Fig. 5). The distance between each indent was 120 μm while the average indent size was 39 μm. Additionally, the first and last indent distance from the sample edge was measured to be at least 80 μm. A total of 8 micro-hardness measurements were performed across the thickness for each sample and the average results are reported in this work.

Results and Discussion

The process feasibility has been verified for each analyzed configuration. The medium high frequency generator was able to create the desired temperature for the sheet deformation zone, without any change in temperature or punch velocity as monitored by the optical sensor. The sensor was calibrated using a thermocouple at each temperature and for both lubricants used. This result confirms a successful forming of Ti-6Al-4V, a nonmagnetic material, by induction heating, both with and without cryogenic cooling.

Regarding the quality of the incremental formed parts, several comparisons were made between parts worked by hot induction and those worked by two other locally heated SPIF alternatives, friction [30] and electric [28], previously investigated by co-authors of the current research.

The comparisons were focused on two main variables: a) surface roughness and b) material springback. Regarding surface roughness, electric heating adversely affects the surface quality most drastically. This occurs because the electricity supplied by a DC power passes through the blank, which is part of a closed circuit. Therefore, heat is generated within the sheet, which causes temperature rise and deterioration of the surface integrity. As a result, the surface roughness increases as can be observed in Fig. 6. In contrast, the friction and the induction methods show similar influences on the roughness, being half of the average value for the electric method for a specific punch pitch. Furthermore, regarding the induction heating, the configuration with MoS_2 was taken into account to avoid any discrepancy among the compared tests. In fact, both friction and electric configuration were carried out by spraying MoS_2 on the sheets.

Regarding material springback, qualitative considerations were reported in detail in the first step. Friction heating has shown a significant sheet springback once the clamp was removed. The sheets appear to form a "dovetail" shape as reported in Fig.7a. This effect was not observed for both electric and induction heating, where after unclamping there was not significant change in shape

(Fig.7). Furthermore, the cryogenic cooling allowed for a consistent springback reduction on the unclamped formed sheet. The profiles of test N°1 and test N°3, characterized by the same working conditions but different cooling phases, were drawn identifying points using a Coordinate-Measuring Machine; the two extracted profiles were compared to an ideal profile as shown in Figure 8.

Finally, some considerations were given to the influence of various process conditions on the microstructural evolution and micro-hardness values of the deformed Ti-6Al-4V sheets. It is important to recognize the sheets are characterized in the as-received conditions (Fig.2) by the presence of the fine beta phase (dark) in the equiaxed alpha matrix (grey). However, the material heating, necessary for processing the alloy due to its low formability at room temperature, along with the applied deformation and the cooling rate, strongly affect the microstructures of the final components. This can be observed from the microstructures of the parts deformed by SPIF at temperatures of 600°C (test N°1) and 700°C (test N°2) and air-cooled (Fig. 9).

The temperature necessary for hot deformation of the alloy is lower than its beta transus [29]. Therefore, no phase transformation has occurred. However, the applied thermomechanical cycle also affects the alloy microstructure. The fine equiaxed alpha-beta structure of the as-received material becomes coarser after hot SPIF processing. This phenomenon can only be attributed to the temperature increase, combined with the relatively long cooling time that is required for grain growth. The most important factor in defining titanium properties is the phase transformation from alpha to beta, while grain size and shape play a secondary role in terms of its influence on the mechanical properties [29]. The effect of the highlighted grain growth has been quantified in Fig. 10, where the influence of the hot SPIF on the Ti-6Al-4V micro-hardness is shown, reporting the values of the worked and as-received sheets. It can be observed that, despite grain coarsening, the micro-hardness for these two samples are slightly lower than that of the as-received sheet. Work hardening during SPIF may have masked the grain growth effect. In either case, a sample N°2 deformed at 700°C exhibited a hardness slightly lower than that of N°1 deformed at 600°C. This can be explained in terms of more favorable conditions for dynamic recovery at higher temperatures.

The cryogenic cooling was introduced to prevent the highlighted grain growth. To investigate the influence of the cooling rate on the obtained microstructure, two tests were repeated using the same working conditions of test N°1 and test N°2 but instead, the sheets were cooled with cryogenic fluid, respectively shown as test N°3 and test N°4 in Table 2. The time interval between the two successive cooling cycles for each test was maintained constant. The obtained microstructures are presented in Fig. 11.

Cryogenic cooling significantly affects the microstructure of the deformed Ti-6Al-4V sheet. From a qualitative point of view, the microstructure of the abruptly cooled alpha-beta alloy is characterized by fine globular particles of beta in a matrix of alpha. The working temperature has proven to affect the final microstructure of the investigated alpha-beta alloy. Coarser grains can be observed, maintaining constant volume despite the cryogenic cooling frequency and increasing the temperature from 600°C to 700°C.
The microstructure influence on micro-hardness has been analyzed quantitatively (Fig. 12). A slight influence of grain size on the Ti-6Al-4V hardness was confirmed. In fact, the influence of the cryogenic cooling on the grain shape and size has been deemed insignificant for these conditions and thus, a direct correlation between hardness and grain size cannot be determined. A slight discrepancy among the hardness results, always lower than 10% with respect to the as-received condition (Fig. 12), confirms that the hardness of the investigated alloy is not significantly affected by the hot working conditions and cooling rate, if the beta transus temperature is not exceeded.

The fluctuation of average hardness values reported in Fig. 12 can be explained by the alpha-beta distribution along the measured sheet thicknesses. In fact, the alpha phase is harder than beta.

Therefore, the beta distribution around the alpha grains can lead to a lower local hardness. Furthermore, the beta phase is characterized by an optimum size, which maximizes the alloy hardness [31]. This deviation from the optimum value must be also considered to justify the highlighted hardness fluctuations. Finally, the effects that some SPIF process parameters have on the Ti-6Al-4V microstructure were investigated by comparing results at different punch speeds and coil pitches, maintaining constant the cooling frequency and working temperature (Fig. 13). The optical microscopy figures did not reveal any significant microstructure variations, while the above process parameters were changed within the investigated ranges.

Regarding the influence of the punch velocity, the obtained results confirm the finding of previous research [11] that the influence of the feed rate, in the range between 6m/min and 600m/min, has a negligible impact on the microstructure of this alpha-beta alloy, as no significant change can be observed utilizing optical microscopy techniques.

Conclusions

An innovative version of hot single point incremental forming (SPIF) was proposed as a valuable process alternative for deforming materials with low room temperature formability. An induction heating system was designed as the heating source while a cryogenic circuit was used to quench the processed sheets. The effects of hot SPIF and various cooling rates after deformation have been investigated using the Ti-6Al-4V, one of the most widely and frequently used titanium alloys. The induction system was utilized to heat up the material to 700°C instantaneously. The obtained results have shown that:

1) The Ti-6Al-4V, a nonmagnetic material, can be hot deformed after increasing sheet temperature using induction heating both with and without cryogenic cooling. In fact, the induction coil is able to reach the target temperature at the investigated punch velocities by starting from cryogenic temperatures.

2) The proposed local induction heating system is competitive to traditional heating methods such as friction, laser, and other methods. Its primary advantages can be summarized as:

a) Lower process cost compared to the laser system.

b) Superior surface quality and more effective and easily controlled temperature compared to the electric system.

c) Lower sheet springback and more effective and easier to control temperature compared to the friction system.

3) The feasibility of using cryogenic cooling with a local induction heating system was tested and verified for a number of working conditions. The influence of the various processing conditions on the fine microstructure of the as-received sheets has been highlighted based on our results. The increase in temperature allows for greater grain growth if the formed parts are air cooled to room temperature. This effect can be avoided if the SPIF process is followed by an abrupt material-cooling step, such as spraying liquid nitrogen onto the Ti-6Al-4V sheets, immediately after the hot SPIF, which was proven to be a valuable and effective solution. Finally, the cryogenic cooling does not significantly affect the hardness of the Ti-6Al-4V. This can be explained by the alpha and beta volume percentage, which does not change during investigated hot forming processes as the temperature has been maintained below the beta transus.

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