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The effect of local heating by laser irradiation for aluminum, deep drawing steel and copper sheets in incremental sheet forming

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Abstract

Incremental sheet forming is a technique where a metal sheet is formed into a product usually by a CNC-controlled (Computer Numerical Control) round tipped tool. The part is formed as the tool indents into the sheet and follows a contour of the desired product. In single point incremental forming (SPIF) there is no need for tailored tools and dies, since the process requires only a CNC machine, a clamping rig and a simple tool.

The effect of applying local heating by laser irradiation from the bottom side of the metal sheet is investigated with a SPIF approach. Using a laser light source for local heating should increase the material ductility and decrease material strength, and thus, increase the formability. The research was performed using 0.50-0.75 mm thick, deep drawing steel, aluminum and copper sheets. The forming was done with a round tipped tool, whose tip diameter was 4 mm. In order to achieve selective heating, a 1 kW fiber laser was attached to a 3-axis stepper motor driven CNC milling machine. The results show that the applied heating increased the maximum achievable wall angle of aluminum and copper products. However, for the steel sheets the local heating reduced the maximum achievable wall angle and increased the surface roughness.

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Keywords: incremental; forming; SPIF; laser; local heating

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1. Introduction

Incremental sheet forming is a flexible forming method, which can form sheet metal by relative movement of simple tools. Single point incremental forming (SPIF) is a die-less process that does not require tailored tools, which allows the parts to be made at low cost and short lead times. In terms of hardware, the process requires a 3-axis positioning system, a clamping rig and a simple tool with a spherical head. However, the lack of supporting die structure influences the part manufacturing accuracy, which is the main obstacle for commercial breakthrough of the process (Allwood et al. 2005). According to Duflou et al. (2007) the process accuracy is mostly limited by spring back and unwanted plastic deformation. Thus, the accuracy can be increased by finding methods to localize the incremental forming effect. In the forming area, which is determined by the tool-sheet contact area, the sheet material should have a low yield strength. On the other hand, the surrounding area should have a high yield strength, so that it provides essential support for achieving accurate forming. Since the processed metal consists of a single material, the solution to increase the manufacturing accuracy is to apply local heating.

In room temperature the ductility of a metal sheet can be rather low, which may lead to cracks and deformations in the forming process. The sheet can be locally heated by a laser beam spot, which increases the material ductility and decreases material strength, and thus, increases the formability (Duflou et al. 2007, Neugebauer et al. 2006). Local heating by laser irradiation has been used in SPIF of aluminum alloy, steel and titanium sheets (Duflou et al. 2008, Göttmann et al. 2011). While there is numerous published work on forming with local heating, there is only little research done related to determining the wall angle limit with different metals and the effect of local heating in forming copper sheets. The wall angle limit is an important parameter that determines the steepest formable angle of a cone structure.

In this paper, the effect of applying local heating by laser irradiation from the bottom side of the metal sheet in a SPIF process is investigated. The forming wall angle limit was determined for different sheet materials with and without heating to research the effect of local heating to the incremental forming process.

2. Single point incremental sheet forming

Several incremental forming strategies have been developed to successfully produce small pre-series batches or prototypes. The forming strategies mainly differ for equipment and forming procedure. The forming process can be divided into three categories as done by Callegari et al. (2006): single point incremental forming, two point incremental forming (TPIF) and full die incremental forming. These strategies can be utilized on CNC (Computer Numerical Control) machines as well as on industrial robots. The use of robot cells, with automatic tool change, can significantly reduce the manufacturing time, since it is possible to deform, bend, flange, load/unload the part with the same fixture, but the stiffness of the robot may not be sufficient for the process (Callegari et al. 2006). The following paragraphs will look into the three strategies in more detail and investigate the factors affecting the accuracy of SPIF.

In single point incremental sheet forming the metal sheet forming is done using a single tool. A typical SPIF configuration is presented in Fig. 1, where α is the wall angle of the part. The tool with a spherical tip makes a series of 2D contour passes according to the outside boundary of the part and takes a step down after each pass. This tool path then forms the desired shape into the metal sheet. It is possible to form complex and asymmetrical parts without dies, unlike in conventional metal sheet forming techniques such as stamping or spinning (Adams, 2013).

In two point incremental sheet forming the forming process is similar to SPIF, but on the other side of the sheet is a local support, which is a partial die. In full die incremental forming the tool deforms the sheet against a die, which can be made of cheap materials such as wood or low cost steel. The use of a die on the other side of the sheet ensures a better and more precise shape of the final part, but the flexibility of the system decreases and the production of dies increases the price of the system.

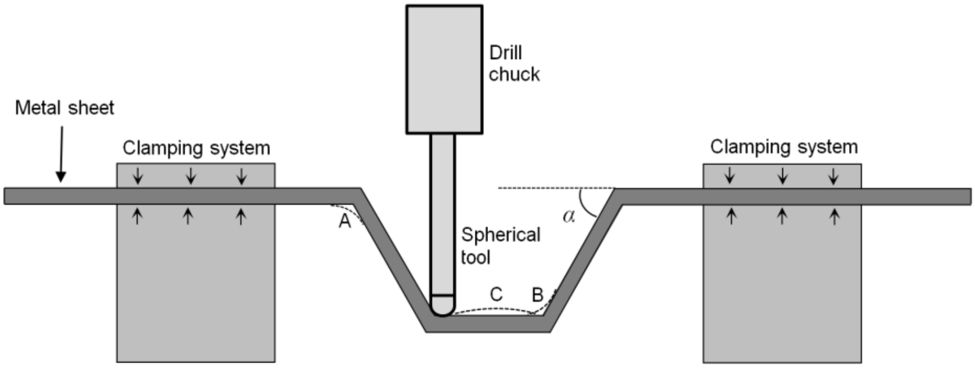

Fig. 1. Single point incremental sheet forming.

The accuracy of a SPIF system is affected by several parameters, which can be divided into process parameters (tool diameter, vertical step size, lubrication, rotation speed), material parameters (normal anisotropy, strain hardening, Young's modulus) and part design parameters (geometry, sheet thickness, wall steepness). There are three fundamental geometrical errors that are present in the SPIF process. Firstly, there is unwanted sheet bending close to the major base of the part, which is depicted as A in Fig. 1. This unwanted deformation can be reduced by adding a so called backing plate below the metal sheet, but it provides no solution for deformations occurring in a later stage of the process. Secondly, the sheet will lift up as the pressure of the tool is removed and result in a too shallow shape (detail B in Fig. 1). Thirdly, at the minor base of the part a "pillow" effect can occur and cause concave curvature (detail C in Fig. 1). In addition to the manufacturing accuracy the forming limits have to be taken into account when designing parts for SPIF. (Duflou et al. 2008, Micari et al. 2007)

The forming limit related to wall thinning is often represented by a maximum wall angle α_{max}. The steepest wall angle that can be successfully formed is thus limited by this value. Increasing the maximum wall angle requires improvements to the SPIF process. The process can be improved by adding local heating, but other factors must also be taken into account.

The manufacturing accuracy is affected not only by sheet material but also the internal structure of the material. For instance, deep drawing steel has a body-centered-cubic crystal structure at room temperature, while copper and aluminum have a face-centered-cubic structure. At high temperatures the microstructure of steel can recrystallize, which affects the mechanical properties of the metal (Bienger and Helm 2012). According to Schreijäg (2013) the recrystallization process for cold rolled deep drawing steel (DC04) is dominated by grain growth and the microstructural evolution is a complex process, which is dependent on individual grain boundaries on impurities and several other factors. As stated by Subramonian and Kardes (2012), deterioration in properties can be reduced by hot forming steel at same temperature as the rolling finishing temperature. Thus, knowing the exact properties of a metal sheet is crucial. In addition to choosing the right material, the forming process can be improved by selecting the right tool size for each shape and controlling the local heating position.

Smaller tool size can produce more accurate shapes whereas increasing the tool size reduces the achievable maximum wall angle as demonstrated by Ham and Jeswiet (2007). The forming process with laser assisted local heating could be more accurate if the laser beam spot location was controlled relative to the tool-sheet contact position. In our research, the spot is fixed at the center of the tool tip, but it could have an inside or outside offset. An inside offset means the laser spot is moving in front of the tool-sheet contact spot and in the outside offset case, the order is reversed. According to Mohammadi et al. (2014) the bulge height, which is denoted as C in Fig. 1, reduced 42% for the outside offset case in comparison to the unheated SPIF case. While for the inside and without offset cases, the bulge height increased by 27.3% and 9.8%, respectively.

In this paper, we investigate the method of locally heating the metal sheet with a laser to increase its formability. To determine the effect of local heating the maximum wall angle of an unheated sheet was compared to the maximum wall angle of a locally heated sheet. The effect of local heating on surface roughness is also investigated.

3. Experimental setup and methods

The experimental SPIF setup consists of a KX3-Mach CNC mill (SIEG Industrial, China), clamping tools and a fiber laser. The setup without the laser system is presented in Fig. 2a. This setup was used to investigate the maximum wall angle of parts without local heating. The setup was then modified by adding a 1 kW fiber laser below the metal sheet and a cooling unit above the sheet. The laser assisted SPIF setup is presented in Fig. 2b. The forming process is explained in the following paragraphs.

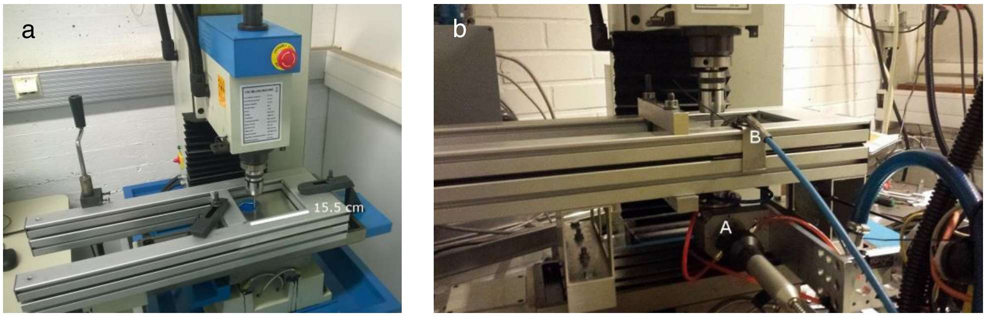

Fig. 2. (a) the experimental setup; (b) the setup with a fiber laser (A) and an air cooling unit (B).

To begin the forming process a CAD (Computer-Aided Design) model of the desired part is required. In this paper we used Rhinoceros 4.0 SR6 to design the shapes. The designed model was loaded into a CAM (Computer-Aided Manufacturing) software, which in this case was Mastercam X4 (CNC Software Inc., USA), to create the necessary tool path according to the contour of the CAD model. The tool path was designed so that the tool path started from the outer edge of the major base and then spiraled downwards to the minor base. A truncated circular cone shape was selected as the target shape for the experiments for determining the maximum wall angle. However, other shapes were also briefly tested. The bottom radius of the truncated cone varied between 32 and 46 mm, the top radius varied between 9 and 20 mm and the depth of the shape varied between 15 and 45 mm. The wall angle was controlled by adjusting these three parameters and in the experiments the wall angle values varied between 53.6° and 74.6°. The created tool path was then saved into a NC file, which has the information of the shape as G-code. This file was then uploaded to the CNC machine operation program (Mach3). The tool would then move according to the G-codes and form the wanted shape. This forming process is affected by several parameters, such as speed of the tool, vertical step size and local heating.

The local heating was applied to the forming process with a 1 kW ytterbium fiber laser (IPG YLR-1000) that operates at 1070 nm. The diameter of the fiber was 50 μm and the beam parameter product was 2.4 mm·mrad. The diameter of the unfocused laser beam at the metal sheet surface was 6 mm. The distance from the fiber end to the sheet was around 100 mm. The beam spot was precisely fixed on the tool tip as shown in Fig. 3. The laser beam was always fixed at the tip's location during the forming process, since the clamped metal sheet moves in the xy-direction and the tool tip moves only in the z-direction. Thus, local heating was applied from below to only the tool-sheet contact area. To avoid severe back reflection damage the beam was inclined 5° to the normal of the sheet. The laser power was adjusted from 70 to 350 W in the experiments for each material to find the optimal power output. The output power was limited to 350 W, due to the recommendation of the fiber laser manufacturer.

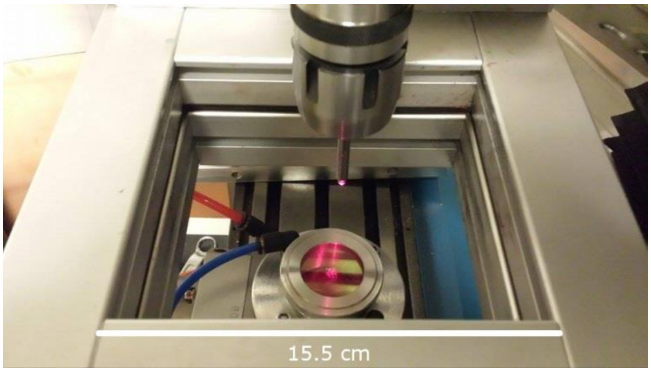

Fig. 3. Laser beam fixed on the tool tip.

The KX3-Mach CNC mill has a travel range of 28, 12 and 27 cm in the x, y and z-directions, respectively. The stepper motor torque in the xy-direction is 4 Nm and 6 Nm in the z-direction. The machine is operated with Mach3 software, which was installed on a computer with a DB25 connector. The movement speed of the tool (or in this case the table) was set to 1,000 mm/min. The tip diameter of the tool was 4 mm and the vertical step after each loop was set to 0.5 mm. To avoid collision between the tool and the clamping structure the size of the formed part was limited to 15 x 15 x 5 cm, although the travel range of the CNC was much larger. Generally, four test shapes were formed into each sheet within the area of 15 x 15 cm. Although, the previously formed shapes may slightly affect the shape of the one under formation, the wall angle of each shape remained unaffected.

Three different metal materials were tested in this research. The thickness of the sheets was 0.50 mm for aluminum (EN AW-1050 A) and copper (Cu-OF-04, CW0008A, half-hard) and 0.75 mm for deep drawing steel (DC04). Before each forming process a small amount of lubricant was added on the area that would be formed. In the unheated approach the lubricant was machine oil and in the laser assisted approach it was copper paste due to its anti-seize properties at high temperatures. With the help of a lubricant the tool tip glides on the sheet instead of sticking and rupturing it.

The formability was evaluated by investigating the maximum wall angles of different metal sheets. The wall angle α was calculated from the measured apex angle φ of the cone. The wall angle can be simply calculated from the apex angle as shown in Eq. 1. The apex angle of each cone was measured with two different methods to achieve high reliability. The first method to measure the apex angle was to take a picture from one side of the cone and import the image to Solid Edge (Siemens PLM Software, USA) modeling software. The apex angle was then determined by adding edge lines to the sides of the cone and measuring the angle between these lines. The second method was to use a high accuracy coordinate measuring machine (Zeiss C700) and Calypso 5.2 software.

$$\alpha = 90^\circ - \frac{\varphi}{2} \tag{1}$$

The wall angle measurements were done for truncated cone parts, although other shapes were also tested. The maximum wall angle was determined by finding the precise breaking point of the sheet. The wall angle was increased if the part was formed successfully and decreased if the cone had visually noticeable cracks or fractures. This process was repeated (usually 5 to 10 times) until the largest wall angle, which could be successfully formed, was determined for each configuration. For locally heated deep drawing steel the actual maximum wall angle was not measured, since the angle was smaller than without heating.

To determine the effect of local heating on the surface quality of the part, each part was visually inspected and the smoothness of unheated and heated counterparts were compared. Depending on the material the surface smoothness decreased or remained nearly unchanged.

4. Results

Truncated cones formed with the SPIF setup are presented in Fig. 4. The accuracy of the produced part was determined by comparing the wall angle of the CAD model with the formed shape. The wall angle of each shape and material was measured with two different methods, which both gave very similar results (difference was around 0.1°). Based on the measurements done for different materials and shapes the wall angle (α) was slightly different than the wall angle of the model (α_{model}). For aluminum the actual wall angle was larger than designed, so that $\alpha_{Al\_unheated}$ = [α_{model}, α_{model} + 0.1°] and α_{Al_heated} = [α_{model}, α_{model} + 0.7°]. For copper and deep drawing steel the wall angles were $\alpha_{Cu\_unheated}$ = [α_{model} - 0.5°, α_{model}], α_{Cu_heated} = [α_{model} - 0.4°, α_{model}] and $\alpha_{steel\_unheated}$ = [α_{model} - 2.3°, α_{model}]. The maximum wall angle measurement results are presented in Table 1. Locally heating deep drawing steel reduced the value of the maximum wall angle, and thus the result was left out. For copper the maximum wall angle was limited to 70.1°, since increasing the wall angle further would have required over 350 W output power. Thus, the actual maximum wall angle for copper was not determined.

Table 1. The measurement results for determining the maximum wall angle.

Process	Material	The steepest wall angle that was successfully formed (°)	The lowest wall angle that failed (°)
Unheated	Aluminum	59.0	61.0
Unheated	Copper	65.8	66.8
Unheated	Deep drawing steel	71.6	72.8
Heated	Aluminum	61.0	62.8
Heated	Copper	70.1	N/A
Heated	Deep drawing steel	N/A	69.4

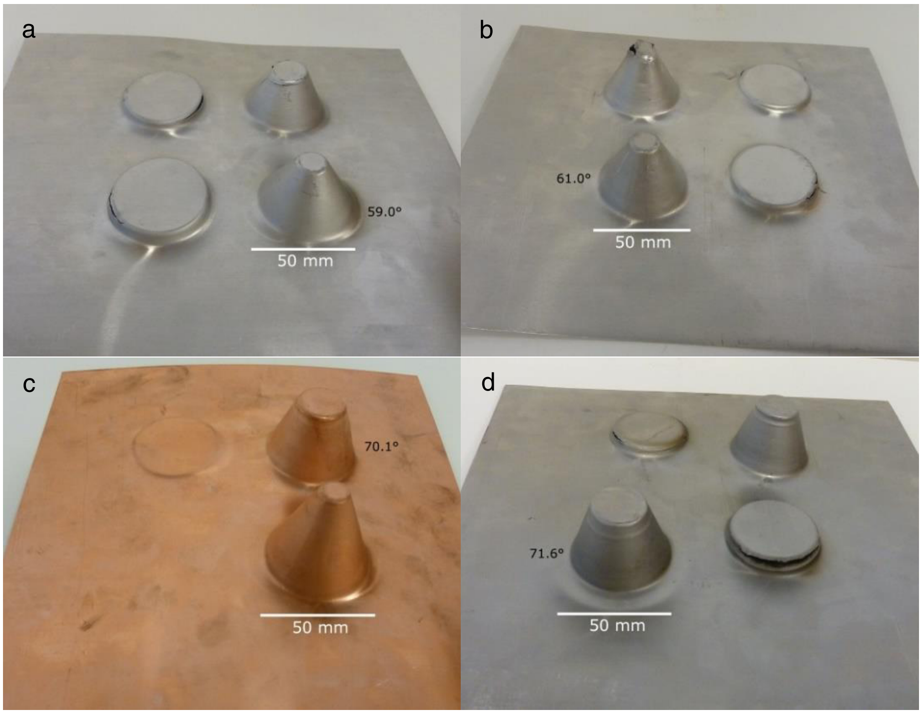

Fig. 4. The steepest formed truncated cones for four configurations, the angle of the steepest successfully formed cone is marked in each image (a) aluminum unheated; (b) aluminum laser assisted (250 W); (c) copper laser assisted (350 W); (d) deep drawing steel unheated.

The surface quality of the shapes depended on the material and whether local heating was applied or not. In Fig. 5 one can notice that the local heating increased the surface roughness in the case of deep drawing steel. Laser assisted local heating also increased the surface roughness in the case of aluminum, but not as significantly as for steel. For copper the local heating did not deteriorate the surface smoothness.

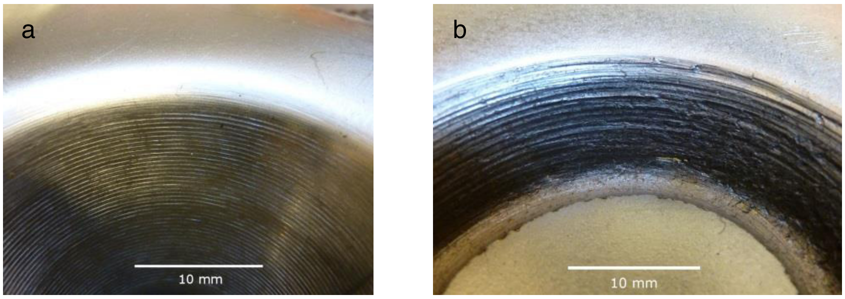

Fig. 5. Surface roughness of the final part made of deep drawing steel (a) without heating; (b) with laser assisted local heating (170 W).

5. Conclusions and discussion

A single point incremental sheet forming system with laser assisted local heating was developed for the purpose of forming palm-sized parts. Aluminum, copper and deep drawing steel were the tested materials. The effect of the local heating was investigated by comparing the maximum wall angle values. For aluminum the maximum wall angle value increased by about 2°. For copper the value increased nearly 5°, but the maximum wall angle was not determined, since the output power of the laser was limited to 350 W. For deep drawing steel there was no improvement in the formability. As a matter of fact, based on the experiments the formability decreased with local heating. The reason for this deterioration is unclear, but most likely it is caused by the structural properties of the cold rolled deep drawing steel (DC04). Future research should be done to investigate the crystal structure of the steel sheet before and after the laser assisted SPIF process to get more information about the microstructural changes.

The surface quality remained nearly unchanged when aluminum and copper were used, which is consistent with previous work (Duflou, 2008). However, for deep drawing steel the surface quality suffered remarkably as shown in Fig. 5. Thus, based on our results, laser assisted heating reduces the formability of deep drawing steel (DC04) and increases surface roughness compared to the unheated forming process.

The laser power output was 350 W for the copper cone with a wall angle of 70.1°; further increasing the wall angle with higher power output was considered unsafe with the current setup. Thus, a laser based heating system should be developed so that high power outputs are usable without dangerous reflectance especially with copper sheets.

The wall angle of a formed shape was slightly different than the wall angle of the model. The error was different for different materials and the error changed slightly when heating was applied. For aluminum, α was larger than α_{model}, but for copper and deep drawing steel $\alpha < \alpha_{\mathrm{model}}$. Adding local heating increased the wall angle for every material when the shape was unchanged. For deep drawing steel the error was larger than for other materials, which is most likely due to the steel sheets being thicker. More experiments should be done to investigate the cause for both $\alpha_{\mathrm{Al\_unheated}}$ and $\alpha_{\mathrm{Al\_heated}}$ being larger than α_{model}. The reason might be that the sheet is stiff at the beginning of the process and then becomes more ductile as the forming continues leading to a slightly larger α than expected.

To increase the forming accuracy the spherical tool and laser power should be chosen based on the shape and material. In Fig. 4d one can see that the top part of the truncated cone has an unwanted impression in the final 5 mm. Due to the impression, the wall angle changes abruptly. This impression is caused by the spherical tool, which was not suitable for forming the shape. In general, the suitable tool size is determined by the vertical step size and wall angle. Thus, more experiments should be conducted to find the optimal tool and vertical step size for each shape.

The forming process with laser assisted local heating could have been more accurate if the laser beam spot location could have been controlled relative to the tool-sheet contact position. In this research, the spot was fixed at the center of the tool tip, but it could have had an inside or outside offset. According Mohammadi et al. (2014) the bulge height could be reduced by 42% with outside offset in comparison to the unheated SPIF case. However, controlling the laser spot position relative to the tool contact position requires that the laser is attached to a moving robot arm, which increases the cost of the system.

Future work will involve measuring the temperature of the sheet with an IR camera. This would provide more information about the temperature distribution for different materials and laser power values. The temperature distribution may also vary based on the formed shape, since the heating may be more significant, for instance, in concave shapes than convex ones. Thus, the effectiveness of the laser assisted heating should be investigated separately for different shapes.

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