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Optimisation of laser assisted forming conditions for improved formability of aerospace materials

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Abstract. ISF technology was gradually considered as a manufacturing technology for fabricating sheet metal parts for both commercial and military aircraft. However, many challenges remain with respect to improving the consistency of the process, such as part thinning and springback. This is especially critical for two phase titanium alloy Ti-6AL-4V which has limited formability at room temperature. Therefore, understanding the correlation of laser system parameters and material properties is a key aspect for successful ISF of non-fractured Ti-6AL-4V. The laser heating is modelled to find the relationships between laser power, beam radius, scan speed, and the resultant temperature. The analysis shows that the temperature from laser heating increases with an increase in power, decreases significantly with an increase in beam radius, and decreases slightly with an increase in scan speed.

1. Introduction

Single point incremental sheet forming (SPIF) is a promising manufacturing technique in which sheet metal is formed without a dedicated die. By removing the need for a die, SPIF significantly reduces lead times on parts and can reduce costs for prototyping and small batch production [1]. Another major advantage of SPIF is the increase in the forming limit of the metal due to localised stresses generated during the forming process [1].

However, numerous deformation mechanisms during the SPIF process have significant impact on the geometrical accuracy of the finished part [2]. Additionally, hard to deform materials such as Ti-6Al-4V still have formability issues in SPIF at room temperature. One potential solution to both of these problems is laser assisted single point incremental sheet forming (LASPIF), in which a laser preheats the area being formed.

The localised heating supplied by the laser alleviates formability issues and improves the geometrical accuracy of the final product [3]. Duflou et al. introduced LASPIF using a laser on the opposite side of the sheet to the tool with a small forward offset [3]. It was found that laser assistance reduced the forming forces, improved part accuracy in 65Cr2 blanks, and increased the formability of Ti-6Al-4V sheets.

Gottmann et al. developed their own LASPIF set up in which the laser was applied to the same side of the sheet as the tool at a forward offset of 45 mm [4]. His work focussed on titanium alloys with the aim of improving formability and accuracy to make LASPIF a suitable process for aerospace. The maximum forming depth of a Ti-6Al-4V sheet was significantly increased. In other papers a method for

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measuring and controlling temperature during LASPIF was to embed a thermocouple in the tool [4] and the deformation mechanisms involved in LASPIF of Ti-6Al-4V were investigated [5].

It has been demonstrated several times that LASPIF can improve the accuracy of parts made with low formability alloys such as Ti-6Al-4V, but the process isn't fully understood. The optimal laser-tool offset is unknown as different papers have used different offsets [3] [4] [6] without any conclusive investigation into which offset gives the most accurate results. Additionally, the laser parameters for each experiment's desired temperature are often found using trial and error or thermal models.

Thermal models are developed in this work reflecting the relationships between the laser parameters and the resultant temperature in the simplest case of a straight path. Due to the specifics of the Hybrid Laser Metal Deposition (LMD) machine used in the current work, the laser system and the SPIF tool (stylus) cannot be used simultaneously. Therefore, laser setups were designed to produce a preheated area on a Ti-6Al-4V sheet and the developed model is used to predict what temperature drop could be expected during tool change between the laser head and the forming tool. Gottmann et al. found that coupled setup of the laser and forming tool induced overheating of the part and tool and leads to significant tool and component surface degradation and therefore negatively influence the materials' formability [7]. It is expected that the machine set up modelled in the current work and used for subsequent validation will avoid the aforementioned issues.

2. Methods and experimental set-up

2.1. Modelling

The models were run on Abaqus 6.14.4. To simulate Ti-6Al-4V, the model used temperature dependent values for density, thermal conductivity, and specific heat, [8] an emissivity of 0.25, and an absorptivity of 0.34 for Ti-6Al-4V [9]. A convective heat transfer coefficient of 50 W/m^2K was used. To model the temperatures resulting from a straight laser path, only half of the heated volume was modelled as symmetry across the laser path can be expected. The laser was modelled as a Super-Gaussian surface heat flux of order 10 using the DFLUX subroutine. Laser parameters ranging from 2mm to 5mm beam radius, 20 mm/s to 50 mm/s scan speed, and 200 W to 1400 W were modelled, with a sheet thickness of 1.6 mm. In order to determine peak temperatures under the laser, the laser path was three times as long as the laser beam diameter. To allow comparison between different setups when each model contains thousands of data points, the highest temperature at any point under the laser was recorded as peak temperature and these peak temperatures were compared.

2.2. Path modelling

To model the temperatures resulting from a laser path designed for the AFRC's setup, a 200 mm by 120 mm region of 1.6 mm thick Ti-6Al-4V sheet was modelled with a 5mm mesh across the entire surface. No symmetry could be exploited. The tool path was designed to preheat a region of sheet before a 25 second tool change and is shown in figure 1a. The path was coded in Fortran and applied using DFLUX. An 85 second air cooling step was considered, to predict the temperatures after the 25 seconds required for tool change and for up to 60 seconds of forming cycle. The laser model followed the path in figure 1a with a scan speed of 50 mm/s and a beam radius of 10 mm. The laser repeated the loop until the sheet lost heat at the same rate as the laser provided heat and the temperature distribution became steady. This required 60 loops. Different laser powers from 675 W to 1200 W were tested to find a range of temperatures.

3. Results and discussion

The temperature range of interest for LASPIF of Ti-6Al-4V is 400 °C to 700 °C as optimal material formability was observed [5]. The peak temperatures from selected thermal models are listed in table 1. The peak temperature was found to increase as laser power increased, decrease significantly as beam radius increased, and decrease slightly as scan speed increased.

In general, the choice of beam radius will depend on the width of heating required by the process. The smallest radii that was modelled can produce high temperatures with low powers. To produce temperatures in the range of 400-700 °C using a larger beam radius, high powers and slow scan speeds are required. The scan speed is limited by the range of appropriate tool feed rates when the forming tool follows the laser.

Table 1. Prediction of peak temperatures for a range of powers, radii, and speeds.

Beam Radius (mm)	Scan Speed (mm/s)	Peak Temp at 200W	Peak Temp at 600W	Peak Temp at 1000W	Peak Temp at 1400W
2	50	314	762	1130	-
3	30	245	595	866	-
3	50	195	487	723	919
5	20	161	400	601	782
5	30	134	332	501	653
5	50	107	266	406	529

The temperature distribution produced by the laser path designed for the AFRC's machine setup is shown in figures 1b and 1c. When the laser heating ends there are steep temperature gradient with temperature ranging from 900 °C to 100 °C. After 25 seconds of cooling the temperature in the central part dropped to 340 ^{O}C and the lower range of the temperature gradient remained almost unchanged.

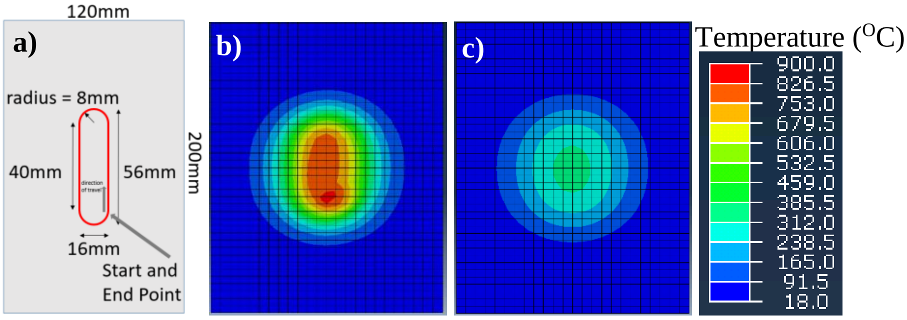

Figure 1. a) laser path used for model; b) temperature distribution after laser heating with power of 1200W after 60 loops; c) temperature distribution after 25 seconds of cooling.

Figure 2 shows the temperature in the centre of the upper surface sheet during 85 seconds of cooling. The peak temperature occurred directly under the laser, not in the centre of the sheet, and so the peak temperature for each model is included in the legend.

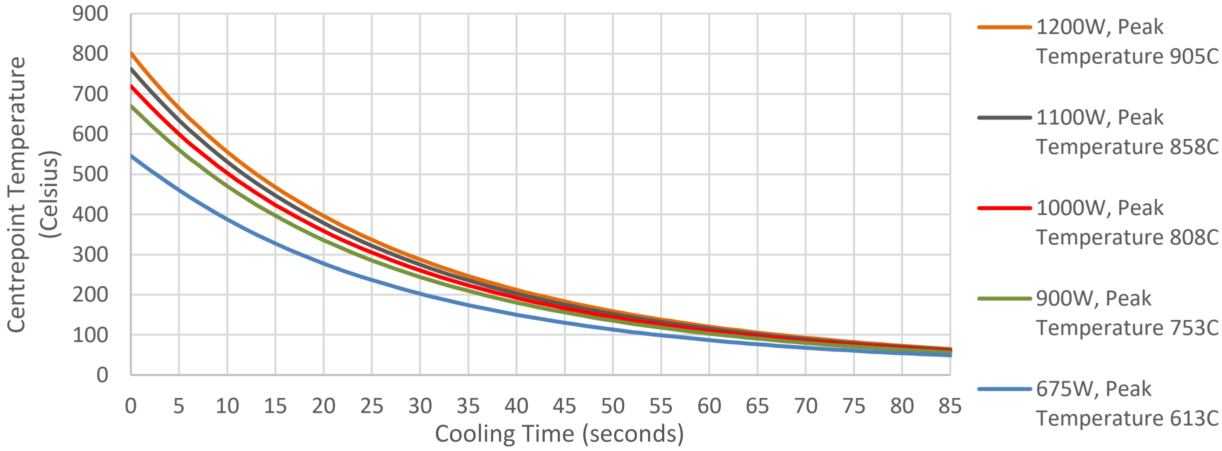

Figure 2. Temperature distribution in the centre of the modelled sheet.

The temperatures after 25 seconds ranged from 200–340 °C which is lower than the target temperature range of 400–700 °C. To achieve temperatures above 300 °C after 25 seconds of cooling, the sheet must be heated above 700 ºC. After 85 seconds, the temperature drops to around 60 °C. The resultant temperatures could be increased by using a thicker sheet, which may require a more powerful laser. Some improvements could also be made by increasing the length of the laser path and increasing the laser power, as these changes would decrease the peak temperature in the sheet without reducing the rate of heat input.

4. Summary and conclusions

Thermal models representing laser heating of a sheet of Ti-6Al-4V were produced to investigate the effect of laser parameters on the temperature distribution. The thermal models found that:

- The peak temperature due to laser heating increases as laser power increases, decreases significantly as beam radius increases, and decreases slightly as scan speed increases.
- Laser heating designed to account for a 25 second tool change has a significantly less localised temperature distribution than is normally found in LASPIF.
- The temperature range of 200-340 °C after a 25 second tool change is achievable for a 1.6 mm Ti-6Al-4V sheet heated by a 1200 W laser.

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