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Holographic measurement of distortion during laser melting: Additive distortion from overlapping pulses

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ABSTRACT

Laser - material interactions such as welding, heat treatment and thermal bending generate thermal gradients which give rise to thermal stresses and strains which often result in a permanent distortion of the heated object. This paper investigates the thermal distortion response which results from pulsed laser surface melting of a stainless steel sheet. Pulsed holography has been used to accurately monitor, in real time, the out-of-plane distortion of stainless steel samples melted on one face by with both single and multiple laser pulses. It has been shown that surface melting by additional laser pulses increases the out of plane distortion of the sample without significantly increasing the melt depth. The distortion differences between the primary pulse and subsequent pulses has also been analysed for fully and partially overlapping laser pulses.

1. Introduction

When metal products are exposed to a temperature increase and melted locally, residual stresses and distortion are inevitable side effects of the heating and subsequent cooling process [1]. Most laser - material interactions involve some kind of permanent plastic thermal distortion, since the temperature is usually so high that the thermal stresses override the material tensile strength of the work-piece. This is an important point to consider when developing processes and designing components with respect to e.g. weld design, so an understanding of distortion is important. Thermal distortion is a complex physical process and the situation is even further complicated in the case where the laser interacts with material which is pre-stressed from mechanical processes such as cold working or thermal stresses, which is the case for most industrial applications. In cases where the distortion is unwanted, such as welding, the laser has established itself as a low heat input, low distortion alternative to traditional torch technologies but, nevertheless, some distortion will generally be apparent. On the other hand, in applications such as laser bending [2] and wire straightening [3] a distortion effect is the desired outcome. Most of the currently published research considers only continuous wave laser processing. In this paper the deformation of a sheet as a result of melting by individual laser pulses is studied empirically.

1.1. Distortion mechanisms

Work by Zhou [4] divides distortion into in-plane shrinkage and out-of-plane bending of the component. Several researchers have used an approach where deformation is divided into three mechanisms, [5–9]:

1. Temperature gradient mechanism (TGM).
2. Buckling mechanism (BM).
3. Upsetting mechanism (UM).

The buckling and upsetting mechanisms are important when the laser creates a local heating pattern where the temperature is fairly uniform through the thickness of the sheet. In both mechanisms the heating and cooling cycle experienced by the sheet causes plastic failure and eventual deflection of the material. In the case of buckling, the final out-of-plane deformation direction is generally determined by the previous residual stress condition of the material (rolling direction, etc.). In the upsetting process the material is thickened in the laser heated area (and often shortened in other directions).

In the case of this experiment the temperature gradient distortion mechanism is dominant. As the name suggests this

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mechanism depends upon a sharp temperature gradient from the surface to the underlying material. When the top surface of a metal plate is locally heated by a laser the material undergoes a cycle of distortion as follows:

1. Heating begins: the top surface of the plate expands locally causing the material to distort. The heated surface moves towards the source of heating (see Fig. 1b).
2. The thermal stresses exceed the yield stress of the material which is then plastically compressed in the heated zone. On cooling, this compressed zone causes the sheet to distort. During cooling the heated spot moves away from the source of heating (see Fig. 1c) and remains in this new position. This laser-material interaction can be complicated by the melting and solidification of the centre of the laser heated zone, but the basic principle remains the same.

1.2. Multiple consecutive distortion

Edwardson et al. [10] has studied the cumulative distortion effects of multiple line laser melting and found that the bend angle increases for up to 60 scans. In work by Shi et al. [11] the elastic-plastic deformation is further described and a new mechanism is proposed; the coupling mechanism, which is a combination of the TGM and the UM.

In the work of Eriksson et al. [1] holography was used to monitor thermal distortion in real time to give information about the history of the deformation. In work by Dovc [12–14], an analytical model was developed and studied for a single pulse, this model confirms the results in [1]. Shi et al. [15] concluded that the deformation for a CW process is not purely 2D for the TGM case and state that the distortions are affected by the elastic properties of the plate. Pirch and Wisenbach [16] found that the TGM model does not explain the fact that the bending angle decreases with increasing amounts of irradiation.

Several researchers e.g. [17–25] have used Finite Element simulations for modelling distortion resulting from laser irradiation processes. Accurate measurements are an important part of the validation process for such simulations. An important aspect is the influence of heat input and heating methods, which has been studied by Shi et al. [18]. In this work the penetration profile in combination with sheet thickness and hence the thermal field were chosen so that the out of plane deformation would be as large as possible with pulsed laser heating. In the current paper the transient time response of a steel blank sheet exposed to multiple laser pulses is analysed by holographic methods, showing how the distortion is additive if several pulses are overlapped or partially overlapped. These results will be of interest to researchers involved in both laser welding and applications like laser forming or straightening, where an in-depth knowledge of distortion is important.

2. Methodology

In this empirical paper the sum of all stresses resulting in an out-of-plane distortion has been measured with time transient, i.e. contributions from TGM, BM and UM are all included. The out-of-plane real time transient deformation has been measured with an accuracy that is a fraction of the wavelength of the green holographic laser, 532 nm. The experimental results presented here show precisely how distortion takes place during the heating-cooling cycle and this is a useful tool for understanding how distortion is created by superimposed laser pulses and partially overlapping pulses.

The experimental setup is shown in Fig. 2 and is similar to that used in earlier work [1]. The imaged object was a 100 x 250 x 2.4 mm stainless steel 304L plate. To reduce the influence of residual stresses from manufacturing and cutting, the plate was annealed at 1100 °C and then stress reduced at 300 °C for 6 h prior to the experiment.

The holographic results was recorded by an unmodified Redlake Motionpro X3 CCD camera with a frame rate of 1000 Hz and an exposure time of 997 μs, to reduce the need for synchronization. The camera recorded phase shift on an area of 24 mm x 32 mm, with a resolution of 600 x 800 pixels. A ROFIN-SINAR RSM 200D/SHG, 532 nm wavelength Q-Switched green laser with an estimated pulse length of 200 ns and peak power of 9 kW, was used as illumination source for the holography. On the opposite side from the measuring system a laser spot weld was produced with a welding laser, HAAS 3006D Nd:YAG laser with a 600 μm fibre diameter and optical configuration of 180:180 mm.

A peak power of 1005 W and a 100 ms long pulse resulted in a small, shallow spot weld on the plate surface. Measurements were performed for square shaped pulses with a pulse energy of 100 Joules. Observations were made of the effect of; a single pulse, five superimposed pulses and five pulses which overlapped by 50% (each surface weld was 1.3 mm wide and the laser spot was moved 0.65 mm between pulses). Further details of the laser parameters are summarized in Table 1. The shielding gas was a coaxial flow of Argon. Table 2 shows the chemical composition of the SS 304L Alloy.

The plate was fixed along its bottom edge and there was an optical boundary condition that the bottom pixel-line of the camera was assumed to have zero movement to reduce scatter from vibrations.

For each 1 ms interval the interferometric phase difference was calculated from the digital hologram through Fourier transforms [26]. The phase information of the reference light is encoded on the CCD as high spatial frequency content. The original image was Fourier transformed and all low frequency pixels were set to zero. Fig. 3 shows a Fourier transform image. The left quarter of the image contains all the low-pass phase information. After the inverse Fourier transform each pixel has a complex value related to the phase difference between the object light and the reference light. By calculating the complex conjugate of two consecutive frames the phase change of the object light is identified and the displacement of the surface can be calculated.

In Fig. 3 the windowed area displayed on the left contains the phase information in the lower phase. The phase differences represent the out of plane (Z) movement of the plate, and if this movement is larger than λ/2 (266 nm) the phase will wrap. This is then compensated for in Matlab by an unwrapping algorithm. The total phase shift was accumulated over time and converted to physical

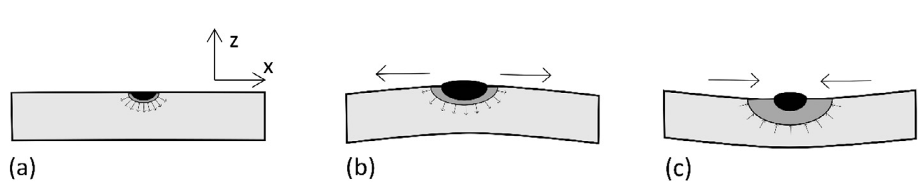

Fig. 1. Distortion from localized surface melting with TGM as the dominant mechanism.