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Root humping in laser welding – an investigation based on high speed imaging

Torbjörn Ilar\textsuperscript{a,*}, Ingemar Eriksson\textsuperscript{a}, John Powell\textsuperscript{a,b}, Alexander Kaplan\textsuperscript{a}

\textsuperscript{a}Department of Engineering Sciences and Mathematics, Luleå University of Technology, SE-971 87 Luleå, Sweden
\textsuperscript{b}Laser Expertise Ltd., Nottingham, UK

Abstract

Regular drop formation (humping) along the weld root during laser welding was studied by high speed imaging of the melt pool underneath the workpiece. The formation of droplets towards the rear of this weld pool was seen to be primarily caused by the pumping of melt from the bottom of the keyhole and the influence of gravity drawing melt into a sagging hump. This is a different process from the one which creates humps on the top surface of welds.

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1. Motivation / State of the Art

The regular formation of drops (the humping effect) in laser welding has been studied and analyzed by several research groups, but generally this research has concentrated on humping on the top surface of the weld. The phenomena behind top surface humping are considered to be widely understood. Together with numerical simulation of the melt flow phenomena,\cite{1, 6, 7, 8, 9} and modeling e.g. of the vapour flow\cite{1, 5, 8, 9}, high speed imaging\cite{3, 4, 10} has significantly contributed to a better understanding of the mechanisms involved. These phenomena are normally characterized by melt pool instabilities leading to the formation of severe undercut in combination with periodic droplet formation on the weld seam top surface. In particular, fluid flow competes against resolidification, eventually capturing and accumulating a droplet of melt which solidifies to become a hump.

However, the related phenomenon of humping on the weld root has not been thoroughly investigated, even though it might also have a severe impact on the mechanical properties of the weld. From stress analysis, Alam\cite{2} has demonstrated the mechanical sensitivity of laser weld root geometries to such
things as resolidified droplets and lack of fusion – both of which need to be avoided.

This paper presents an investigation of weld root humping based on high speed imaging (HSI).

2. Experimental

In this experiment the welding was carried out using a 15 kW fiber laser at powers between 8.5 kW and 10 kW, a welding speed of 3 m/min, an inclination angle of -7°, a lens focal length of 300 mm and a focus position 6 mm into the material. The melt behavior on the root side of the weld was monitored with laser illuminated high speed imaging (HSI). The material was 8 mm stainless steel, 304, with butt joint (machined) geometry. This work presents images taken by a Photron SA1 (San Diego, California) high-speed camera with a Micro-Nikkon 105 mm lens, at 4000 frames per second with an exposure time of 370 ns. A fibre-guided pulsed diode laser (Cavitar, peak power 500 W) with a wavelength of 808 nm was used to illuminate the workpiece surface, and was correspondingly narrow bandpass-filtered by the camera objective. The typical experimental arrangement with HSI camera is shown in Fig 1.

![Fig. 1. Typical experimental setup overview](image)

The Cavitar laser was set to illuminate the back of the plate and a mirror was positioned to reflect the root side image to the HSI camera. The goal of the experiment was not to obtain high welding qualities but to document the humping formation on the root side of the weld.
3. Results and Discussion

As can be seen in Fig 2 the experiments, as planned, resulted in poor quality weld profiles both on the top surface (undercut) and the bottom surface (root humping). However, there is no obvious direct correlation between the humping on the root side and the topology of the top side.

Fig. 2. Typical weld appearance: (a) on the top (undercut); (b) at the root (humps)

The two pictures (from HSI) presented in Fig 3 show the formation of one of the droplets in Fig 2 (the second hump from the right in Fig 2 b). The time taken from droplet initiation to the final evolution of the droplet was 16 ms, which is the interval between the 2 pictures. During filming a 1 mm scale was placed next to the weld line for reference (see fig.). From Fig 3 it can be observed that the weld pool is quite long (more than 8mm in this case) even at the root - and the formation of the droplets occurs in the tail section of the melt pool. Both these points were found to be true whenever root humps were generated.

Fig. 3. High speed images of the melt pool at the root (welding direction towards right). Upper: initiation of a droplet; lower: termination of droplet growth (scale 1 mm)

Fig. 4 shows a time series with 2 ms interval between each picture, starting with the upper picture in Fig 3 and ending with the bottom picture in Fig 3. It illustrates how high speed imaging can give a good insight into the root humping phenomena. The main mechanism that initiates humping seems to be an increase in the amount of material flowing in the melt pool, originated from instability in the bottom of the keyhole.
It is then clear that the droplet is gradually built up from the melted material stream towards the tail of the melt pool. Note that first some regular drops are initiated from the keyhole that do not cause humps but disappear again, but after a certain time a drop starts to grow and eventually solidifies. A close up of the key hole region shows how melted material is pushed out of the keyhole crater (marked with an arrow...
in Fig 5a) and this creates a wave that starts to move towards the droplet formation zone. The wave movement involves material transfer from the keyhole end of the weld pool to the solidifying end.

Fig. 5. High speed image sequence (0.25 ms steps) of the bottom of the keyhole that shows the pushing out of melted material and creation of a wave front in the melt pool

Once the droplet achieves a certain volume (and mass) it begins to sag below the bottom surface of the substrate under the action of gravity. This sagging action tends to draw more melt into the area – which then solidifies as a hump. This growth mechanism is further supported by two pictures in Fig 6 that show that the solidification starts in the base material. This hump growth mechanism is therefore based on a combination of surface tension effects, melt availability and gravity. The influence of gravity in this case means that the root humping phenomenon is profoundly different from top surface humping.

Fig. 6(b) indicates areas of lack in fusion that can act as stress raisers or crack initiators and this is one of the main reasons why root humping should be avoided.

Fig. 6. Root drop: (a) bottom view; (b) cross section, showing the solidification pattern and lack-of-fusion
4. Conclusions

This preliminary work has established that root humping is caused by a number of phenomena – including surface tension and gravity effects. The inclusion of gravity into the primary contributors means that root humping is profoundly different from top surface humping in laser welding.

The investigation is continuing and it is hoped that a more profound understanding of root humping phenomena will eventually lead to an improved laser welding process with suppressed root humping.

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