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# Using pulse shaping to control temporal strain development and solidification cracking in pulsed laser welding of 6082 aluminum alloys

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ABSTRACT

High-speed observation of visible and infrared radiation was performed to measure the molten pool geometry, velocity of the solid–liquid interface and temperature profile during laser spot welding of aluminum. Hot cracking occurred at a late stage of solidification for the investigated laser pulse shapes. Hot cracking could be minimized by using a pulse shape with two distinct power levels and a final cooling slope to shut down the laser power. The drop of the laser power from the first to the second power level led to a high cooling rate and high interface velocity at the beginning of solidification. This drop in temperature and molten pool diameter released strains originating from thermal contraction and solidification shrinkage at the beginning of solidification, where spot welding is expected to have a higher ductility. After this initial high solidification rate, low interface velocities were observed during solidification within the second power level. The final solidification rate increased again as a function of the cooling time of the last laser pulse section. This type of solidification process was also found in metallographic microstructures with greater dendritic structures during solidification within the second power level. The strain release at the beginning of solidification minimized residual strains for the remaining solidification, so that crack-free and full penetration bead-on-plate seam welding with overlapping spot welds was possible.



## 1. Introduction

Hot cracking is one of the major challenges in laser welding of aluminum alloys of the 2XXX, 5XXX and 6XXX series. The welding conditions play a significant role in the formation of hot cracking. Tirand et al. (2013) showed that the hot cracking susceptibility in continuous wave laser welding of 6056 aluminum alloys is dependent on the feed rate and welding regime. Higher feed rates and keyhole welding led to a higher risk of hot cracking because of higher cooling rates. The study of Wang et al. (2015) examined the effect of the restraint intensity in continuous wave laser welding of 6013 aluminum alloys. The authors found the mechanical strain, crack initiation and crack propagation to be controllable by the restraint conditions. The welding conditions are also affected by the laser operating mode; continuous wave (cw) or pulsed wave (pw). Cieslak and Fuerschbach (1988) welded aluminum alloys with a cw laser and a pw laser to compare the hot cracking susceptibility of both processes. The study found that rectangular laser pulses led to hot cracking in pulsed laser welding of 5456 and 6061 aluminum alloys. This was also presented in the study of Sheikhi et al. (2009) who showed that rectangular laser pulses caused hot cracking in 2024 aluminum alloy spot welds and overlapping seam welds. Katayama et al. (1997) found that high cooling rates were created by rectangular laser pulses. Recent hot cracking models, such as that of Hatami et al. (2008), forecast that hot cracking susceptibility increases for higher cooling rates, which explains the found results of the stated studies.

Typical pulsed laser sources allow shaping of the laser pulses to influence the cooling rate during solidification. The concept of pulse shaping is illustrated within the work of Tzeng (2000). The ramp-down laser pulse shape was used by Michaud et al. (1995) to weld different aluminum–copper alloys and by Zhang et al. (2008) to weld 6061 aluminum alloys. This pulse shape starts with a constant laser power for a defined time to generate the required weld pool. After this welding duration, the laser power is linearly decreased during a cooling duration to achieve moderate cooling rates during solidification. Both studies found that ramp-down laser pulses

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avoided hot cracking within the heat conduction welding regime. The relationship between the laser pulse parameters of the ramp-down laser pulse and the solidification conditions in aluminum welding was investigated by von Witzendorff et al. (2015), who observed the spot weld solidification with high-speed cameras. The study found the solid–liquid interface velocity to be controllable by the slope of the laser pulse cooling duration. The reduction of the solidification rate decreased the strain rate and coarsened the dendritic microstructure. Both proved to reduce hot cracking within the heat conduction welding regime. However, at solid–liquid interface velocities below 0.1 m/s an increased hot cracking susceptibility was observed, which was expected to be caused by increased hydrogen diffusion at the interface. A significant increase of the strain, spot weld deformation, was observed when increasing the laser pulse peak power in order to transition from the heat conduction to the keyhole welding regime. These large strains caused a high hot cracking susceptibility regardless of the solid–liquid interface velocity. The magnitude in strain could not be affected by the laser pulse cooling duration. This restricted the crack-free achievable weld penetration depth. The numerical simulation of Desai and Bag (2014) demonstrated that spot weld deformations increase for higher laser power. The study of Michaud et al. (1994) determined that only the temporal development of the strain was controllable by pulse shaping. The magnitude of strain was dependent on the laser pulse peak power or pulse energy.

The motivation of this study is to perform pulse shaping in order to affect the temporal strain development, so that, strains appear during the beginning of spot weld solidification when the spot welding is mostly molten. Weld testing experiments with externally applied loads performed by Nakata and Matsuda (1995) found a higher weld metal ductility at an early stage of solidification. Hot cracking sensitivity coefficients, which are based on the Rappaz–Drezet–Germaud model (Rappaz et al., 1999), also state that a greater fraction of liquid decreases the hot cracking susceptibility (Sistaninia et al., 2012). In addition, accumulated strains tend to be low at the beginning of laser spot weld solidification (Liu et al., 2014). Therefore, pulsed laser welding of 6082 aluminum alloys is done with step-down laser pulses. This pulse shape consists of two power levels and a final cooling slope. A similar pulse shape was used by Matsunawa et al. (1999) for suppression of hot cracking in aluminum welding and was shown numerically to further reduce the solidification rate in comparison to the ramp-down pulse shape. In the present study, the drop in laser power from the first to the second power level is intended to release strains at the beginning of solidification during a stage of higher weld metal ductility. The investigations also aim to give deeper insight into the relationship between the pulse shape, solidification conditions, metallographic microstructures and hot cracking mechanisms.

## 2. Experiments

The experimental setup and the investigated laser pulse shapes are presented in Fig. 1. Two high-speed cameras observed the welding zone to capture the temperature profile and the size of the molten pool within the welding process. The infrared camera was capturing thermal radiation emitted by the molten pool in the wavelength range of 2–5.7 μm at a frame rate of 2000 fps. The camera was tilted by an angle of 45° with respect to the sample surface. The acquired images have 32 × 36 pixel$^2$ at a resolution of 50 μm/pixel. The temperature image was calibrated for molten aluminum with temperatures above 1000 °C. The emission coefficient ($e$) was assumed to be constant and $e = 0.2$ (Totten and MacKenzie, 2003).

The high-speed camera which captures visible radiation was aligned coaxially to the laser radiation. The scene was illuminated

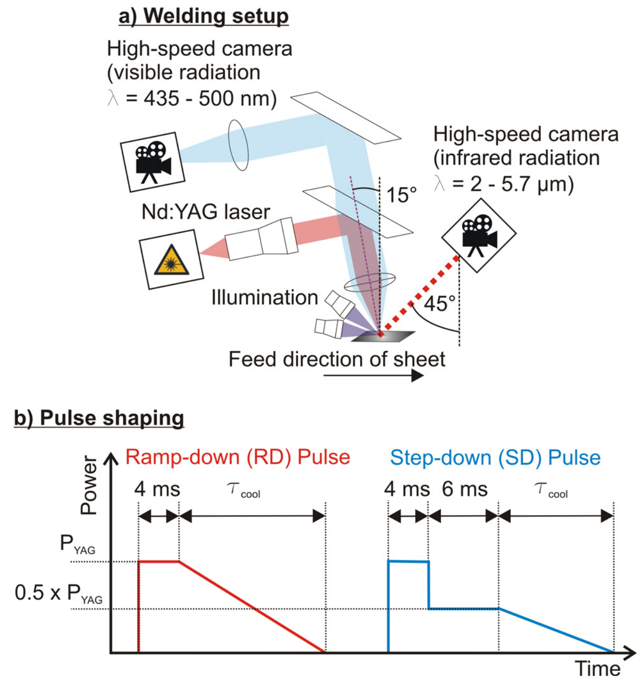


**Fig. 1.** (a) Welding setup and (b) pulse shaping.

with two light emitting diodes with 1 W output power at a central wavelength of 455 nm. Process radiation was suppressed by a band-pass colored glass filter which transmits radiation between 435 and 500 nm. The image size was 140 × 140 pixel$^2$ with a resolution of 8 μm/pixel. The images were acquired at a frame rate of 1856 fps.

The welding head was tilted by 15° with respect to the vertical direction. Argon shielding was applied to the molten pool at a flow rate of 5 l/min. The weld root was shielded with argon at a flow rate of 10 l/min.

Two pulse shapes were investigated, the ramp-down (RD) laser pulse and the step-down (SD) laser pulse. Both pulse shapes start with a constant welding duration (4 ms) with the laser pulse peak power $P_{YAG}$. After this welding duration, the RD and SD laser pulse shape differ. The RD laser pulse decreases the laser power linearly during the cooling duration ($\tau_{cool}$). The SD laser pulse instantly decreases the laser power to 50% of $P_{YAG}$. This power level is held for 6 ms; afterwards the laser power decreases linearly during $\tau_{cool}$. The terminology for the experiments is: pulse shape – $\tau_{cool}$ – $P_{YAG}$, for example: RD – 3.5 ms – 1.8 kW.

Spot and seam bead-on-plate welding experiments were performed in unrestrained conditions. The welding specimens were Al6082-T6 aluminum alloy sheets with a thickness of 0.5 mm, the composition of which is stated in Table 1. The samples were cleaned with acetone before welding. The experiments were repeated three times for statistical validation. The hot cracking susceptibility was investigated throughout the spot welding experiments. The spot welding was performed with a single laser pulse without movement of the aluminum sheets. The focal position was set to be on the aluminum surface.

The hot cracking susceptibility increases during laser spot weld solidification (Liu et al., 2014). The end of solidification occurs in the spot weld center at the top surface. The spot weld center can be identified by circular solidification bands which illustrate the movement of the solid–liquid interface. The crack radius ($R_{crack}$) was used as an indicator for the hot cracking susceptibility which is the distance of the crack tip from the spot weld center. The authors always considered the crack with the largest extent (Fig. 2). The crack radius was also used by Nakashiba et al. (2011) to evaluate