Changes in Laser Weld Bead Geometry with the Application of Ultrasonic Vibrations

S. Venkannah and J. Mazumder

***Abstract*— The weld bead geometry has been found to be a function of the parameter settings, such as welding speed and welding power, during fusion welding. Vibrations (both sonic and ultrasonic) applied to conventional casting and welding processes have changed the mechanical properties of many metals and alloys usually with a decrease in power requirements, processing temperature and time. Vibrations also affect the pool dynamics bringing along a change in the surface topology of the resultant solidified weld bead. Researchers have related the growth rate, cooling rate, thermal gradient and solidification rate to the weld bead geometry which is being disturbed by vibrations during ultrasound assisted welding.**

Mild steel plates were subjected to ultrasound of low acoustical power during "bead on plate" laser welding at different speeds. The mild steel plate was held at one end by the ultrasonic horn through which ultrasound was injected. A bead on plate weld of length 80 mm was then performed along the center of the plate using a CO_2 laser (1 kW). After several trial tests, the following two welding speeds; 400 and 2000 mm per minute were used. The ultrasonic powers selected were 3W and 6W respectively for each welding speed as higher acoustical power was causing ejection of molten metal from the pool during welding.

The surface topography of the weld beads have been affected by ultrasound and the effect is clearly dependent on both the welding speed and acoustical power. The welding speed affects the size of the molten pool while the acoustical power influences the magnitude of the forced vibration on the pool. The different layers in the molten pool are being pressed against each other and forced to move backwards on eth solidified weld bead in some cases.

***Index Terms*— Ultrasound, Laser Welding, Weld Bead Geometry, Surface Topography, Steel.**

I. Introduction

The weld pool volume is controlled by the welding parameters and is directly proportional to the heat input and inversely proportional to the welding speed. The thermal conditions in and around the weld pool along with the fluid dynamics during the fusion welding process have an influence on the size, shape and surface morphology of the weld beads.

Researches have been conducted to determine the effects of the rate of heat input on the bead morphologies and the properties of the welds obtained for different fusion welding processes. Ultrasound (US) applied to conventional fusion welding processes has been found to alter the properties of the weld beads to different extent depending on acoustical power. The vibrations are also causing physical displacement of molten metal along with vibrating the molten pool, therefore affecting the weld bead topology.

The effect of the vibrations is not uniform throughout the length of the welds but depends on the ultrasound wavefront propagation in the sheets being welded. The standing waves in the plates are almost sinusoidal with regions of high amplitudes and low amplitudes. The contact angle of water on a paraffin coated substrate was seen **[1]** to change from non-wetting to wetting with the application of ultrasonic oscillations and the change is dependent on the ultrasonic power. The acceleration due an ultrasonic power of 0.91 W is about 3000 times that of gravity hence forcing the water droplet to spread on the vibrated surface. The liquid is therefore being pressed against the solid plate with higher force resulting in better contact between the liquid and solid.

The objective of this research is to concentrate on the weld pool shape during welding in the presence of ultrasonic vibrations. The last puddle to solidify is being considered as this the point where the laser beam stops and the displaced molten metal does not have time to flow back in the cavity because of the force exerted by the beam. The plate is momentarily at rest with the laser beam still on. Hence an instantaneous picture of the pool is obtained giving details of the weld pool shape as well as the distribution of the molten metal in the pool.

There are two modes of welding with laser beam: conduction and "keyhole". In keyhole welding there is enough energy/unit length to cause evaporation and create a hole in the melt pool. The hole is stabilized by the pressure from the vapor being generated. The "keyhole" behaves like an optical black body in that the radiation enters the hole and is subject to multiple reflections before being able to escape. The efficiency of laser welding **[2]** can range from very low in highly polished aluminum or copper to very high in deep penetration keyhole welding or in materials with low reflectivity.

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Research **[3]** in the laser welding of quartz and aluminum highlighted two principle areas of interest in the mechanism of keyhole welding. The first is the flow structure since this directly affects the wave formation on the weld pool and hence the final frozen weld bead geometry. This geometry is a measure of weld quality. The second is the mechanism for absorption within the keyhole which may affect both this flow and entrapped porosity.

The shape of the pool is determined **[4]** by the heat and fluid flow conditions and the resultant thermal fields. The shape of the pool is constant during steady state welding for any given speed. Matsuda *et al.* **[5]** showed that there is a critical growth rate when the weld pool shape will change. A critical growth rate exists for an elliptical weld pool beyond which the minimum thermal gradient present at the weld centerline cannot dissipate the generated heat of fusion sufficiently quickly. For growth rates above this critical value, the weld pool changes and becomes more elongated and tear drop shaped.

The weld pool volume is controlled by the welding parameters. The volume is directly proportional to the arc current (in arc welding) and inversely proportional to the welding speed. Thermal conditions in and near the weld pool and the nature of the fluid flow have been found to influence the size and shape of the weld pool.

Suutala **[6]** reported that the weld bead shape and the growth rate in arc welding of stainless steel are dependent on the welding speed. Under low-heat input/low-speed welding conditions, the molten pool in fusion welding has an elliptical shape **[7]** and columnar crystals grow by curving in the welding direction. On the other hand, under high heat-input/high speed welding conditions, the molten pool assumes a teardrop shape and that, when no nuclei for heterogeneous nucleation are present inside the weld metal, the crystals linearly grow and collide at the welding center. If nuclei are present, however, equiaxed crystals are formed. With an increasing degree of nucleation, more new crystals are formed and grain refinement occurs.

The size and shape of the weld pool depend on the conductive and convective heat transfer. The presence of electromagnetic or surface tension gradient forces will enhance the convective heat transfer and this will result in variations in the size and shape of the weld pool. Fluid flow conditions in the weld pool not only influence the weld penetration but also can influence macrosegregation, porosity in the weld, and the solidification structure.

Surface tension gradients can develop as a result of the temperature variation on the weld pool surface combined with the temperature dependence of the surface tension. In addition, any compositional variations across the pool surface can result in surface tension gradients and corresponding convective flows. The direction and magnitude of the surface tension gradient forces are dependent on the exact composition and temperature dependence of the surface tension.

II. Experiment

Bead on plate laser welds were made in the presence of ultrasonic oscillations at two different welding speeds and compared with reference welds. The bead on plate weld is not a joining process but simply a “melting and solidification” process of the material. A constant laser power of 1 kW was used with beam mode TEM_{01} and the laser beam was focused on the surface of the plate. The welding speeds used were 400 and 2000 mm/min and the acoustical (ultrasonic) power used were 3 and 6W. At the slowest speed of 400 mm/min, the depth of penetration achieved was on average 1.6 mm whereas the 2000 mm/min speed gave an average depth of penetration of 0.95 mm.

The mild steel plate (200 x 60 x 1.9mm) was held at one end by the ultrasound horn during the laser welding process using a 5 mm bolt as shown in Fig 1 and the other end was free. A “bead on plate” weld was performed along the center of each steel plate from the free end for a length of 90 mm. Ultrasound at a frequency of 20 kHz was introduced in the plate through the transducer throughout the duration of the welding process. The same set up was used for reference welds but the ultrasonic transducer was switched off.

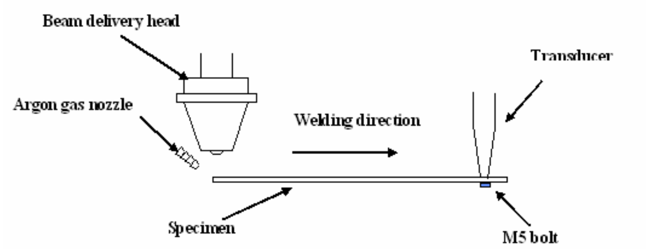


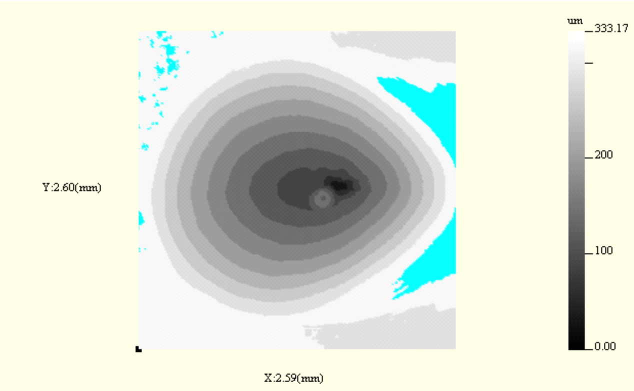
Fig 1: Set Up for the Laser Welding

The end of the weld bead was measured on a Talysurf and the 3D and 2D profiles were analyzed using the Surfstand® software. The range of the diamond stylus on the Talysurf was ±540 μm. The US assisted weld bead profiles are compared with the respective reference weld beads in the sections. 3D views of the different welds have been reproduced using the software and 2D profiles have been extracted at various positions of interest from the reproduced weld bead.

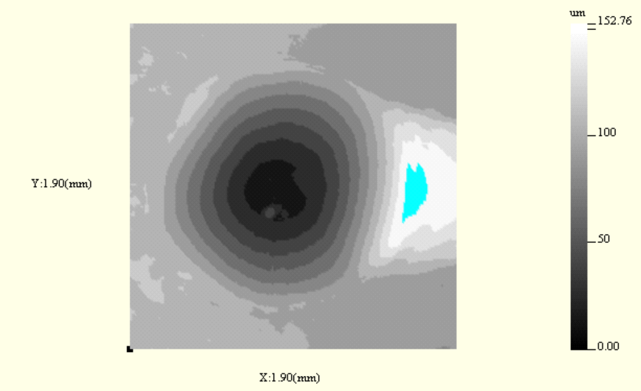
III. Results

A. Weld Bead Geometry

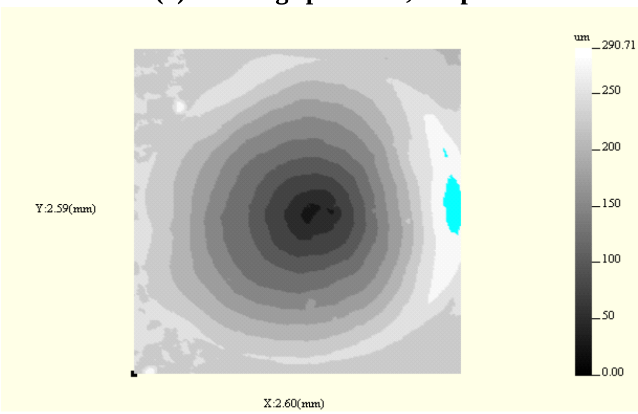
The shape of the weld bead of the laser welds for the weld at a speed of 400 mm/min and 2000 mm/min for the same laser power but different ultrasonic power are shown in the Fig 2. The area selected are different for each welding speed because of the size of the weld beads but the same length and width have been selected for each speed (2.6 mm x 2.6 mm for 400 mm/min and 1.9 mm x 1.9 mm for 2000 mm/min). The scale on the right hand side of each figure indicates the height of each of the profiles with respect to the lowest point in the pool. The maximum value gives the distance between the lowest point to the highest peak in that portion of the weld.



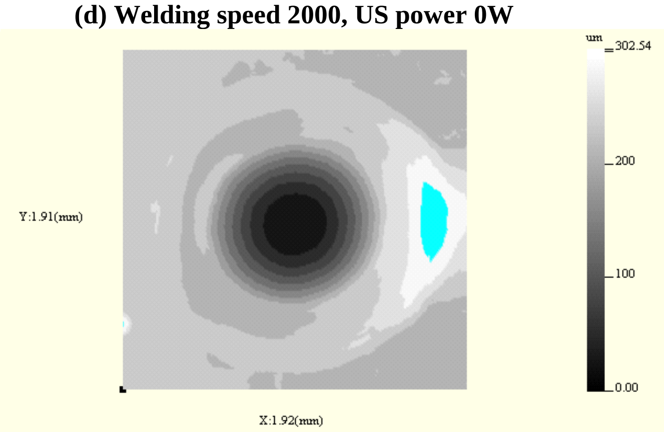
(a) Welding speed 400, US power 0W



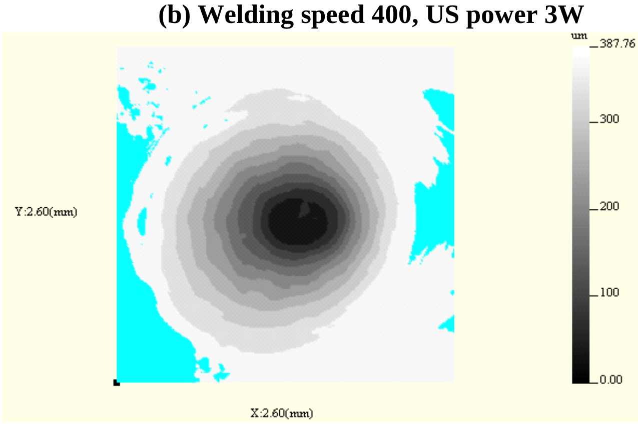
(d) Welding speed 2000, US power 0W



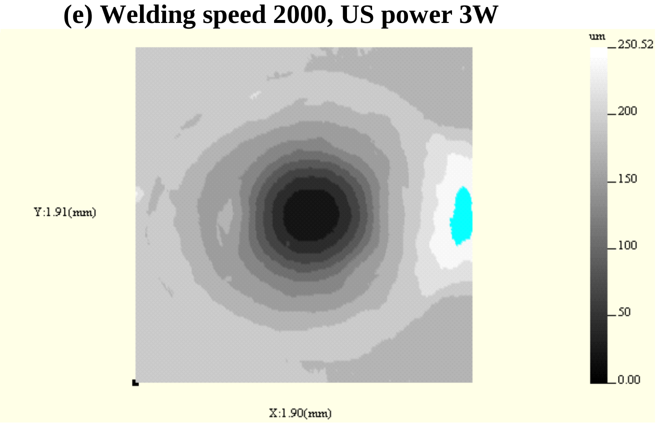
(b) Welding speed 400, US power 3W



(e) Welding speed 2000, US power 3W



(c) Welding speed 400, US power 6W

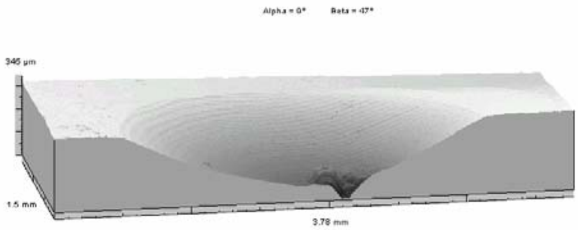


(f) Welding speed 2000, US power 6W

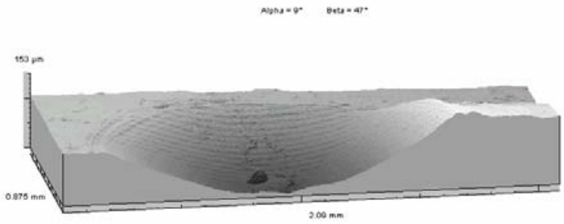
Fig 2: 2D Weld Bead Geometry Showing Material Distribution

The weld bead made at a speed of 400 mm/min has a tear drop shape whereas the weld made at a speed of 2000 mm/min is almost circular. The large mass of the steel plate rapidly dissipates the heat from the welding zone with a 2000 mm/min weld. At the slow speed, there is some conduction of heat to weld bead, hence slowing the cooling rate and changing the weld puddle to almost circular. The contours for the height distribution in both weld beads are regularly spaced around the center of the bead. This means that the slope of the welds bead from the center to the outside of the bead is almost uniform.

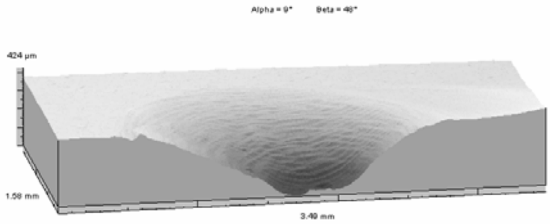
Ultrasonic oscillation is modifying the shapes of both weld beads giving rise to clearly defined circles around the center. At the same time, the molten metal is being subjected to a force due to the vibrations pressing it against the surrounding parent metal. From the above figures (Fig 2), it can be seen that the shape of the contours are circular and very close to each other in the central core of the weld made becoming wider towards the outside of the weld. The ultrasonic oscillations are forcing the molten metal to arrange itself symmetrically around the vertical axis passing through the center of the weld. The molten metal at the center of the weld pool is forced towards the outside of the weld resulting in a very deep and hemispherical weld bead (Fig 3) with a region consisting of a small slope around the central hemisphere.



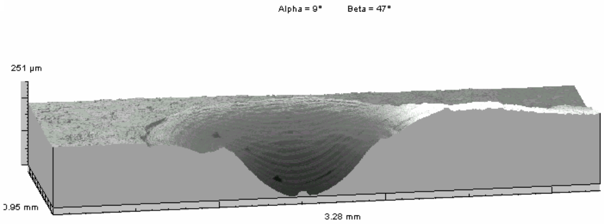
(a) Speed 400 mm/min, US power 0W



(b) Speed 2000 mm/min, US power 0W



(c) Speed 400 mm/min, US power 6 W



(d) Speed 2000 mm/min, US power 6 W

Fig 3: 3D Section Though Weld Bead

The characteristic chevron pattern is clearly visible on the reference weld bead and the profiles from the puddle merges smoothly with ripples of the weld bead. In the 6W ultrasonically assisted weld, a discontinuity is present immediately outside the puddle where the profiles change from circular to “V” shaped. This is due to extra molten metal from the puddle spilling over the weld bead. It is, therefore, clear that the US oscillations are forcing the molten metal from the weld bead puddle backwards over the weld.

B. 2D Longitudinal Cross Section

The 2D profile along the longitudinal center of the reference and vibration assisted welds are shown in Fig 4. The length of the section is 3mm in all cases. At both speeds, it is evident that the ultrasonic oscillations are changing the weld bead surface morphologies. There is a smooth interaction between the weld puddle and the weld bead in the reference weld made at 400 mm/min but a sharp peak is visible on the right of the weld bead puddle for the weld made at a speed of 2000 mm/min. This is probably due to the momentum of the molten pool as the plate suddenly comes to rest. Given that the pool is small compared to the reference weld made at 400 mm/min, there is less internal resistance due to friction between different layers in the pool.

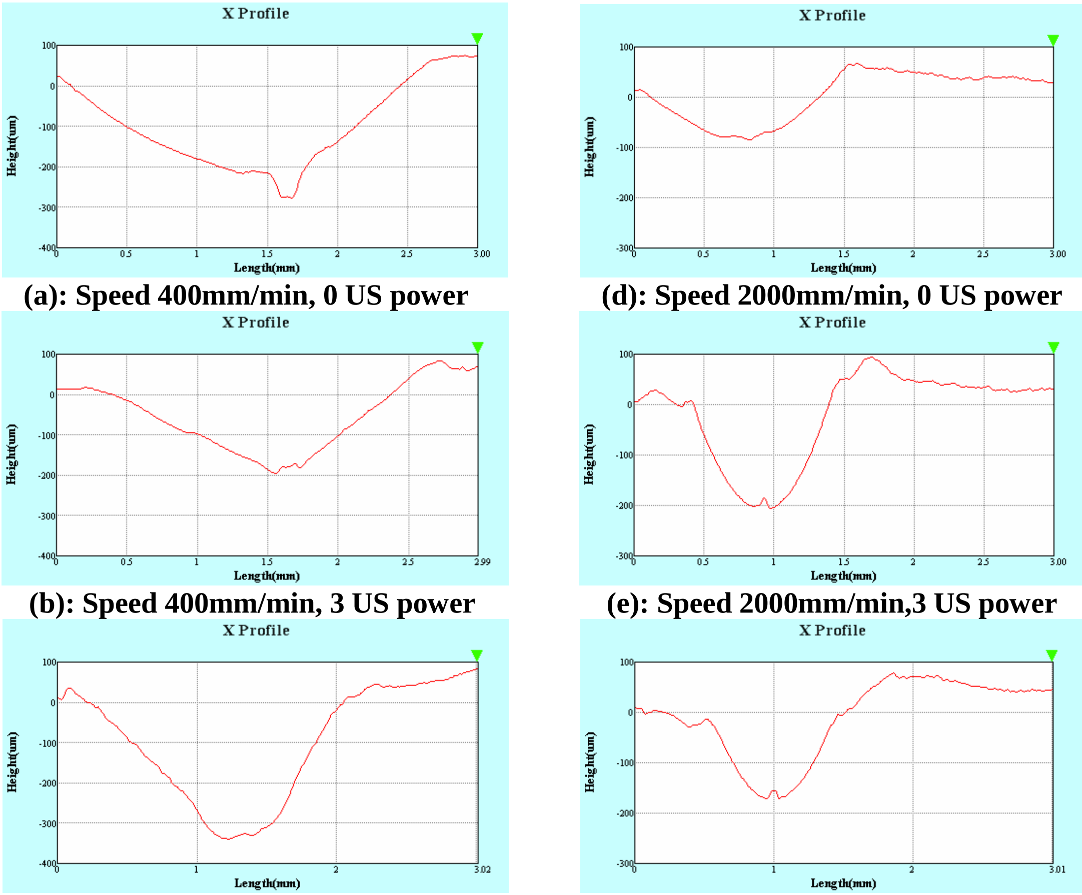
The 3W US oscillations are affecting the weld bead but the effect is more visible in the case of the 2000 mm/min speed. This may be due to the fact that solidification rate is higher in this case.

US oscillation is helping in dissipating heat away from the weld bead. The effect is more pronounced in the case of the 2000 mm/min weld as the laser heating is more localized at high speed as compared to lower speed. The low speed allows more uniform heat conduction from the weld pool to the parent metal. Hence the effect of US oscillations is more visible in the case of 2000 mm/min.

The depth of the groove below the surface of the plate has been determined from the surface profile and is given in Table 1. The average depth of penetration is 1.6 mm and 0.95 mm for the welding speed 400 and 2000 mm/min respectively. The volume of metal melted is larger with the 400 mm/min speed and this mass of molten liquid would provide some damping, due to internal friction, during a sudden stop. The momentum of the liquid at 2000 mm/min is higher than the 400 mm/min speed and during a sudden stop some molten metal will have a tendency to move backwards with a smaller resistance due to the lower liquid layers.

US oscillations are also causing movement of molten metal as can be seen from the profiles in Fig 4 (b) and 4 (e). There was no peak with a welding speed of 400 mm/min in the absence of ultrasound but when 3W US is applied a peak is formed just outside the weld puddle. The peak in the case of 2000 mm/min is higher than that in the reference weld made at the same speed.

The effect of 6W US oscillations is to increase the force due to the mass of the pool as well as acting on the viscosity, therefore it can be seen that the peak is lower than with the 3W oscillations. The peak has almost disappeared at the speed of 400 mm/min and in the case of 2000 mm/min, the peak is smooth and not as sharp as that obtained with 3W ultrasonic oscillations.



(a): Speed 400mm/min, 0 US power

(d): Speed 2000mm/min, 0 US power

(b): Speed 400mm/min, 3 US power

(e): Speed 2000mm/min,3 US power

(c): Speed 400mm/min, 6 US power

(f): Speed 2000mm/min, 6 US power

Fig 4: 2D Profile along Center of Weld

IV. Discussion

The forced vibration of the molten pool is increasing the acceleration of the pool which can be calculated knowing the amplitude of vibrations. The amplitude of vibrations is varying continuously along the center of the plate and the average minimum and maximum with 3W ultrasonic power are 0.8 µm to 4.5 µm respectively. The calculated acceleration due to ultrasonic vibrations is in the range 823g m/s^2 to 4636g m/s^2. The average maximum amplitude with 6W was 6.2 µm giving a maximum acceleration of 6381g m/s^2. This high acceleration will have an effect on the forces acting on the molten pool.

The extreme high acceleration acting on the weld pool changes the surface tension on the pool. The weld puddle can be considered as part of a sphere. The shape has large radius of curvature in the case of reference weld (without US) and it changes to a small radius of curvature as the US power is increased.

The ultrasonic oscillations are enhancing the heat transferred by conduction and convection in the plate and the rate of heat dissipation seems to be dependent on the US power. If the heat transfer rate is very high, the area of the parent metal achieving melting temperature is reduced. This is shown by the change in the shape of the weld bead puddle with a welding speed of 400 mm/min. The heat dissipation from the pool is more regular changing the shape from tear dropped to almost circular. The size of the surface of the weld bead puddle is seen to increase with 3W US power because the flow of molten metal is parallel to the surface of the pool. With 6W US power, the molten pool is further depressed due to the high acceleration acting on the pool and the molten pool is in contact with a smaller surface area of the parent metal. Hence the top surface of the weld pool is not affected by the higher heat dissipation. The pool being depressed further, the heat is dissipated to part of parent metal which is at a lower temperature than the heat affected zone. This is not sufficient to melt the metal.

Table 1: Peak to valley height.

SPECIMEN		Depth of puddle below surface of plate (μm)	Peak (on the right of weld puddle) above surface of plate (μm)	Peak to Valley height (S_t) for weld puddle (μm)
Speed 400 mm/min	US 0W	324	9	333
	US 3W	230	59	289
	US 6W	376	12	388
Speed 2000 mm/min	US 0W	106	20	136
	US 3W	205	98	303
	US 6W	189	46	235

The type of welding is most probably conduction in the 2000 mm/min specimen and keyhole in the 400 mm/min specimen. The laser beam is very much localized in the case of 2000 mm/min therefore the thermal gradient is very high. The amount of heat transferred in keyhole welding is already relatively high due to multiple reflections in the hole. Heating due to conduction results in a relatively large weld bead and heat affected zone leading to a lower thermal gradients. If heat is transferred to the HAZ at a higher rate then more metal may melt whereas in the case of keyhole welding the surrounding metal is at a low temperature. Increase in the rate of heat transfer to this region merely raises the temperature but not enough to cause melting of additional metal. US oscillations is enhancing heat dissipation from the molten pool in conduction welding but it may also be affecting the multiple reflections that take place inside the keyhole cavity.

The forced vibration on the weld pools in both cases cause uniform displacement of the metal in the weld pool about the laser beam. Hence the shape of the weld puddle is symmetrical. The weld bead seems to consist of two parts an outer rim surrounding the inner central core of the puddle. This is due to the effect of US vibrations on the surface tension which is preventing the formation of a smooth transition from the center of the weld to the outer rim of the weld puddle.

V. Conclusion

Ultrasonic vibrations are forcing the different layers in the molten pool against each other and against the solid metal plate supporting the pool. The molten metal is being displaced to the sides of the pool as the plate is moving due to the elasticity of the pool. The shape of the bead and distribution of material in the bead are being affected to a great extent. The large force on the molten metal will enhance the contact between the pool and the solid backing plate but this dependent on eth welding speed and the acoustical power.

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