# Comparison of Theoretical Disc and Point Source Profiles with Actual-Melt Source Profile in Conduction Welding

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***ABSTRACT:*** Prediction of fusion zone in numerical modelling of welds using a modified heat transfer model requires experimental results for validation. Primarily, the modified heat transfer models are developed from the point and disc source heat models which can be assumed to be a semi-circle or spherical shape. In this study, a simple relationship between melt areas, the depth of penetration and weld width was proposed for point and disc source profiles to represent the actual weld profile. The results obtained for focused and defocused laser beams indicate that the actual weld profile is closer to a point source than the disc source. The transition between the conduction and keyhole regimes was achieved when the actual weld depth of penetration is below that of the point source.

## I. INTRODUCTION

Laser welding has three regimes: conduction, transition and keyhole Chelladurai *et al*, (2014); Assuncao *et al*, (2012). In conduction regime, the heat is conducted radially into the bulk of the material in three dimensions (3D heat flow) which results in a semi-circular weld profiles, as shown if Figure 1a (Assuncao *et al*, 2012). In keyhole regime (Figure 1b), a 2D heat in transfer is present due to low or lack of temperature gradient across the thickness Suder, (2012). The heat conduction is more parallel to the laser beam axis. Thus, the welds produced with this regime are characterised by a high aspect ratio of depth width weld profiles. Transition regime combines the characteristics of the conduction and keyhole regimes (Figure 1c). At the top of the weld is a semi-circular shape with narrow structure down the base which gives it a "nail" shape. In Figure 1, examples of weld cross sections for each regime are shown.



**(b) Keyhole weld.**



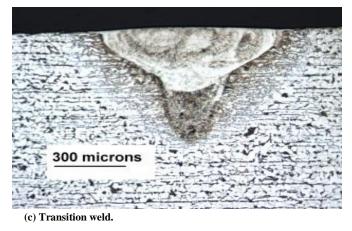**(a) Conduction weld.**



**(c) Transition weld.**

**Figure 1: Classification of laser welding regimes (Assuncao, Williams and Yap, 2012).**

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Different heat flow models have been developed to quantitatively and accurately predict the heat flow pattern and the resulting weld beam shapes for laser-based material processes Steen, (1988); Kaplan *et al,* (1999); Wahab *et al,* 1998). In the study of Bag *et al* (2009) numerically computed results of a finite element heat transfer model of conduction laser spot welding using an adaptive volumetric heat source were compared with measured bead-on-plate welds. A good agreement between the model and measured weld was reported. Yadaiah and Bag (2014) mentioned that surface heat flux may not sufficiently account for the heat transfer within the material due to the effect of momentum transport of the material. It was also suggested that convection within the melt pool can be replaced by a volumetric heat source. However, to apply volumetric heat source model, some experimental data are needed to set up different geometric parameters of the heat source. But such an approach allows the achievement of non-symmetric heat density distribution, such as ellipsoid and double ellipsoid to account for complex melt flow in heat transfer modelling. The maximum discrepancy noticed between the developed model and the actual weld was 10 % Yadaiah and Bag, (2014). However, originally these modified heat models are based on point and disc sources models Rosenthal, (1941); Eager and Tsai, (1983). All laser-based welding processes heat source models were primarily initiated from point or disc source models. In this study, attention is less on the developed of heat transfer model but on the ability of point and disc source models to represent actual laser weld profiles in conduction regime.

There is a high likelihood of a geometrical relationship existing between the melt volume, depth of penetration and weld width resulting from absorption and heat flow patterns. Similarly, a relationship between bead area, height and width should exist in powder deposition. This means that it may not be possible to increase one aspect of the weld without another, that is the depth of penetration or bead height cannot be changed without a corresponding change of width of weld or powder track. Any attempt to increase the resolution will result in simultaneous decrease of the build rate according to 3D heat flow pattern and its effect on the melt volume. In this study, two scaling laws, which correlate the melt volume and weld width to the depth of penetration or build height are proposed. The hypotheses are based on the fact that parts created by a moving laser spot during welding or powder melting are either equal to a half of a cylinder or a flattened half of a cylinder according to the point source or disc source profile theory of heat transfer Zhang *et al,* (2013); Kruth *et al,* (2004). Depending on the heat source approximation (point source or disc source), different relationships between weld profiles and depth of penetrations are possible, as given by Equations. 1 to 4. The schematic diagrams are shown in Figure 2. The objective of this experiment was to determine if the actual melt area of focused and defocused beams is closer to theoretical point or disc source approximation.

*Point source melt area* $(A)$
$$= \tfrac{1}{2}\pi(d)^2 \qquad (1)$$
*Point source weld width* $(ww)$
$$= 2 * d \qquad (2)$$

*Disc source melt area* $(A)$
$$= BD * d + \tfrac{1}{2}\pi(d)^2 \qquad (3)$$
*Disc source layer width* $(ww)$
$$= BD + 2 * d \qquad (4)$$
*Where BD is beam diameter, A is melt area, d is the depth of penetration and ww is the weld width*
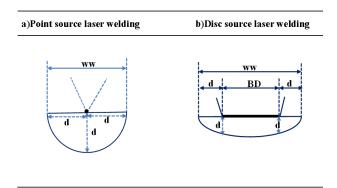


**Figure 2: Fusion zone dimensions based on theoretical approximation of laser conduction welding with different heat sources a) point source and b) disc source.**

## II.   METHODOLOGY

### A.   Experimental Procedure

An IPGYLR-8000 Continuous wave (CW) fibre laser with a maximum output power of 8.0 kW was used to produce a set of bead-on-plate welds. The laser beam delivery system consisted of an optical fibre with a diameter of 300 μm and a collimation lens with a focal length of 125 mm. To get different beam diameters a range of focusing lenses with focal lengths of 250, 680 and 950 mm was used. To prevent the laser head from back reflection, the optical head was tilted at a 10°angle. The material used for this study was S275 mild steel plates of size 160x250x12 mm. The plates were cleaned with acetone solution to avoid organic contamination and coated with graphite to improve absorptivity before welding. The samples were clamped firmly and experiments were done without shielding gas. The samples were cross sectioned at a half-length and then polished and etched with 2% Nital solution to reveal the weld bead.

To compare the theoretical bead profiles according to the point and disc source with the actual welds, different beam diameters were used to produce bead-on-plate welds. The initial investigation was carried out with two focusing lenses of 250 and 680 mm to examine if the same depth of penetration and weld width can be produced. This was done by examining the longitudinal sectioning of the samples. While the lens of 680 mm was used in focus position, the 250 mm lens was positioned in out of focus position to achieve the same beam diameter of 1.70 mm, as shown in Figure 3. The laser and travel speed were adjusted to achieve power density of 64 kW/cm$^2$ and interaction time of 60 to 240 ms.

The main study, comparing theoretical and actual weld bead profiles was carried out with beam of diameters 0.97,

1.37, 2.45 and 4.00 mm. The beam diameter of 2.45 mm had a top-hat profile (focus beam) and 0.97 mm, 1.37 mm and 4.00 mm had a pseudo-Gaussian power distribution (defocused beam). The feature analysis of the intensity distribution of the focused and defocused beams for the same nominal beam diameter and power density can be found in Ayoola *et al* (2020). The beam properties of the optical set-up are shown in Table 1. The detailed analysis of the interaction parameters can be found in Fuerschbach and Eisler, (2002), Ayoola *et al*, (2017); Suder, (2012). The relationships between depth of penetration, weld width and melt area were analysed and compared with theoretical ones. In all investigations, the theoretical melt areas for point and disc source were calculated according to Eqns.1 and 3. The weld widths of the point and disc source beam profiles were obtained from Eqns. 2 and 4. In each of the cases, the expected weld width and melt area were calculated based on depth of penetration of the real welds for a given set of conditions.
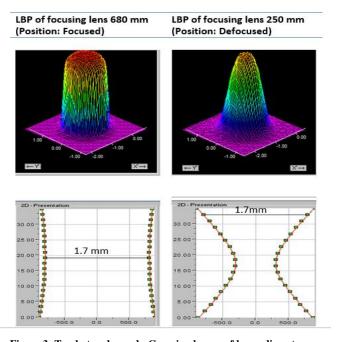


**Figure 3: Top hat and pseudo-Gaussian beams of beam diameter 1.70 mm.**

**Table 1: Beam properties of the optical set-up.**

| Focusing lens (mm) | Focusing distance (mm) | Beam diameter (mm) | Power density (kW/cm²) |
|---|---|---|---|
| 250 | Defocused by 8 | 0.97 | 64.0 |
| 250 | Defocused by 13 | 1.37 | 64.0 |
| 250 | Defocused by 40 | 4.00 | 28.0 |
| 950 | Focused | 2.45 | 33.1 |

### III. RESULTS AND DISCUSSION

*A. Result*

Figure 4 shows the longitudinally sectioned macrographs of bead-on-plate welds produced in conduction mode with focused and defocused beams with a nominal diameter of 1.70 mm. The samples were produced to compare if there is a disparity in the weld bead profiles. The penetration depth of samples was very consistent for the focused and out of focus beams, as shown in Figure 4. Figure 4 further suggests that increasing the interaction time, which produced wider and deeper welds does not bring about a significant fluctuation of penetration depth as long as the welds are in conduction mode. The variation in depths of penetration of the samples was less than 10 %.

Shown in Figure 5 are the macrographs of the bead-on-plate welds produced with beam diameters of 0.97, 1.37, 2.45 and 4.00 mm. The produced bead-on-plate welds have the aspect ratio (depth/width) of ≤ 0.50. In each set of the macrographs presented, the weld profile is changing with increasing interaction time and beam diameter at constant power density. The melt area increases with increasing depth of penetration for both theoretical sources and actual melt area, as shown in Figure 6. The disc source has a higher melt area than the point and actual melt source for a given depth of penetration. The actual melt area is much closer to the point source than the disc source.

The same trend can be observed for all beam diameters studied, as shown in Figure 6. In addition, the larger the beam diameter, the closer is the actual melt area to the point source melt area. Figure 7 shows the dependence of the weld width on the depth of penetration. The weld width of the larger beam diameter of 4.00 mm approached saturation when the maximum weld width is equal to the beam size while for the smaller beam expanded beyond the diameter as shown in Figure 7. It is also interesting to notice that at a certain point the weld width and melt area intercepts with the theoretical width and area calculated form Eqns. 1 and 2 and eventually drop below it. This indicates a change of welding regime from conduction to transition or keyhole. This is because the aspect ratio of the welds has gone beyond 0.5, which characterised transition or keyhole welds.

*B. Discussion*

In laser welding, the heat propagates radially from the heat source to the inner parts of the substrate in a 3-dimensional manner. Depending on the size of the laser beam and its power density distribution, the system can be approximated by a point or disc source. The ratio between depth of penetration and weld width and melt volume will be different for each heat source models. In theory, with a point source profile, to make a weld deeper at the same time we need to make it wider due to 3-D heat transfer within the material (Steen *et al*, 1988). So, for the point source, the melt volume increases as the square of depth (Figure 2). In the disc source model, the relationship will be slightly different (Figure 2). This will have a significant effect on the resolution and deposition rate in powder bed additive manufacturing (Ayoola *et al*, 2021). Large beam diameter of 4.0 mm behaves like a disc source where the weld width does not expand beyond the spot size (Figures 5 and 7d). With the small beam of 1.37 mm, the weld width can be much greater than the spot size, according to the point source model, provided that there is no vaporisation (Figures 5 and 6c). In addition, the actual melt volumes were much lower than the theoretically expected from disc model melt volumes (Figure 6). This indicates that the threshold energy for melting was not
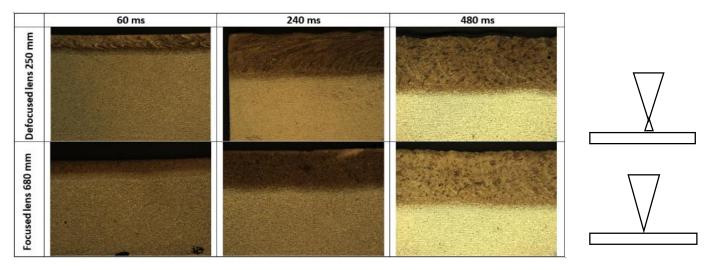
**Figure 4: Longitudinally sectioned bead on plate weld samples of top hat (focused) and pseudo-Gaussian beams (defocused).**
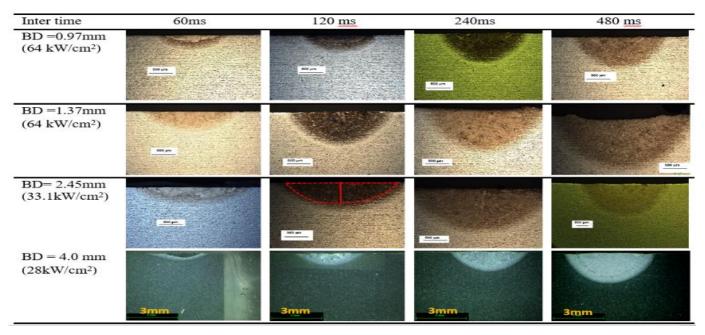


**Figure 5: Macrographs of bead on plate welds produced for the analysis of the scaling relationship between weld geometries.**

provided across the entire spot size *(Ayoola et al, 2017; Ayoola et al, 2021)*. This can be attributed to the intensity profile (Suder, 2012). Note that the large beam diameter (4.0 mm) was achieved with a defocused beam.

The comparison between the actual weld profile and the theoretical point and disc source profiles also indicates that the actual welds are much closer to the point source model than the disc source model for smaller beams (Fuerschbach and Eisler, 2002). Furthermore, the theoretical disc source assumes a uniform threshold energy distribution across the spot size. Therefore, the aspect ratio was significantly lower compared to the point source and actual profiles. The higher the depth of penetration, the closer the actual weld to a point source (Figure 7). Furthermore, the disc source profile indicates enhanced resolution. However, in an ideal situation of welding, the theoretical melting volume according to the disc source may not be achievable. This is because in laser welding the actual

weld width does not increase indefinitely with the depth of penetration. At a certain point, the weld width reaches a plateau with increasing depth of penetration. This situation causes the process to change from conduction to keyhole regime. This behaviour was observed for all range of beam diameters used in this study.

The relationship between the point source weld bead profile and the actual melt area may be used for the classification of welding regime. Figures 6 and 7 indicate that welds that have their melt areas below the point source melt area exhibit characteristics of keyhole welds, such as high aspect ratio and underfill at the surface. This is very clear for samples produced at the interaction time of 480 ms (Figure 5). In this condition, the depth of penetration of the actual welds is lower than that of theoretical point source.
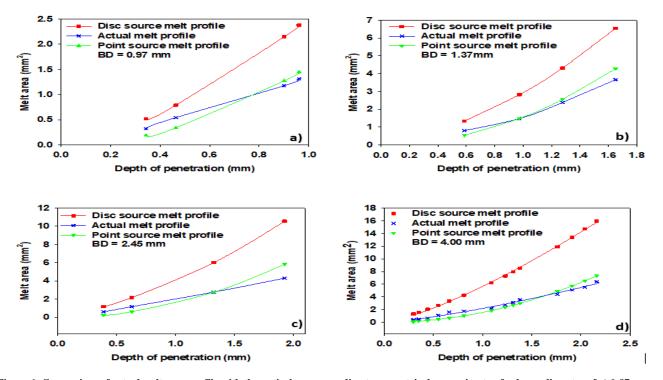
**Figure 6: Comparison of actual melt area profile with theoretical ones according to geometrical approximaton for beam diameter of a) 0.97 mm, b) 1.37 mm, c) 2.45 mm and d) 4.00 mm.**
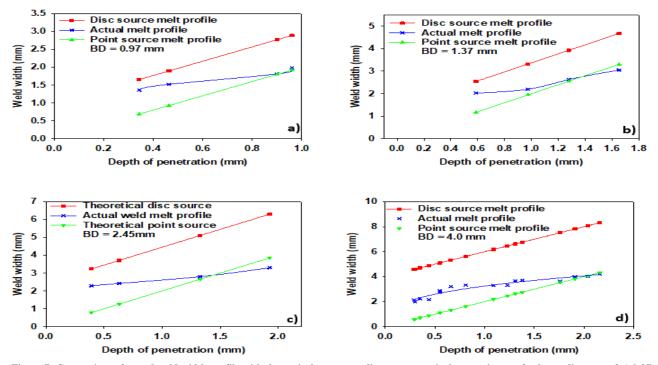


**Figure 7: Comparison of actual weld width profile with theoretical ones according to geometrical approximaton for beam diameter of a) 0.97 mm, b) 1.37 mm, c) 2.45 mm and d) 4.00 mm.**

Such welds have been classified to be in the transition regime where the evaporation recoil vapour pressure is generated causing an increase in depth of penetration but not significantly high enough for keyhole formation. Therefore, it can be suggested that the macrographs (Figures 6 b & c and Figures 7 b & c) that are below the point source profile are in the transition regime.

## IV. CONCLUSION

The following conclusions were drawn from this study where solid melting in mild steel was used as a case study to understand the effect of spatial energy distribution on the weld bead profile:

- ✓ A relationship between weld profile and depth of penetration was observed. Conduction welds are closer to the point source approximation than to the disc source. This means that the depth of penetration increases with weld width and the melt area increases as square of depth. This implies that if conduction regime is to be used in powder bed additive manufacturing, the build area can be increased only at the cost of lower resolution and higher remelting.

- ✓ It has been shown that the power density distribution of a laser beam has a significant influence on the weld profiles in conduction welding. Defocussed beams with a pseudo-Gaussian power density profile resulted in deeper welds than focused beams with a top-hat profile for the same nominal beam diameter. This means that changing the beam diameter by defocussing may introduce additional aspects to the profiles of the resulting welds.

- ✓ Conduction welding can be done with various sizes of beams. This study indicates that small beam diameters are closer to the point source profile while process with larger beam diameters behaves more like the disc source profile.

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