Procedia Manufacturing
Volume 5, 2016, Pages 232–247
44th Proceedings of the North American Manufacturing Research Institution of SME http://www.sme.org/namrc

The Effects of Pulse Shaping Variation in Laser Spot-Welding of Aluminum

R. Hajavifard[1*], M. Motahari[2], H. Özden[3], H. Miyanaji[4], S. Kafashi[5]

[1] *Ruhr University Bochum, Bochum, Germany*
[2] *Tabriz University, Tabriz, Iran*
[3] *Ege University, Izmir, Turkey*
[4] *University of Louisville, Louisville, USA*
[5] *University of North Carolina at Charlotte, Charlotte, USA*
ramin.hajavifard@ruhr-uni-bochum.de, me.motahari@gmail.com, huseyin.ozden@ege.edu.tr, h0miya02@louisville.edu, Skafashi@uncc.edu

Abstract
Aluminum alloys are important structural materials because of their high strength to weight ratio. Unfortunately, due to their high reflectivity and complexity in heat treatment, aluminum alloys are some of the hardest metals to be laser welded successfully and very high laser power is usually required. In this study, the feasibility of using a 220 W Nd:YAG laser for spot welding of aluminum is investigated and mostly focused on shaping of the laser pulse. All aspects of the laser pulse including initial coupling, weld fusion, and cooling will be discussed. Different pulse shaping methods like standard pulse shaping, ramp-down pulse shaping and ramp-down with rectangle initial coupling were used to investigate their effects on the weld characteristics. The results show that, with proper control of welding parameters, the success of aluminum welding can be achieved at considerably low laser power with minimal formation of typical welding defects (porosity, cracking etc.). The deepest penetration achieved was 834 µm with ramp-down pulse shaping. From quality point of view, ramp-down pulse shaping and ramp-down with longer initial coupling gave the best results.

Keywords: Laser welding, aluminum, pulse shaping, coupling, fusion, cooling rate, cracks, porosity

1 Introduction

Recently, utilizing laser light for welding different parts with various sizes and properties has significantly increased because of its low price and also its increasing capabilities. Welding by laser light has many attributes which make it appropriate approach to join all types of materials including metals, ceramics, glasses, and plastics. Some of laser welding advantages are very high precision, close tolerance, excellent repeatability, unit cost reductions, material versatility, contact-free, very

 Selection and peer-review under responsibility of the Scientific Programme Committee of NAMRI/SME

doi:10.1016/j.promfg.2016.08.021

localized energy which means low thermal and mechanical strain on parts, low heat input/minimal heat affect, fine grain structure/excellent weld quality, etc.

There are two approaches that lasers can be used, pulsed mode and CW (Continuous Wave) mode. In pulsed mode parts are being welded like resistance spot welding and in CW mode laser welding is similar to arc welding process. While CW mode is a common way for larger structural welds and competes with traditional arc welding processes, pulsed welding is common for welds in smaller components such as pacemakers, microwave enclosures, batteries, and sensors. Pulsed mode lasers can be used to make seam welds where overlapping pulses are able to produce a hermetic seal (Kelkar, 2008).

Probably, the main attribute that has led to the growing implementation of lasers for welding is their capabilities to make spot welds. A laser beam focused down to a spot heats, melts, and solidifies metals in a very small amount of time, milli-seconds, with the minimal disturbance to adjoining volume of material and components. As a result, laser spot welding is becoming a more popular and well-known method for producing and manufacturing different parts where the accuracy and precision is important. Furthermore, there have been significant improvements in laser power supply capabilities and its components including closed-loop feedback and pulse shaping. As laser pulse welding is being improved to its limits in new and unique applications, it will be increasingly critical to have good understating of the laser pulse and its effects on the parts being welded (Kelkar, 2008).

In other hand, aluminum and aluminum alloys have many outstanding attributes that lead to a wide range of applications, including good corrosion and oxidation resistance, high electrical and thermal conductivities, low density, high reflectivity, high ductility and reasonably high strength and relatively low cost. Considering numerous applications of aluminum alloys in different industries, it seems that carrying out researches, in which laser welding is utilized for joining aluminum alloys, is valuable and also necessary.

Although a number of authors (Zhao, 2009, Mackwood, 2005, Dowden, 2009, Neto, 1994, Sonti, 1989, Zhao, 2003) have studied pulsed laser beam welding experimentally and numerically, most of these studies have been focused on process parameters like pulse duration and pulse power with thermal, metallurgical, and geometrical aspects of the welding seam. With respect to laser-based micro-joining processes, a very limited number of papers (Chang, 2002, Lin, 2008, Kim, 2002) have investigated the effects of the different pulse shapes on the characteristics of the welds and eventual defects. Therefore, in this paper the effects of changing pulse shapes and all aspects of the laser pulse, including initial coupling, weld fusion and cooling, on the welding process of thin aluminum foils have been studied. In other words, in order to achieve a better insight into the relationship between the details of a complex pulse shape and its effects on the geometry (such as penetration depth, underfill, and spot diameter) and metallurgy of the spot welding, the particular parts of the pulse shape consisting of coupling, fusion, and cooling sections, were systematically varied and the resulting welded spot were accordingly inspected. Finally the best combination of welding power, pulse shape and pulse duration is proposed to acquire experimental results as close as possible to ideal welding.

2 Experimental Procedures

Aluminum alloy 1100 was selected for this study which has the best weld-ability among all aluminum alloys, excellent workability, excellent electrical conductivity, good formability and high resistance to corrosion. The size of aluminum sheets used for the experiments was 100x100 mm with thickness of 1 mm. samples were wiped with acetone before welding. The laser system used for welding the samples was a Nd:YAG laser. This laser has a output range from 10 to 220 W with a wave length of 1064 nm. The laser is connected to a plug-in optical fiber up to 60 m length with a core diameter of 400 µm. It is projected on the work piece using a standard LLBK 45 welding head. This welding head has 50 mm focus lens which results in 400 µm spot diameter. Distribution of intensity in focal plane is top-hat. The welding process was performed in a box with a fixture which was embedded inside. Also, in order to avoid oxidation during the welding process, argon was used as a shielding gas in the welding box. The experimental set-up is shown in the figure1. Having completed all the experiments, it was necessary to carry out a careful sample preparation. The practical steps of sample preparation can be divided into cutting, mounting, grinding, polishing and etching steps. Once the samples were polished carefully, in order to distinguish the eventual defects such as cracks, pores, underfill, etc., they were etched with sodium hydroxide (2 grams NaOH in 100 ml distilled water) in 50º C for 2 minutes.

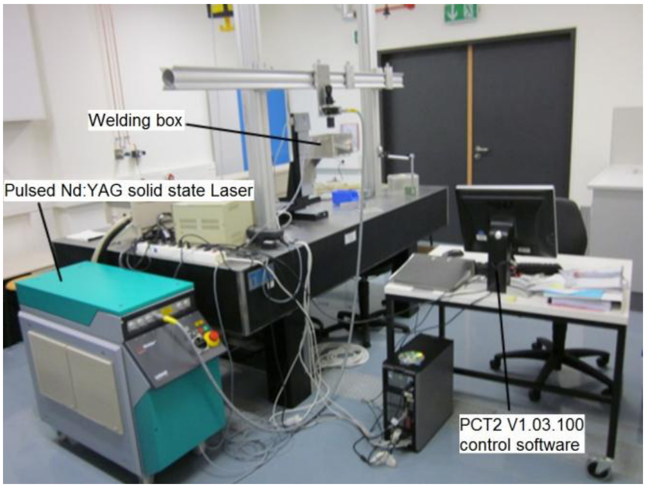

Figure 1: Experimental set-up

3 Results and Discussion

3.1 Standard Pulse Shape

3.1.1 Increscent Peak Power

In order to examine the effects of variation of peak power of laser pulse with standard pulse shape on weld depth and its quality, nine different peak power were used to make nine spot welds in a way that the difference of peak power value between two tandem spots was 0.05 kW. In the meantime, the pulse duration was kept the same at 3 ms.

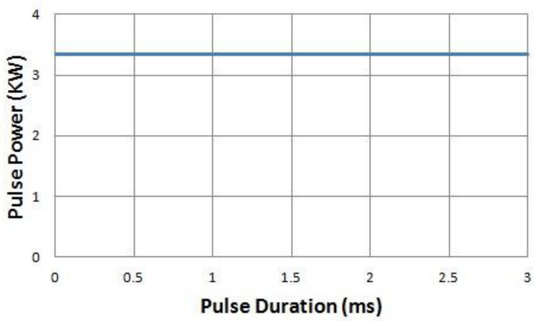

Figure 2: Standard pulse shape

Figure 3 shows the cross-sections for this test. From left to right the peak powers of laser pulses are increasing.

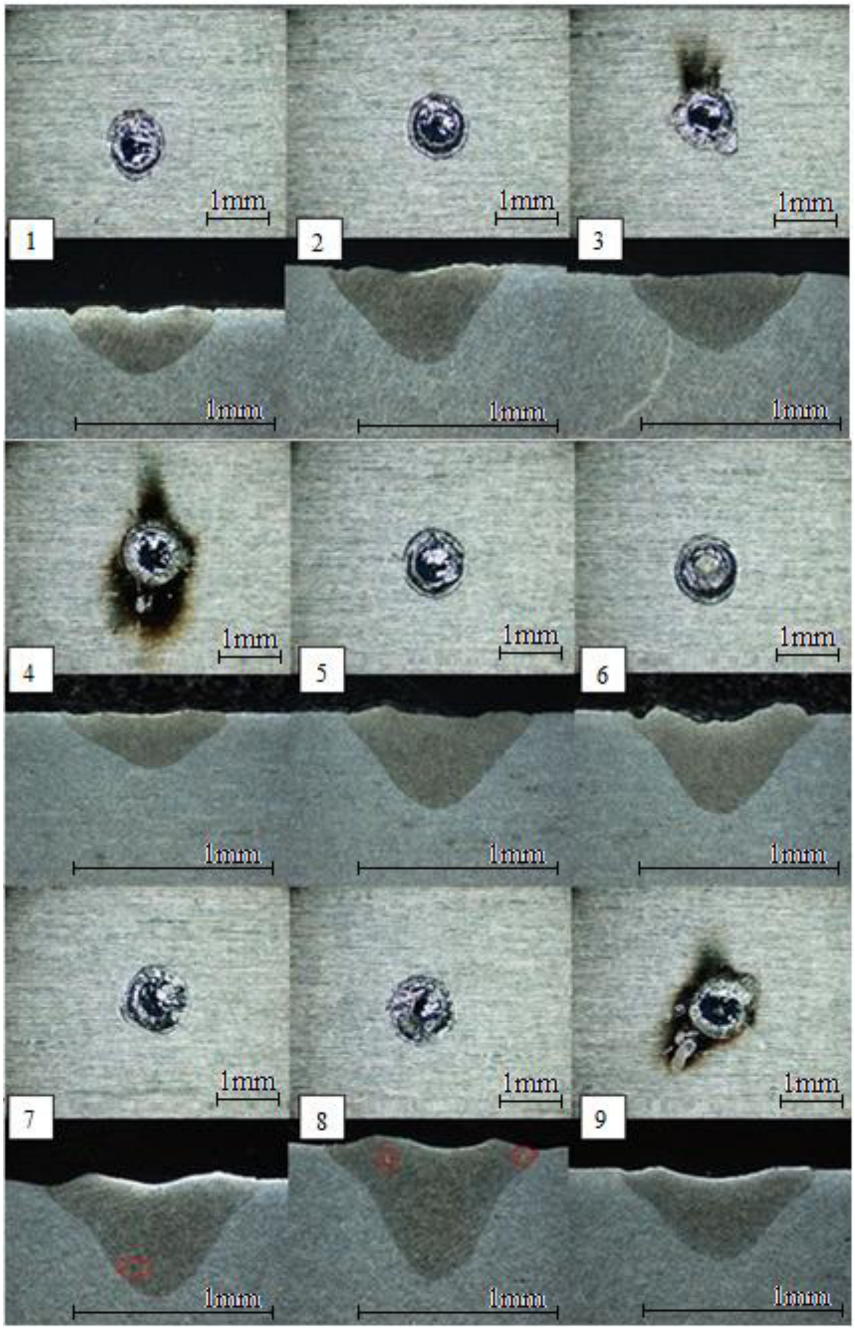

Figure 3: Spot welds and related cross-sections with standard pulse shape, increscent peak power and constant pulse duration. Magnification ratio for spots and related cross-sections are respectively: 10X, 30X. Peak powers are respectively: 3.150, 3.200, 3.250, 3.300, 3.350, 3.400, 3.450, 3.500, 3.550 kW. Pulse duration is 3 ms.

It is observed that as a general trend, the penetration increases up with increasing peak power (thereupon pulse energy) with the exception of the spot welds that had the black stains on the surface. In spots with black stains, the penetration depth drops considerably. This can occur in different ways; from dust and stains on the surface of aluminum, impurities in shielding gas or aluminum. Since samples were wiped with acetone before welding and also inasmuch the used samples are aluminum 1100 which does not have noticeable alloy elements, the origin of these impurities probably is the impurities which were embedded at the surface of aluminum while rolling in the factory or impurities in the shielding gas.

The lower peak power welds are free from major defects like cracks or porosity. However, a small amount of underfill can be observed at the surface. Underfills are due to vaporization of impurities on the surface of samples and probably of some aluminum. For the higher peak power welds, again a small amount of underfill can be observed. Also the last spot welds (with the highest peak powers) have some porosities circled with red lines in the picture. This can happen because of shielding gas, entrapped hydrogen from moisture, not having enough time for plasma or other gases to escape before the molten pool solidifies, not having stable key-hole, or aluminum oxide mixed in the molten pool, etc. Figure 4 shows the variation of penetration depths, spot diameters and underfills in this test.

As figure 4 shows, the aspect ratio (penetration divided by weld width) of 1 could not be reached in this test.

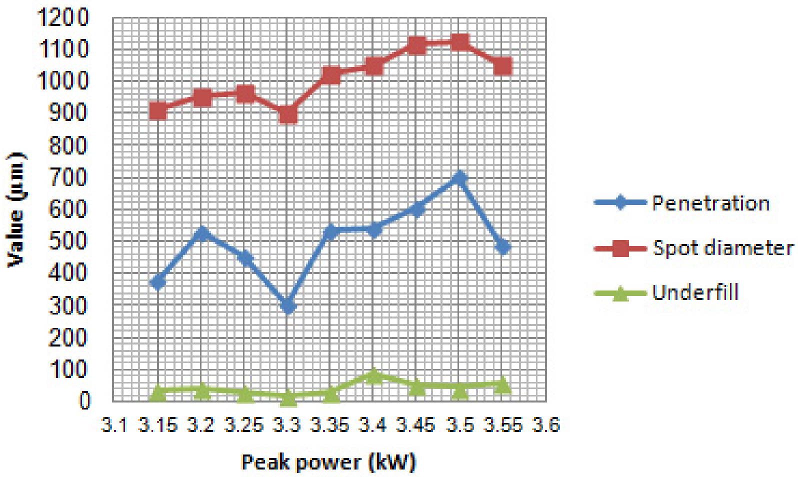

Figure 4: Variation of penetration, spot diameter and underfill in spot welds (first series)

3.1.2 Increscent Pulse Duration

With the aim of examining the roles of peak power and pulse duration on penetration and also welding defects, two series of spot welds were carried out. In the first series, the peak power was kept at 3.350 kW and in the second one the peak power was kept at 2 kW. The pulse durations were increscent in both series. Pulse durations were chosen in a way that the corresponding pulses of every group (these two groups and pulses in previous welds) had almost the same energy. It means that the first pulses of these three groups have the same energy and second pulses have the equal energy and so on.

Figure 5 shows the cross-sections for 3.350 kW spot welds. From left to right the duration of laser pulses are increasing.

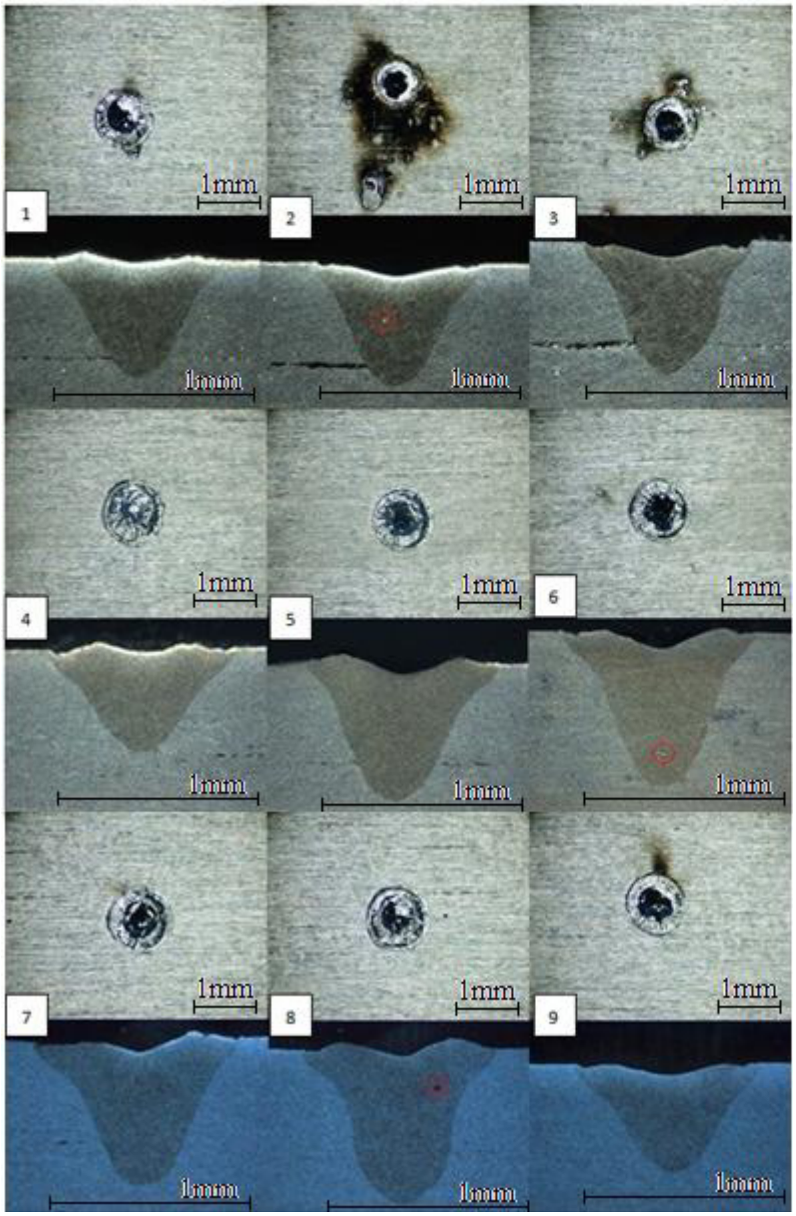

Figure 5: Spot welds and related cross-sections with standard pulse shape, increscent pulse duration and constant peak power. Magnification ratio for spots and related cross-sections are respectively: 10X, 30X. Pulse durations are respectively: 2.84, 2.88, 2.92, 2.96, 3, 3.04, 3.08, 3.12, 3.16 ms. Peak power is 3.350 kW.

In this case, the trend is pretty similar with the previous test. The penetration increases up with increasing pulse duration (thereupon pulse energy). Similar to the previous test, spot welds are free from cracks. A small amount of underfill can be observed at the surface of welds and some of them have porosity. Figure 6 shows the variation of penetration depths and spot diameters and underfills in this test.

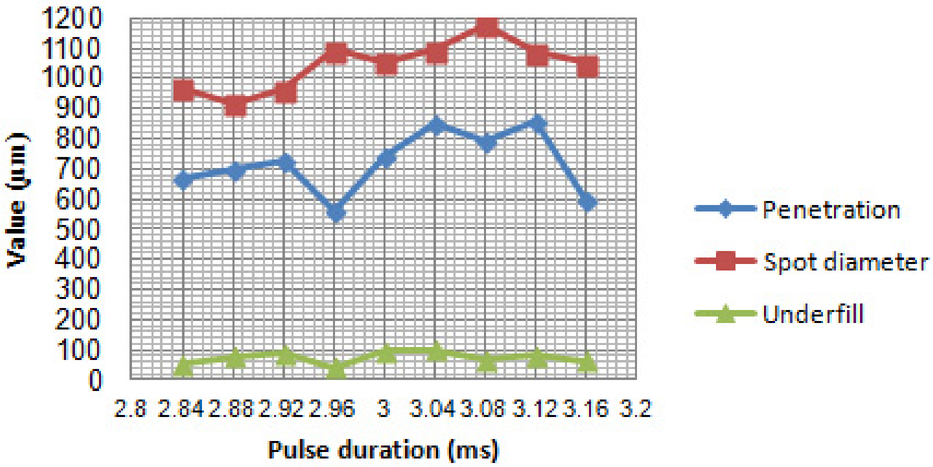

Figure 6: Variation of penetration, spot diameter and underfill in spot welds with uprising pulse durations (second series)

As figure 6 shows, similar to the previous test, the aspect ratio (penetration divided by weld width) of 1 could not be reached in this test.

Figure 7 shows the cross-sections for 2 kW spot welds. First three spot welds had little to no penetration. This is most probably because of reflective surface of aluminum that the used initial spike in related pulse duration was not able to start melting of surface noticeably. Because of this the pictures of these three spot welds are not shown in figure 7.

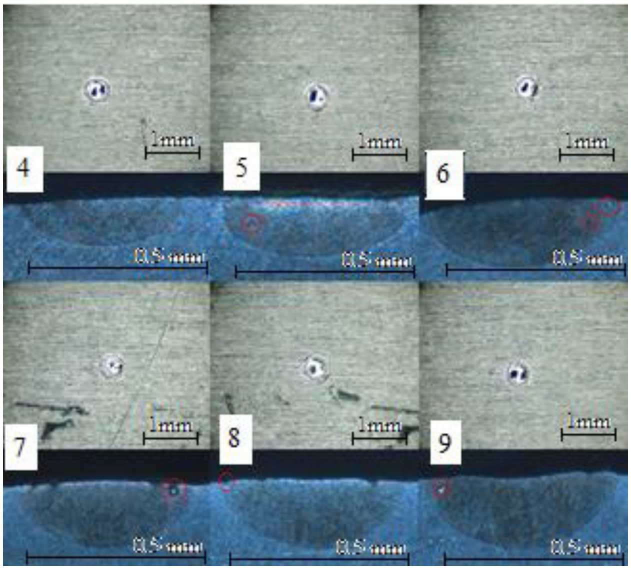

Figure 7: Spot welds and related cross-sections with standard pulse shape, increscent pulse duration and constant peak power. Magnification ratio for spots and related cross-sections are respectively: 20X, 70X. Pulse durations are respectively: 4.7, 4.775, 4.850, 4.925, 5, 5.075, 5.150, 5.225, 5.300 ms. Peak power is 2 kW.

Spot welds are free from cracks and underfill. Porosities (circled with red lines in the figure) can be observed near the surface and outer side of welds. It is probably because of not having enough time for gases to escape from the molten pool before it solidifies. Using higher peak powers or longer pulse durations would lead to better results. Figure 8 shows the variation of penetration depths and spot diameters in this test.

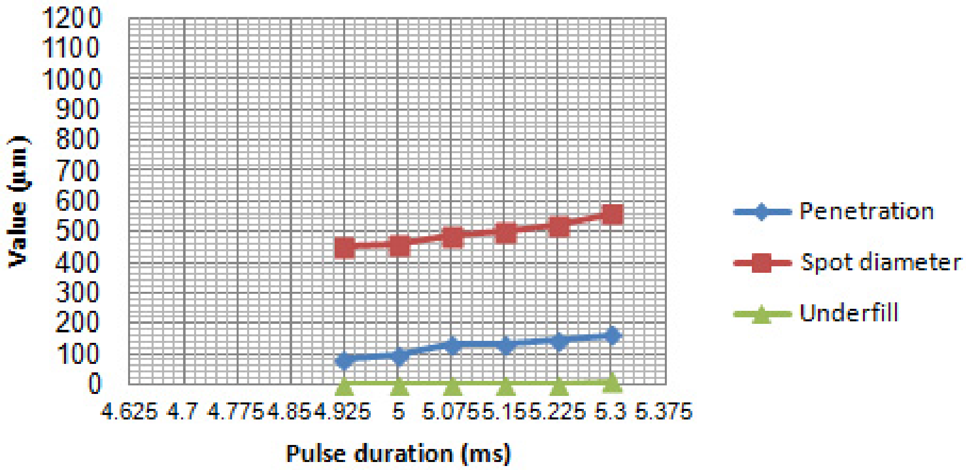

Figure 8: Variation of penetration, spot diameter and underfill in spot welds with uprising pulse durations (third series)

It can be understood from this diagram that increasing in penetration and diameter of the spot welds with increasing of the pulse durations are small.

So far from pictures and diagrams it can obviously concluded that weld characteristics such as penetration or widths are different from each other, even though they had almost the same pulse energy. It shows that for reaching desired aims, it is important to choose the best combination of pulse parameters like pulse peak power and pulse duration, etc. Figure 9 is an example that compares the variation of penetration depths resulting from these tests.

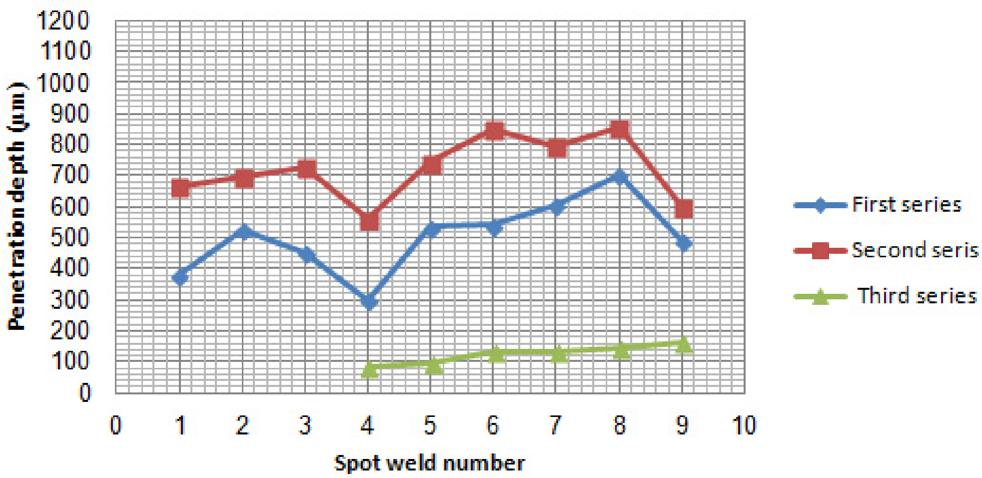

Figure 9: Variation of penetration depths in different peak power and pulse duration combinations with the same pulse energy

3.2 Ramp-Down Pulse Shape

Ramp-down pulse shaping consists of sectors in which first section has the highest peak power followed by sectors which have lower and lower peak powers. So the energy of laser pulse reduces slowly and it results in slower cooling. The pulse used in this trial consisted of five sectors and the lengths (duration) of these sectors were not the same. Figure 10 shows the ramp-down pulse shape used in this investigation.

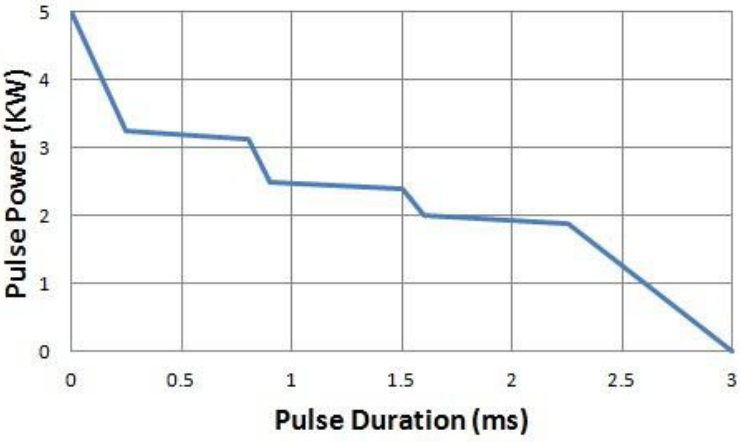

Figure 10: Ramp-down pulse shape

Similar to standard pulse shape tests, nine different peak powers were used for making nine spot welds in a way that the difference of peak power value between two tandem spots was 0.1 kW and the pulse duration was kept the same at 3 ms.

Figure 11 shows the cross-sections for this test. From left to right the peak powers of laser pulses are increasing.

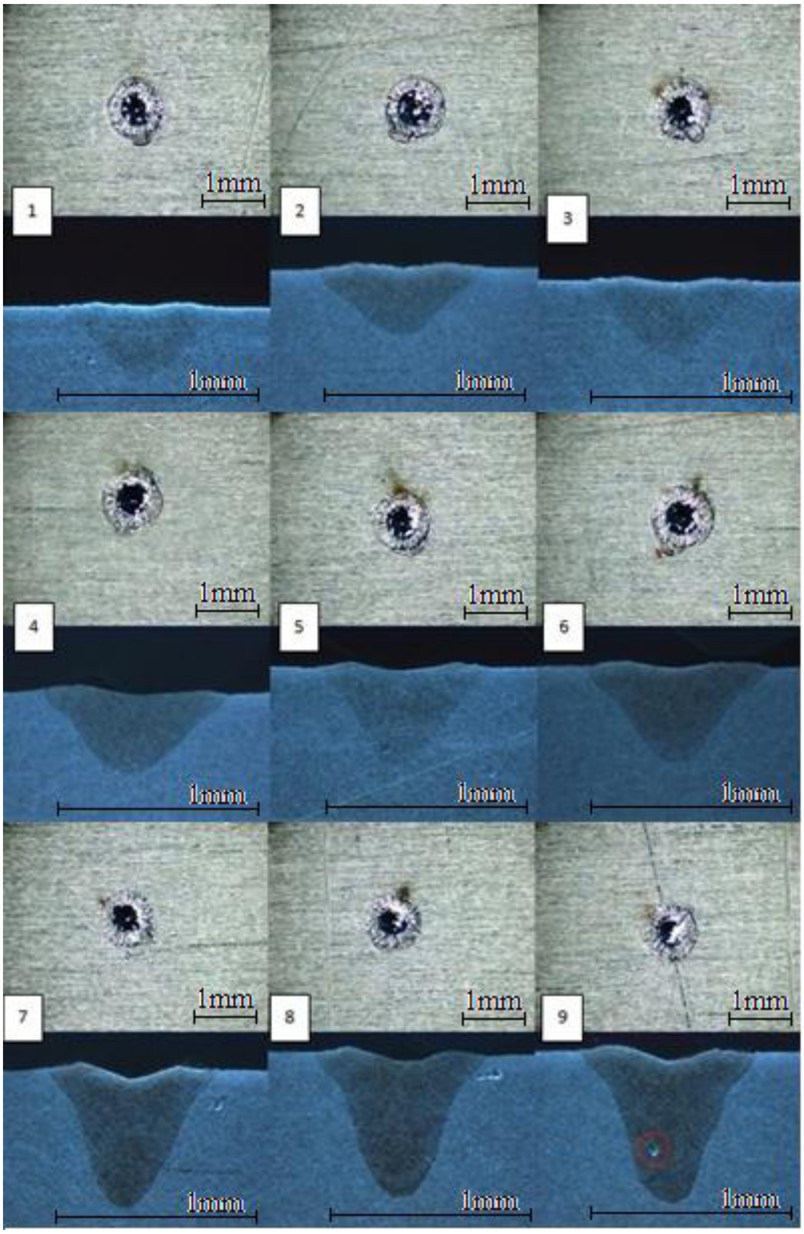

Figure 11: Spot welds and related cross-sections with ramp-down pulse shape, increscent peak power and constant pulse duration. Magnification ratio for spots and related cross-sections are respectively: 10X, 30X. Peak powers are respectively: 5, 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 kW. Pulse duration is 3 ms.

It is apparent that as a general trend, the penetration increases up with increasing peak powers (thereupon pulse energy). From quality point of view, it seems that this trial gave the best results by now. The spot welds are free from major defects like cracks or porosity (except last one with the highest peak power). However, a small amount of underfill can be observed at the surface of welds with higher peak powers. Figure 12 shows the variation of penetration depths, spot diameters and underfills in this test.

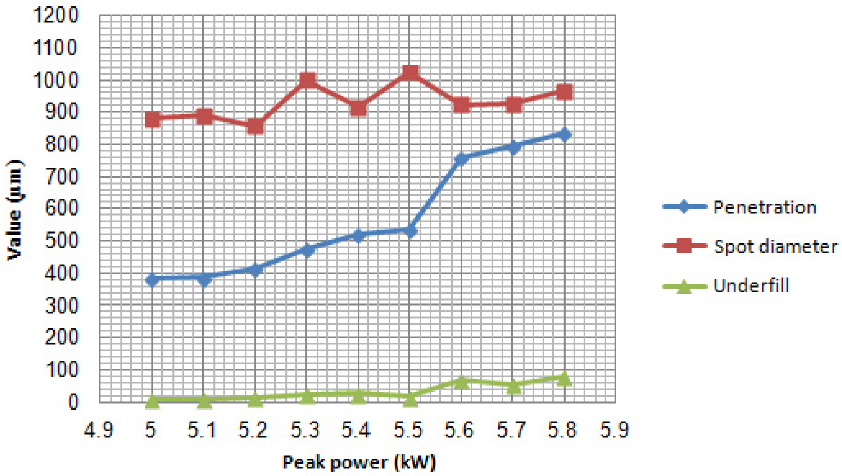

Figure 12: Penetration, spot diameter and underfill in spot welds with increscent peak powers

As figure 12 shows, although the aspect ratio (penetration divided by weld width) of 1 also could not be realized in this case, this welding condition resulted in the highest aspect ratio so far.

3.3 Ramp-Down with Rectangle Initial Coupling

Coupling was another type of pulse shapes investigated in this study. Since the material used in this study was aluminum which has one of the highest reflectivity among metals, it was of interest to examine the effects of having longer initial peak power on the weld characteristics. Nine different peak powers were applied for making nine spot welds in a way that the difference of peak power value between two tandem spots was 0.1 kW. The pulse duration was kept the same at 3 ms. Figure 13 shows the ramp-down with rectangle initial coupling pulse which was used in this test.

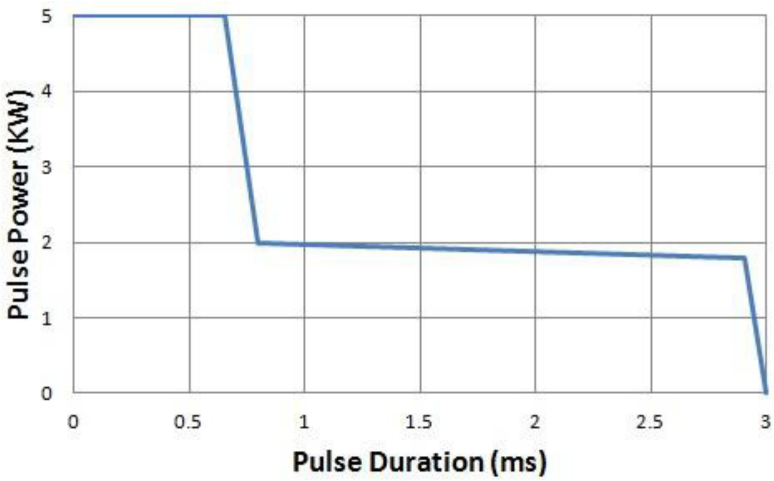

Figure 13: Ramp-down with rectangle initial coupling pulse shape

Figure 14 shows the cross-sections for this test.

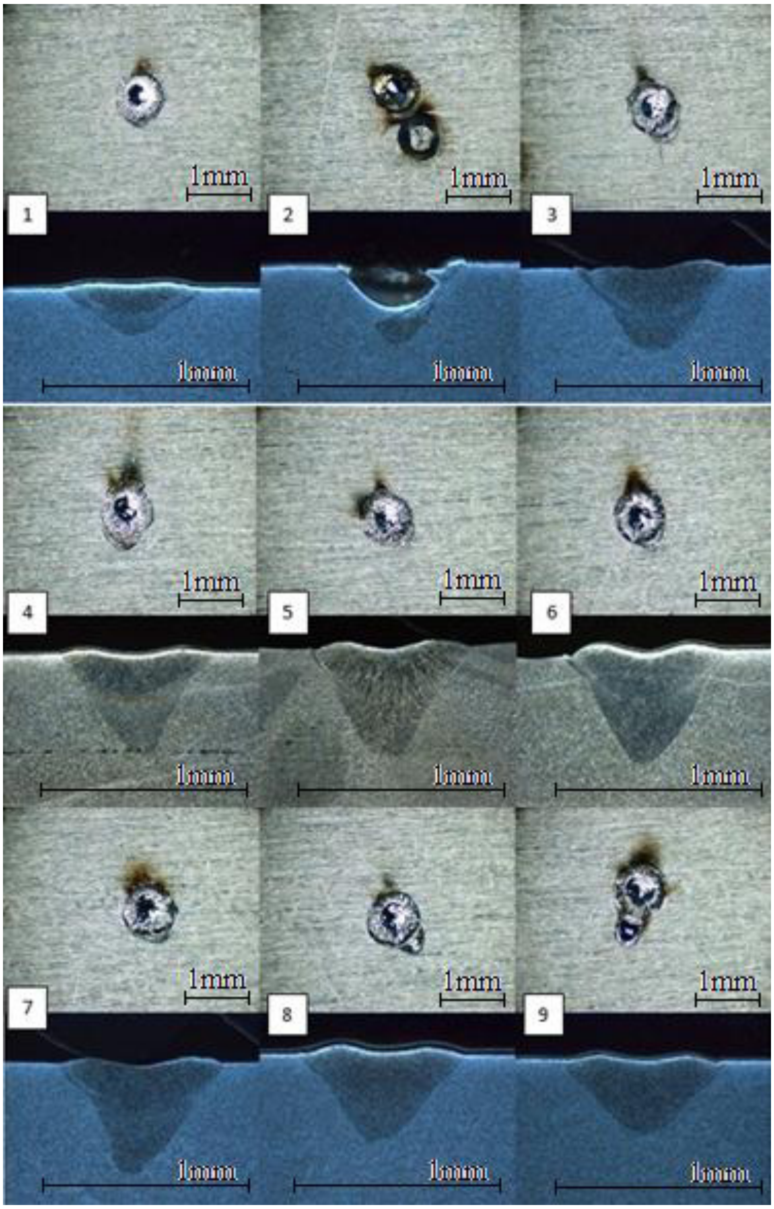

Figure 14: Spot welds and related cross-sections with ramp-down with rectangle initial coupling pulse shape, increscent peak power and constant pulse duration. Magnification ratio for spots and related cross-sections are respectively: 10X, 30X. Peak powers are respectively: 4.6, 4.7, 4.8, 4.9, 5, 5.1, 5.2, 5.3, 5.4 kW. Pulse duration is 3 ms.

It can be observed that as a general trend, the penetration increases up to a certain point with increasing peak powers (thereupon pulse energy) and then falls down again. This probably happens because the further the keyhole penetrates the material, the harder it is for the plasma to escape out of it. The plasma then acts as a lens and defocuses the beam and also absorbs some of the energy of the beam. The spot welds are free from major defects like cracks or porosities and underfill. Figure 15 shows the variation of penetration depths, spot diameters and underfills.

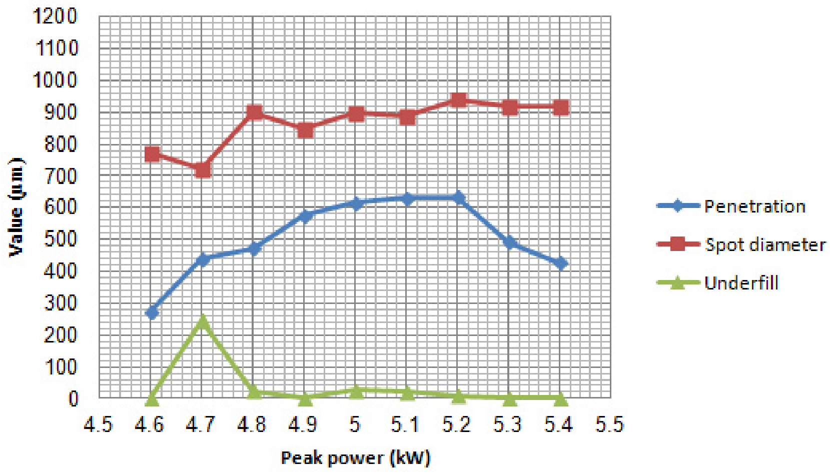

Figure 15: Penetration, spot diameter and underfill in the spot welds

Pulse parameters were chosen in a way that the corresponding pulses of ramp-down pulses and ramp-down with rectangle initial coupling pulses had almost the same energy. It means that the first pulses of these two groups had the same energy and second pulses had the equal energy and so on. This gives the possibility of comparing the weld characteristics of corresponding spot welds. It can be observed that they have different penetrations even though they had almost the same pulse energy. Figure 16 compares the variation of penetration depths resulting from these two series.

It is pretty apparent that in lower peak powers, the ramp-down with rectangle initial coupling pulse shape gives deeper penetration depths but in pulses with higher peak powers, the ramp-down pulses result in deeper penetrations.

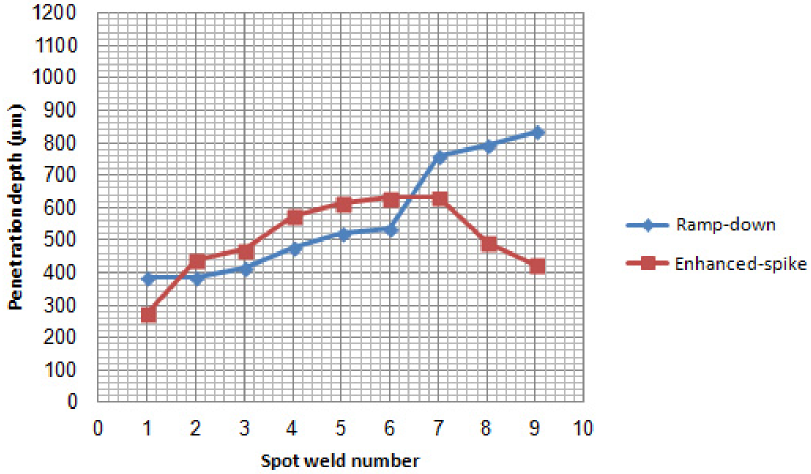

Figure 16: Comparison of the penetration depths between spot welds resulted from the ramp-down and the ramp-down with rectangle initial coupling pulse shaping

3.4 Eventual Effects of Diverse Pulse Shaping on Coupling and Cooling Segments in a Ramp-Down Laser Pulse

A typical ramp-down laser pulse can be divided into three different segments: coupling, melting and cooling. Understanding the functionality of these three segments allows the user to tailor the welding pulse carefully for desired result. In this part the effects of different pulse shapes in coupling and cooling parts were investigated. As before, parameters were chosen in a way that all pulses had almost the same energy for having the possibility of comparison of their eventual effects on the weld characteristics. The duration of pulses and their peak power were kept the same at 3 ms and 4 kW, respectively. Five types of ramp-down laser pulses were used in this test.

In figure 17 the first column shows the used pulse shapes (n1, n2, n3, n4, n5 respectively), the second column shows the pictures of the related spot welds and the third one shows the related cross-sections of these welds.

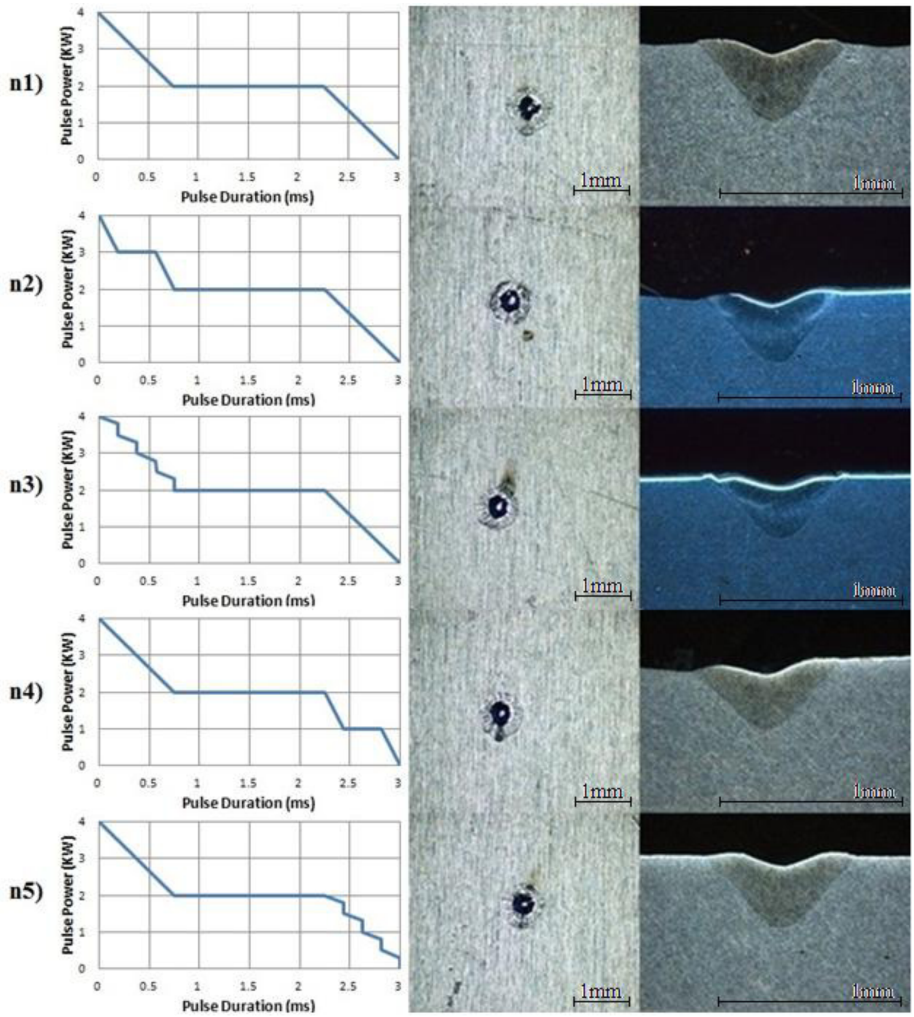

Figure 17: Pulse shapes, the related spot welds and cross-sections for welds with different ramp-down pulse shapes and the same pulse energy. Magnification ratio for spots and related cross-sections are respectively: 8X, 25X. Peak power is 4 kW. Pulse duration is 3 ms.

It can be observed that almost all of welds have the same shape and style. The spot welds are free from major defects like cracks or porosities. However, a little bit underfill can be observed at all surfaces. Figure 18 shows the variation of penetration depths and spot diameters and underfills.

Based on the observations, it seems that adding new sectors in coupling and cooling sectors causes that the penetration falls down, but about spot diameters or underfills no concrete trend can be observed.

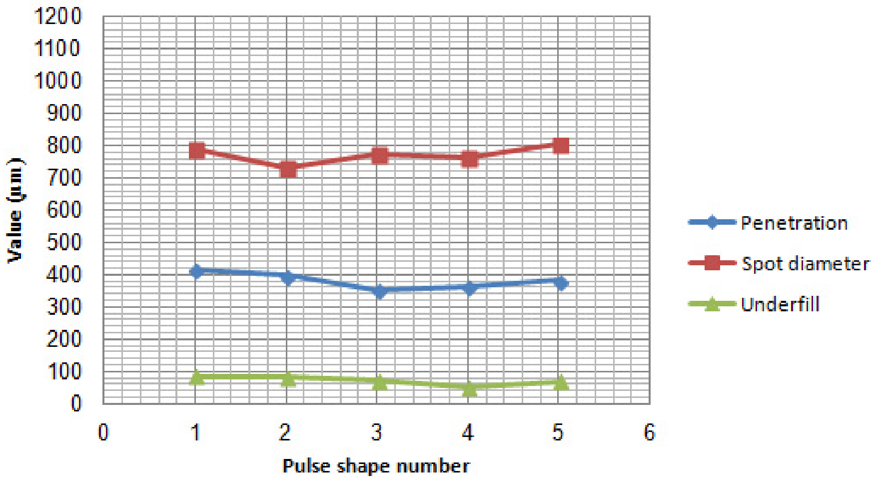

Figure 18: Comparison of the penetration depths, spot diameters and underfills between spot welds resulted from the diverse ramp-down pulse shapes

4 Conclusion

- In this study, the 220 W Nd:YAG laser was utilized to create spot welds with depth of just over 1 mm. Different pulse shapes were investigated to create spot welds with minimal defects. Underfills and porosities are the biggest defect concerns.
- It was found that laser pulses which have the same pulse energy but different combination of peak powers and pulse durations give different results. For reaching desired aims, it is important to choose the best combination.
- The ramp-down pulse shaping gives the deepest penetration with 834 µm in higher peak powers and it also gives the highest aspect ratio. From quality point of view, it seems that this pulse shape gives the best results. The spot welds are free from major defects like visible cracks or porosities.
- The standard pulse shape gives the second deepest penetration. Spot welds are free from visible cracks but the surfaces of welds have some underfills and some of them have porosity.
- Ramp down with rectangle initial coupling pulse shape gives spot welds free from major defects like visible cracks or porosities and underfills, but in comparison to the ramp-down pulse shaping, they have shallower penetration depths.

References

Chang, W.S., Na, S.J. (2002). A study on the prediction of the laser weld shape with varying heat source equations and the thermal distortion of a small structure micro-joining. J. Mat. Proc. 120:208-214

Dowden, J. (ed.) (2009). The theory of laser materials processing, Springer Series in Materials Science 119

Kelkar, G. (2008). Pulsed laser welding. Retrieved from *www.welding-consultant.com*

Kim, B.-C., Kim, T.-H., Kim, J.-S., Kim, K.B., Lee, H.Y. (2002). Investigation on the effect of laser pulse shape during Nd:YAG laser microwelding of thin Al sheet by numerical simulation. Metall. Mater. Trans. 33A:1449-1459

Lin, H.L., Chou, C.P. (2008). Modeling and optimization of Nd:YAG laser micro-weld process using Taguchi method and a neural network. Int. J. Adv. Manuf. Technol. 37(5-6):513-522

Mackwood, A.P., Crafer, R.C. (2005). Thermal modelling of laser welding and related processes: a literature review. Opt. Laser Techno. 37:99-115

Mazumder, J., Steen, W.M. (1980). Heat transfer model for CW laser material processing. J. Appl. Phys. 51:941-947

Neto, O., Lima, C. (1994). Nonlinear three-dimensional temperature profiles in pulsed laser heated solids. J. Phys. D 27:1795-1804

Sonti, N., Amateau, M.F. (1989). Finite-element modelling of heat flow in deep-penetration laser weld in aluminium alloys. Num. Heat Trans. A 16:351-370

Zhao, H., White, Z.R., DebRoy, T. (1999). Current issues and problems in laser welding of automotive aluminium alloy. Int. Mater. Rev. 44:238-266

Zhao, H., DebRoy, T. (2003). Macroporosity free aluminium alloy weldments through numerical simulation of keyhole mode laser welding. J. Appl. Phys. 93(12):10089-10096