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Surface modification methods for fatigue properties improvement of laser-beam-welded Ti-6Al-4V butt joints

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Abstract

Surface and internal defects formed upon laser beam welding (LBW) have been recognized as a serious problem because they cause stress concentration leading to premature failure of a welded component. This paper seeks to remedy these weld imperfections by applying various post-weld treatments and analyzing their effect on the high cycle fatigue (HCF) performance of welded joints. High efficiency of laser-based post-processing techniques after welding such as laser surface remelting (LSR) and laser shock peening (LSP) was demonstrated and compared with conventional approaches. The study reveals that welding porosity determines the internal crack initiation of the surface-treated weldments. Influence of process parameters on porosity level and the HCF properties is presented in detail. Based on an extensive experimental study, practical guidelines needed to mitigate the notch effect from defects and to maximize the fatigue performance of the laser-welded Ti-6Al-4V butt joints are given.

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Keywords: Laser beam welding; defects; porosity; high cycle fatigue; laser shock peening.

1. Introduction

Laser beam welding (LBW) has received significant attention over the last decades due to high efficiency and superior technical characteristics compared to conventional fusion welding methods. Implementation of the LBW process into manufacturing chain offers important economic benefits (Duley, 1998). However, it has been found that these benefits are compensated by poor fatigue and damage tolerance behaviour of the joints, which primarily stems

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from the inherent welding-induced defects in the fusion zone (FZ). Although some types of weld imperfections are implicitly taken into account in existing standard guidelines (Maddox, 1991), fatigue-life predictions are typically too conservative with the aim to offset the inevitable fatigue scatter band. Designing a component based on such overconservative empirical guidelines is highly impractical and does not fit with the modern tendency to weight reduction and fuel efficiency. Thus, a deeper understanding of the fatigue failure mechanisms as well as opportunities for fatigue-life prolongation of the laser-welded joints are of paramount significance.

The current paper presents a set of post-treatment methods for reduction of the notch severity of surface and internal defects in the laser-welded Ti-6Al-4V butt joints. So-called "fish-eye" fracture and conditions needed for its appearance were experimentally investigated. Positive effect of conventional machining of the surface weld imperfections is compared with a novel and more effective technique – laser surface remelting (LSR). Crucial role of internal porosity in the fracture of the surface-treated weldments was demonstrated. Effect of the LBW process parameters on the porosity level and the fatigue performance of the weld was quantitatively characterized. Finally, it is shown that the laser shock peening (LSP) technique has a high fatigue-life-extension potential and can be considered as a powerful tool for post-weld mechanical treatment of laser-welded joints.

2. Experimental procedure

The material used in this study was a Ti-6Al-4V titanium alloy (ASTM Grade 5) in the form of hot-rolled and annealed sheets with a thickness of 2.6 mm. Autogenous LBW was performed in argon atmosphere by an 8kW continuous-wave ytterbium fibre laser YLS-8000 (IPG Photonics). LSR was conducted using the same equipment as for the LBW process. Parameters employed for LSR were as follows: laser power 3.4 kW, welding speed 2.0 m/min, focus position +80 mm, spot diameter 3.5 mm. Load-controlled uniaxial fatigue tests were conducted using a Testronic 100kN RUMUL resonant testing machine at a frequency of around 80 Hz with an applied load ratio R = 0.1. The specimen geometry is shown in Fig. 1(a). Lateral X-ray inspection of the FZ has been applied to characterize the porosity distribution. Inspection length of 75 mm was used. The X-ray analysis was carried out using Y.Cougar Basic microfocus X-ray inspection system (YXLON) operating at a tube voltage of 90 keV and current of 30 μA. LSP treatment was conducted using a Q-switched Nd:YAG laser with a wave length of 1064 nm operating at a frequency of 10 Hz and a pulse duration of 20 ns. Pulse energy of 5 J was focused in a square spot of 1 mm x 1 mm on a specimen surface covered with a steel foil. The treated area covered the welding seam and the neighboring region of 10 mm from each side, see Fig. 1(b). LSP treatment was applied on both sides of the S-N specimens, following the shot pattern shown in Fig. 1(b); three shots were applied at the same position (3x overlapping).

3. Results and discussion

3.1 Fatigue properties in the as-welded condition

The results of fatigue testing expressed by S-N curves are presented in Fig. 2(a). Overall, no clearly pronounced fatigue limit can be observed regardless of the surface state of the joints, i.e. S-N curves gradually decrease with increasing number of cycles. As evident from Fig. 2(a), the fatigue behaviour of the as-welded joints without any post-processing technique is relatively poor. Surface defects such as underfills and reinforcements play the role of stress concentrators and, therefore, have a strong deteriorative effect on the fatigue life, see Fig. 2(b). As a result, the as-welded condition is characterized by a fatigue limit of about 180-200 MPa. Failure of the as-welded joints always occured in the welding seam due to surface crack nucleation at the top or root underfill (Fig. 2(b)).

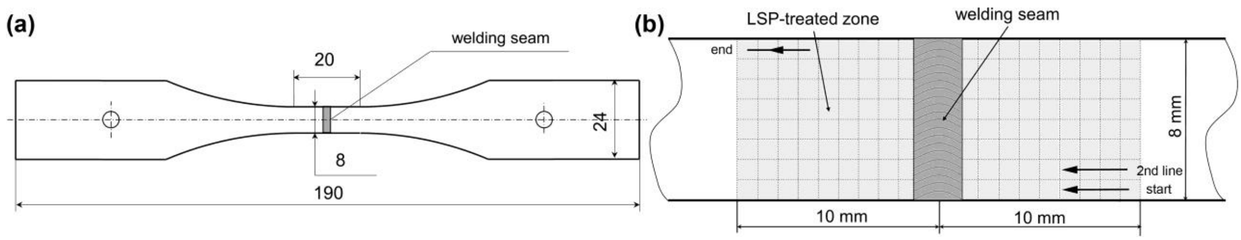

Fig. 1. (a) Geometry of the S-N specimen used (dimensions in mm); (b) schematic view of the LSP-treated region.

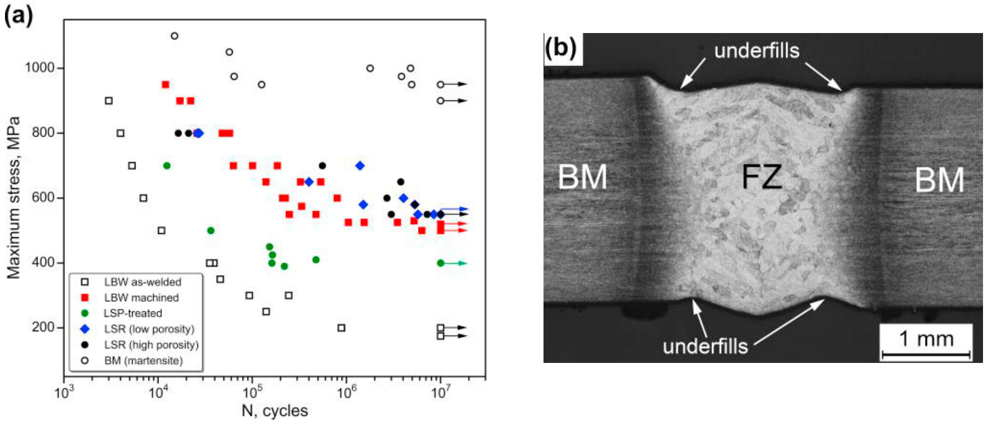

Fig. 2. (a) S-N curves of the laser-welded Ti-6Al-4V butt joints and the effect of different types of post-processing on the fatigue properties; (b) typical geometry of the laser-welded Ti-6Al-4V butt joint (welded with: P = 7 kW, v = 4 m/min, no filler material).

Since the failure always occured in the FZ regardless of the surface state, fatigue cracks initiate and grow solely in the martensitic microstructure of the FZ. Therefore, S-N curve of the as-received BM cannot act as a reference because it corresponds to the fatigue behavior of a globular microstructure prior to welding. To produce and test S-N specimens with martensitic morphology, microstructure of the weld zone was simulated by a heat treatment followed by water quenching. Parameters of the heat treatment were varied to achieve the highest similarity to the FZ in terms of microhardness and average grain size. As shown in Fig. 2(a), martensitic microstructure has an un-notched fatigue limit of above 900 MPa, that is appreciably higher than that of Ti-6Al-4V with a globular microstructure (700 – 720 MPa), as reported by Fomin et al. (2017). Increased unnotched fatigue strength of the martensitic microstructure is attributed to strengthening effect upon high cooling rates. In spite of lower ductility, quenched martensitic Ti-6Al-4V has higher strength and resistance to fatigue crack initiation compared to the as-received BM. Therefore, it can be inferred that in the absence of any defects, the FZ would have higher HCF performance than that of the BM.

3.2 Effect of machining

The S-N curve of the laser-welded joints machined flush with the sheet surface is given in Fig. 2(a). Milling the surface weld imperfections, such as underfills, provides a significant increase in the fatigue strength, and the fatigue limit achieves approximately 500-520 MPa. Thus, machining is one of the simplest and most effective methods for improving the fatigue performance. In spite of extremely smooth surface after milling, the fatigue failures were always detected in the FZ of the weldment similarly to the as-welded condition. The underlying reason is the fatigue crack nucleation at internal welding-induced defects inevitably produced within the FZ.

Upon removing the surface stress concentrators, internal defects become the most detrimental notches in the joint. Fractographical observations of machined joints revealed that internal porosity is the typical type of defects at the crack initiation site. In experiments with the as-welded butt joints, the stress concentration at the weld underfills is much more severe than that due to porosity within the welding zone; therefore, internal defects are less important for as-welded joints. A typical fracture surface of the machined joint after failure in the HCF region is illustrated in Fig. 3(a). Owing to subsurface crack initiation, a bright circular area, called “fish-eye”, was typically observed around the crack nucleation site. This circular pattern of fracture surface is a common attribute of fatigue fracture originating from internal defects (Murakami, 2002). Fish-eye region is normally composed of two areas: the optically dark area (ODA) in close proximity to the pore and the smooth area at the periphery of the fish-eye. A more detailed analysis of the fish-eye fracture of laser-welded Ti-6Al-4V butt joints was reported in Fomin et al. (2017).

3.3 Effect of laser surface remelting

Despite its beneficial effects, machining as a post-processing technique has several major drawbacks. It is well known that titanium alloys exhibit relatively low machinability. As a result, the introduction of the milling step into the manufacturing process would inevitably lead to higher costs and lower productivity. The concept of non-contact LSR treatment eliminates the inherent problems of machining. It provides high processing speeds, flexibility of the process and allows using the same laser equipment as for welding. A typical cross section of the weld subjected to the LSR post-weld treatment is shown in Fig. 3(b). Since the focal spot size of the defocused laser was larger than the weld width, LSR processing has a pronounced smoothening effect, thus, reducing the notch effect from the weld underfills. Although some insignificant residual curvature is usually present after the post-processing, Fig. 3(b), the surface stress concentration is negligibly low compared to that induced by subsurface porosity. Therefore, fatigue cracks most likely nucleate at internal defects as observed for machined joints. All the specimens subjected to LSR exhibited the fish-eye type of fracture indicating that internal crack initiation took place. As shown in Fig. 2(a), fatigue properties of the LSR-treated joints, either with low or high porosity (see Section 3.4), are slightly higher in comparison to the machined condition. The fatigue limit of 530-550 MPa was the highest among the investigated post-processing techniques.

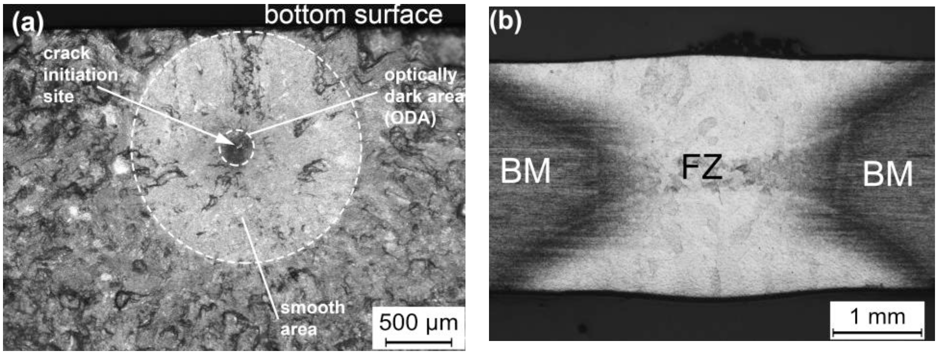

Fig 3. (a) Fish-eye fracture surface of the machined joint (530 MPa; 3,569,700 cycles); (b) effect of the LSR treatment on the shape of the weld.

3.4 Effect of porosity

As previously discussed, welding-induced pores play a crucial role in the nucleation and growth of internal fatigue cracks. In order to quantitatively characterize how the porosity level is affected by the welding parameters, laser power and welding speed were consistently varied, and the obtained welding seams were subjected to lateral X-Ray inspection. In accordance with AWS D17.1 standard, the porosity level was evaluated by the accumulated length of pores in 75mm weld length. For simplicity, the total length of pores was normalized by the inspection length. Porosity level as function of laser power for different welding speeds is shown in Fig. 4(a). The joints with incomplete penetration or insufficient quality due to excessive laser power were not considered in the assessment. As can be seen, for each welding speed level, the accumulated length of pores has the tendency to increase for higher laser powers. Remarkable growth of porosity level typically occurs when the laser power reaches 4.5–5.0 kW, depending on the weld speed. For lower laser powers, the accumulated length of pores is slightly decreasing with increasing welding speed, however, this effect is far less pronounced than that of change in the laser power.

Visual inspection of the welds revealed that there is a strong correlation between the porosity level and the spattering of the FZ. Fig. 4(b) and (c) show the bottom appearance of the weldments produced with two parameter sets. Parameter set 1 (3.5 kW, 2 m/min) corresponds to a low porosity level and set 2 (7 kW, 4 m/min), on opposite, has the highest porosity level. It was observed that for each welding speed, the increase in the number of pores is always accompanied by the enhanced spatter on the bottom surface. Apparently, the main reason for spattering is the penetration of the laser beam through the whole thickness of the welding zone. This occurs when the laser power is sufficiently high and the keyhole tip reaches the rear side of the plate. As a result, the keyhole becomes open and plasma plume is formed not only above the plate but also under the bottom surface. Fig. 4(a) shows that the spatial distribution of pores is different between the welds produced with the open and closed keyhole. After welding with the open keyhole, the majority of pores is concentrated near the bottom surface of the FZ. LBW with the closed keyhole yields a more uniform distribution of pores over the weld thickness, as shown in Fig. 4(a). These results indicate that depending on the keyhole behavior, pores are formed via different mechanisms. In the region of low laser powers, keyhole instability and collapse have the strongest influence on the formation of pores. At high laser powers, the keyhole is open and the inert gas can also enter the keyhole from the bottom surface (Tsukamoto et al., 2003). This leads to formation of bubbles in the root surface layer and increases the overall porosity level.

In order to study the effect of pores on the fatigue strength, S-N specimens with different porosity levels were welded and parameter set 1 and 2, see Fig. 4(a), were used. To prevent surface crack initiation, LSR treatment was applied after welding. Surprisingly, no significant difference was found in the fatigue life between low and high porosity level, see Fig 2(a). In conclusion, no relationship between the fatigue limit and the distribution of defects could be determined.

The increased number of pores can have an impact on the fatigue life primarily through the increased probability to have a larger defect within a specimen. However, when defects are too small and cannot be described by conventional linear elastic fracture mechanics, the effect of defect size on the fatigue properties is not straightforward. Until now, there is no established consensus on the effect of small defects on the fatigue crack initiation in Ti alloys. Murakami (2002) studied the effect of small defects and inclusions on the fatigue limit of steel and found out that the fatigue limit decreases with increasing defect size. Our results imply that for Ti alloys this relationship is weaker or does not exist at all. Further experiments should verify and support this hypothesis. The main conclusion that can be drawn here is that the fatigue performance of laser-welded Ti-6Al-4V butt joints after LSR or machining are not altered significantly by the welding parameters. Variations in the process parameters can reduce the number of pores, but it is impossible to completely avoid them. As a result, the fatigue properties stay almost unchanged.

3.5 Effect of laser shock peening

LSP is an effective local modification technique for generating deep compressive residual stresses in the surface layer up to several millimeters deep. The induced residual stress field has a strong beneficial effect on the fatigue performance because it suppresses the surface crack growth in the early stages. As shown in Fig. 2(a), the LSP treatment of the as-welded joints has a pronounced positive impact on the fatigue behavior, leading to a fatigue limit of approximately 380-400 MPa, which is close to the fatigue limit of the machined joints. Thus, residual stresses around the weld enable to mitigate the severity of the notch effect induced by the weld underfills. In spite of high residual stresses, surface crack initiation was observed for all as-welded and LSP-treated specimens. It implies that compressive residual stresses reduce the underfill notch effect to some extent, however, it is not sufficient to shift the crack nucleation to the subsurface region.

The concept of LSP application on machined or LSR-treated joints has some peculiarities to be considered. Taking into account the mechanism of internal crack initiation, the depth of compressive residual stresses is of great importance. To achieve a retardation of the crack nucleation and growth, the residual stress field should cover the potential crack initiation site. To verify the fulfillment of this condition, the depth profile of residual stresses was measured by the hole drilling technique (Steinzig and Ponslet, 2003). The results shown in Fig. 5(a) suggests that compressive residual stresses are present in the surface layer of 0.9 mm depth after LSP. Since the typical depth of the pores on the fracture surface is around 0.4–0.5 mm, one should expect a positive effect of the LSP treatment on the fatigue behavior.

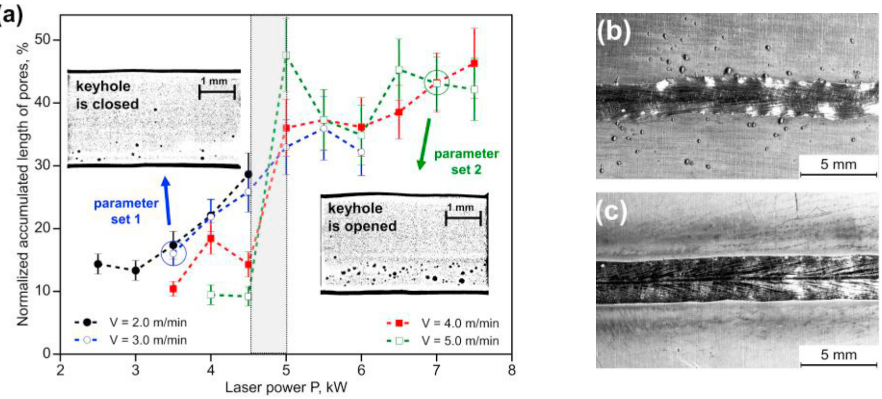

Fig. 4. (a) Effect of the LBW process parameters on the porosity level; (b) spatter on the bottom side of the weld due to the open keyhole (welded with parameter set 2); (c) bottom side of the joint after the LBW with closed keyhole (welded with parameter set 1).

To study the effect of LSP on the internal crack initiation and growth, 16 machined and 16 machined and subsequently LSP-treated specimens were tested at an equal stress level. The need for this approach was demonstrated after first fatigue trials in which the effect of LSP treatment was comparable to the fatigue scatter, i.e. a big scatter in fatigue life can overshadow the effect from LSP on surface-treated joints. Statistical analysis showed that two-parameter Weibull distribution can adequately represent the fatigue scatter. The results of the fatigue tests of both sets of specimens are presented by the Weibull probability plot in Fig. 5(b). The fitting of experimental data to Weibull distribution was done by the least square technique. As can be seen, the experimental points fall onto a straight line implying that the Weibull distribution describes the distribution of the fatigue life fairly well. Some points in the right tail of the machined condition do not follow the line due to slightly different initiation mechanism. On the fracture surface of these specimens, small deep pores were found, whereas larger subsurface pores were observed in most cases. As shown in Fig. 5(b), the application of LSP increased the Weibull scale parameter N_0 (characteristic life) almost by a factor of 3. The Weibull shape parameter β (slope) decreased from 1.54 to 1.14 after the LSP treatment indicating that the spread of fatigue life is slightly higher. It is evident from the results that compressive residual stresses have, on average, positive impact on the fatigue life; however, the increased fatigue scatter band should be considered with caution.

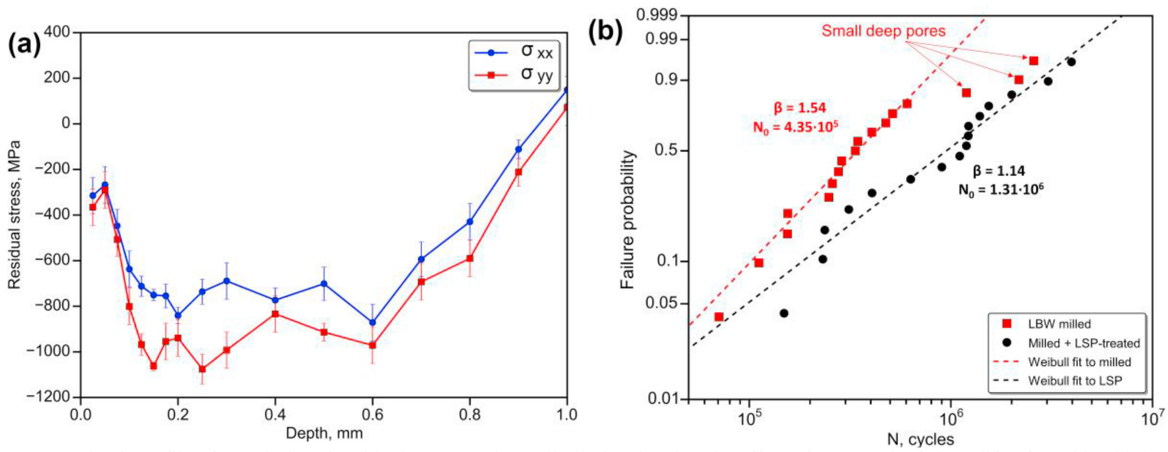

Fig. 5. (a) In-depth profile of LSP-induced residual stresses; (b) Weibull plot showing the effect of LSP on the fatigue life of machined joints.

4. Conclusions

The methods for notch-effect mitigation of the laser-welded Ti-6Al-4V butt joints were experimentally studied. Machining has a strong beneficial effect on the fatigue performance because it shifts the crack initiation from surface to interior. LSR is a more simple and cost-effective technology which enables the improvement of fatigue limit by approximately 275%. Internal welding-induced porosity determines the fatigue life of the joints after any surface-smoothening technique. Enhanced porosity formation at high laser powers can be attributed to the open keyhole during LBW. In spite of dramatically different porosity levels, the fatigue properties were unaffected by the LBW process parameters. It was demonstrated that the effectiveness of LSP for fatigue life extension is more pronounced for surface defects than for internal defects as porosity. Effect of compressive residual stresses on internal fatigue crack initiation and growth was statistically analyzed by the Weibull distribution. Although the characteristic life increased almost by a factor of 3 after LSP, special attention should be paid to the slightly larger fatigue scatter band.

References

Duley, W.W., 1998. Laser welding. John Wiley & Sons, INC., New York.

Fomin, F., Ventzke, V., Dorn, F., Levichev, N., Kashaev, N., 2017. Effect of Microstructure Transformations on Fatigue Properties of Laser Beam Welded Ti-6Al-4V Butt Joints Subjected to Postweld Heat Treatment, in "Study of Grain Boundary Character", Tański, T. (Ed.), IntechOpen, Rijeka, pp. 111–141.

Maddox, S.J., 1991. Fatigue strength of welded structures. 2nd ed. Abington Publishing, Cambridge.

Murakami, Y., 2002. Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions, 1st ed. Elsevier, Oxford.

Steinzig, M., Ponslet, E., 2003. Residual stress measurement using the hole drilling method and laser speckle interferometry, Part I. Experimental Techniques 27(3), 43–46.

Tsukamoto, S., Arakane, G., Kawaguchi, I., Honda, H., 2003. Keyhole behaviour in high power laser welding of thick steel plates, Proc. ICALEO, A176–A183.