EUROfusion

WPRM-CPR(17) 17611

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Preprint of Paper to be submitted for publication in Proceeding of 13th International Symposium on Fusion Nuclear Technology (ISFNT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Fabrication of advanced structural steels for fusion reactors by laser-laser hybrid joining

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Structural components in the European DEMO and other planned fusion reactors are expected to be manufactured from Reduced Activation Ferric Martensitic (RAFM) steels, such as Eurofer. The desired mechanical properties from RAFM steels are achieved due to dispersion strengthening with fine precipitates. Joining of such steels is complex as the welding heat and the resulting thermal cycle normally destroys the tailored wrought microstructure and forms hard phases, if the cooling rate is uncontrolled. This in practice means longer post heat treatment to recover the properties in the welded area and significant increase in process time. A laser-laser hybrid welding process, using two laser beams, was developed for use of RAFM steels. The power density and total applied energy for each laser beam could be independently controlled to tailor the transient thermal cycle during the welding process. Using two beams in different welding regimes, thick section welds were produced with better weld profile, tolerance to fit-up and control of microstructural constituent compared with standard single-beam laser welding. The process also enables efficient addition of filler wire with better stability, control, and lower spatter than standard laser-arc based hybrid processes. In addition, it has been demonstrated that, by changing the laser application modes, the same laser setup can be used to apply in-situ heat treatment to welded components.

Keywords: DEMO fabrication, laser welding, laser heat treatment, thermal cycle control

1. Introduction

Reduced Activation Ferritic Martensitic (RAFM) steels have been identified as a potential structural material for fusion nuclear reactors[1]. The matrix of the steel comprises of tempered martensite with dispersed carbides, which generate the necessary creep resistance. Similarly to other ferritic-martensitic steels, welding of such alloys generates high hardness in the weld metal and associated heat affected area. In these regions, the temperature from the transient thermal cycle is high enough to re-austenitise, which on cooling generates hard martensitic structure [2]. The hardness in such area reaches close to 500 HV, as compared to 220 HV in the parent metal [3].

Normally an arc-based welding process is used followed by a lengthy heat treatment to recover properties of RAFM steel welded joints [4]. A standard recommended time for the post weld heat treatment is two hours plus the heating time [4,5]. However a new faster joining method is needed to facilitate the replacement of cooling pipes of the reactor as a part of the regular maintenance procedure [6].

Laser welding has been identified as one of the potential processes, which may perform both the welding and cutting operation with very high productivity. However, the low heat input associated with the high speed and high energy density of the process, generates high cooling rates in the weld metal and heat affected zone [7,8]. The benefits of hybrid laser-arc welding process, such as better weld profile, lower likelihood of defects, better tolerance to fit-up and higher productivity compared to laser and arc welding used separately, have been demonstrated [9-11]. However, due to many restrictions imposed by the design of the fusion reactors it is not suitable to use arc-based welding processes, therefore a laser-laser hybrid or a single beam laser welding has been selected as preferable options. This work investigates feasibility of application of laser-laser hybrid process with laser beams operating in two different regimes. One used in keyhole regime to penetrate and create the joint, while the other laser used in conduction regime to provide additional heating and tailor the thermal cycle to a particular application.

2. Materials and Methods

2.1 Material

Three different materials were used in this work. All process study experiments, including process set-up, study of interactions and process development were carried out using a 10 mm thick S355 carbon steel. Then for the metallurgical investigations and study of meltflow characteristics a 10 mm thick P91 steel was used. Due to scarcity of Eurofer only final welds were performed in Eurofer 97. In this case a thickness of 6 mm was available and to compare the welding performance some welds in a 6 mm P91 steel were also performed. All plates were tack welded prior to laser welding and no bevel was used.

2.2 Welding

Experiments were carried out using two fiber lasers in 2G configuration, as shown in figure 1. Two laser

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heads were positioned in such a way to achieve both conduction and keyhole regimes with a concentric configuration, as shown in figure 2. The lasers used were fiber lasers with an 8 kW and a 3 kW of power respectively. The optical set-up was varied to achieve different ratios of beam diameters. The 3 kW laser was operated at the focal point, i.e. laser beam focused on the surface of workpiece to achieve a 0.1mm beam diameter. This laser was always operated in the keyhole regime to achieve deep penetration. The 8 kW laser was used in two different configurations: a standalone laser welding process with a beam diameter of 0.6 mm, by welding at the focal point or in a hybrid configuration. In the hybrid welding the laser beam was defocused appropriately to achieve beam diameters in the range between 10 and 15mm. In addition some ancillary equipment, such as shielding nozzle and monitoring equipment was used. Pure shield argon was used as shielding gas. Some welds were instrumented using R-type thermocouples to measure thermalcycle. No filler wire was used in all experiments.

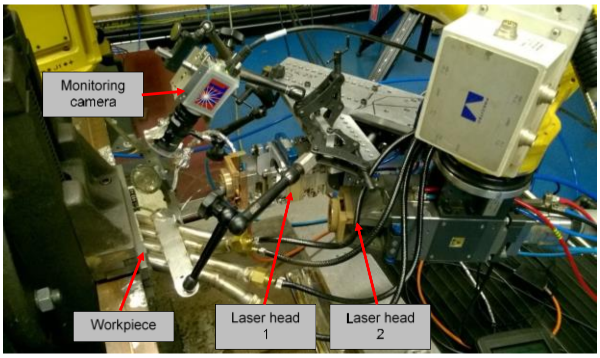

Fig. 1. Experimental set-up.

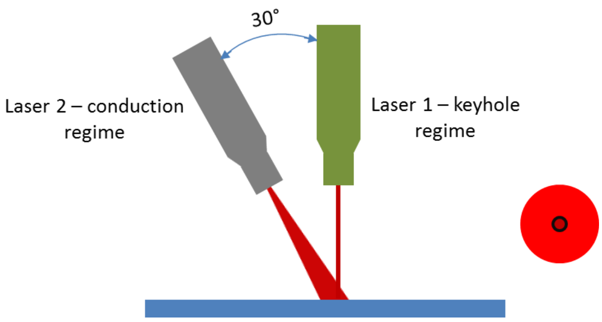

Fig. 2. Orientation of two laser beams

3. Results and discussion

The benefit of two laser beams acting simultaneously is shown in figure 3. In hybrid process the weld profile is similar to the traditional arc-based processes, but with all benefits of laser welding, i.e. deep penetration, process control and flexibility. By varying the ratio of the energy between the two beams and their energy distributions it is possible to tailor separately the top part and the root of the welds.

Comparison of melt pool dynamics between a single laser process and a laser-laser hybrid (figure 4 and figure 5) reveals good stability of the hybrid process. The hybrid welding exhibits relatively still and stable meltpool, despite using a very small beam diameter (0.1 mm) of the keyhole laser. The process seems to be even more stable than the single laser beam process with a 0.6 mm beam diameter, despite higher power density and higher likelihood of evaporation and melt expulsion. The wide melt pool generated by the conduction laser reduces surface tension and power required from the keyhole laser to penetrate the workpiece. The keyhole beam has to penetrate through a partially melted top surface and it encounters solid metal only at a certain depth when it reaches beyond the heating zone of the conduction process. Thus in the laser-laser hybrid configuration the meltpool is relatively still even with a high power density keyhole beam.

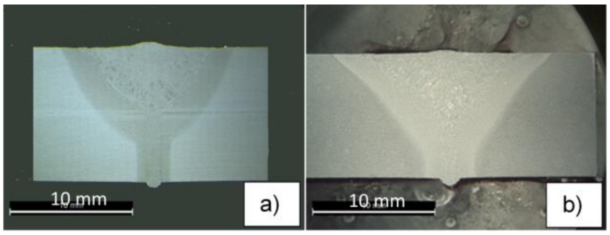

Fig. 3. Laser-laser hybrid welds in S355 steel at 0.5 m/min welding speed; a) 0.1 mm beam diameter of keyhole laser and 10 mm of conduction laser, b) 0.1 mm beam diameter of keyhole laser and 15 mm conduction laser

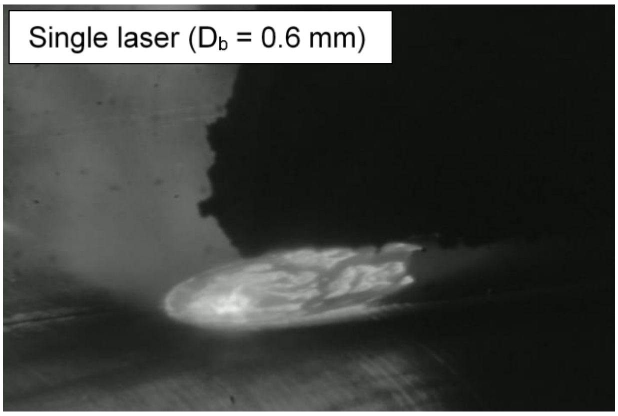

Fig. 4. Image of single laser melt pool in P91 steel

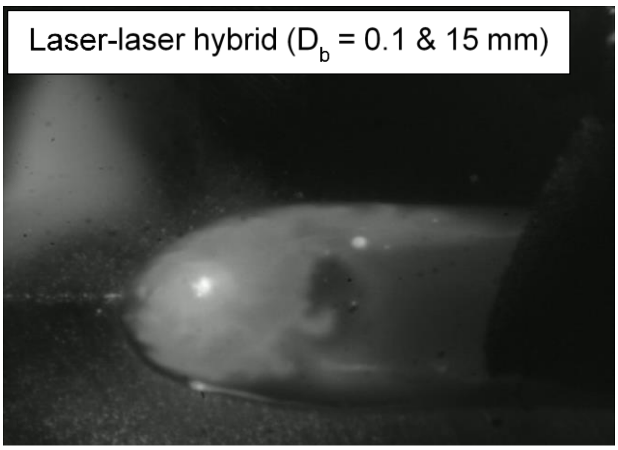

Fig. 5. Image of laser-laser hybrid melt pool in P91 steel

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As shown in figure 6 the use of two lasers in hybrid configuration has a significant benefit on cooling rate. By applying two lasers in different modes it was possible to reduce the cooling rate by a factor of three, as compared to a single laser process in keyhole mode for the same thickness and welding speed. Note that a further increase of the laser power of the single laser process would not increase the cooling time because in fully penetrated welds the system is in a self-balance and the excessive energy would result in expulsion of metal at the root side. In hybrid process, in contrast, the keyhole process provides just sufficient energy to penetrate the workpiece and the additional energy for heating is applied by the conduction process, hence it is applied over a wide area as a surface source. The additional energy is retained in the material. The difference in peak temperatures in figure 6 is due to the fixed location of thermocouples in the workpiece, which means that, in the case of the hybrid weld the thermocouple was in a direct contact with the liquid metal, and in the case of the single laser weld, the measurement was taken in the heat affected zone due the narrower profile of that weld.

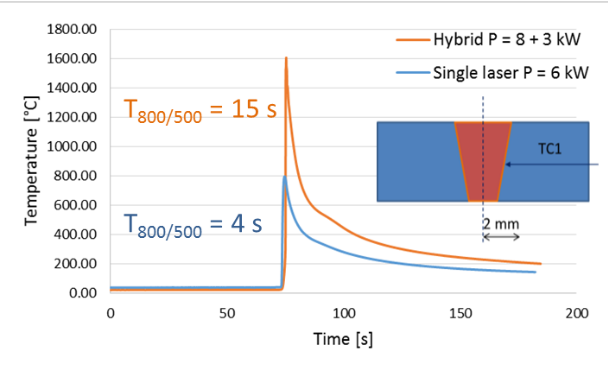

Fig. 6. Comparison of thermal cycles between single laser and hybrid process for a welding speed of 0.5 m/min

Another benefit of hybrid process is independent control of penetration depth, weld profile and cooling rate. As shown in figure 7 the laser source can also be used for pre-heating. In this case the wokpiece was irradiated by the conduction laser beam to increase its temperature prior to laser-laser hybrid welding, which resulted in a significant extension of the cooling time. This shows flexibility of the process in tailoring the thermal cycle to suit a particular application.

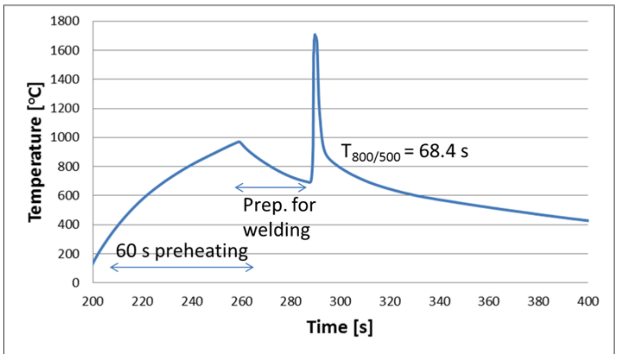

Fig. 7. Extended thermal cycle with laser pre-heating

In the final part, a set of welds in Eurofer 97 were manufactured. As shown in figure 8 it was possible to achieve high quality welds in Eurofer 97. The single laser weld (figure 8b) is not much different to the weld in P91 steel (figure 8a), which means that the welding performance, in terms is melt flow and thermal properties is similar for both materials. In addition a hybrid weld in Eurofer 97 was also achieved, as shown in figure 8c. In this case some underfill can be observed due to deficiency of liquid metal before solidification. This was caused by excessive penetration due to excessive laser energy of the keyhole laser. Due to the scarcity of Eurofer 97 it was not possible to replicate this weld with more optimum conditions. The benefits of hybrid process, in terms of weld profile, are less significant in this thin material.

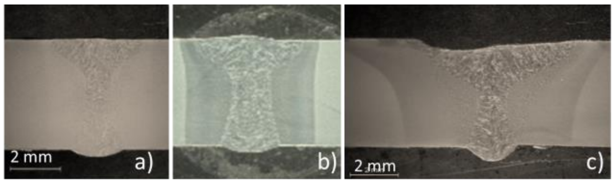

Fig. 8. Comparison of welds in 6 mm steels; a) single laser welding in P91, b) single laser welding in Eurofer 97 c) laser-laser hybrid welding in Eurofer 97

4. Conclusions

Combination of two laser beams with different processing regimes can be useful for independent control of weld profile and thermal cycle. Significant reduction of cooling rate could be achieved as compared to a single beam process. The hybrid process exhibited good stability of the meltpool despite its extensive size and exposure to high power density of the keyhole beam. Both the single laser process and the laser-laser hybrid process enable achievement of visually sound welds in RAFM steels.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/I501045]. The views and opinions expressed herein do not necessarily reflect those of the European Commission

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