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Utilization of electric arc for preheating of special steels during laser welding

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Abstract

Laser welding is characterized by high cooling rates. We found out both experimentally and numerically that during our welding experiments it reaches about 500 °C.s^{-1}. Such cooling rates lead to the formation of undesirable microstructures in some steel grades affecting weld mechanical properties. In our research, we verified the control of weld cooling rate by preheating with electric arc of TIG torch placed close to the laser beam impact. The stabilization of discharge burning in the neighborhood of laser-induced plasma above the keyhole was studied experimentally and optimal stand-off position of the TIG torch towards the beam axis was found. The flow of protective gas was visualized by schlieren method. Further, the effect of DC/AC arc mode on both weld and electrode was examined. The stability of low-current (20-60 A) arc was proved during casual laser welding speed. The effect of arc preheating was examined for HSLA and creep-resistant steels.

Keywords: Laser welding; preheating; arc discharge

Introduction

Laser welding technology has been used in industry for many years. High welding speed, large depth-to-width aspect ratio and low heat input are the main benefits of this technology. On the other hand, a small volume of fused metal compared to the volume of surrounding material results in rapid cooling rates of the weld. Such cooling rates are in order of magnitude higher than those present during conventional arc welding technologies. For example, if we use laser for welding of the high-carbon steel, rapid cooling rates will result in the formation of hard brittle structures with high content of martensite. This problem can be solved by the preheating.

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According to high laser welding speed, it is quite complicated to apply the preheating methods usually used in industry for arc welding technologies (volume heating in the furnace, resistance heating, induction heating – possible only for small parts). Laser-TIG technology has been solved more groups, for example Kese 2013, Gao et al. 2013, but the arc discharge has created a weld pool. This contribution deals with the solution of problem of material preheating during laser welding by the implementation of additional heat generated by the electric arc discharge of the TIG torch associated with the laser welding head. First, the effect of additional heat source on the cooling rate of laser weld is simulated in Sysweld software. Then, experimental set-up with detailed description of adjustable TIG torch holder is presented. The experiments focused on the stabilization of the arc discharge by laser-induced plasma plume were conducted. The argon shielding gas flow in the zone of the welding process was also studied. Finally, examples of possible use of this laser-TIG technology for welding of specific steels are briefly presented.

Welding process simulation

Three variations of butt welding of high-strength low-alloy (HSLA) steel with thickness 3 mm were simulated in SYSWELD finite element method software: laser weld, TIG weld and finally the weld with combined laser-TIG heat source, where TIG electrode is placed 3 mm before the laser beam. In all cases, a full penetration was required. Table 1 presents simulated welding parameters (welding speed v_{weld}, laser power P_{las}, arc current I_{TIG} and voltage U_{TIG} and heat input Q_{inp}) and calculated cooling time $t_{8/5}$ in the interval 800-500 °C and corresponding cooling rate CR.

Table 1. Welding simulations variables and calculated results

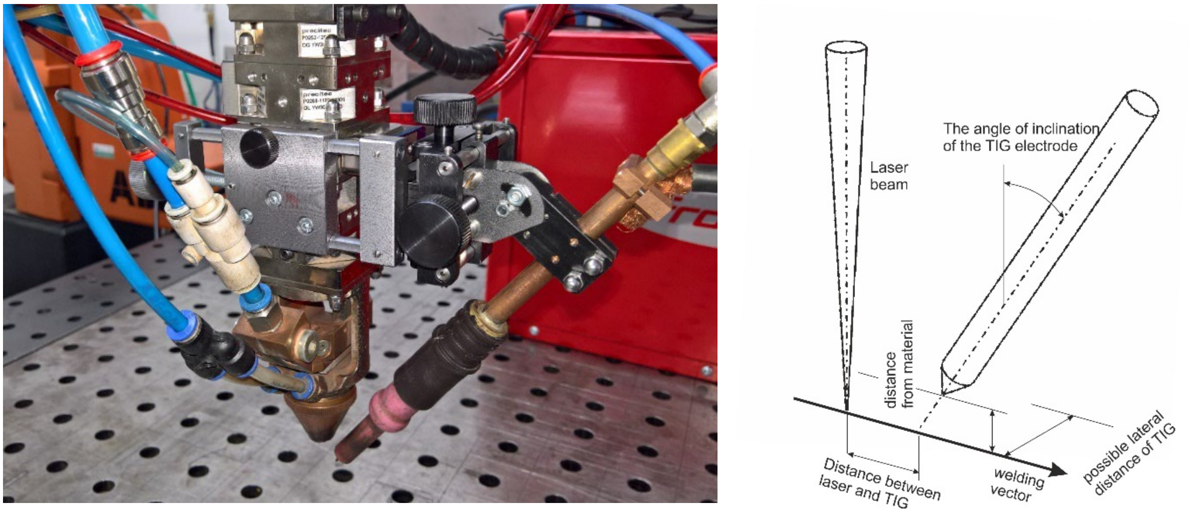
method	v_{weld} [mm.s^{-1}]	P_{las} [W]	I_{TIG} [A]	U_{TIG} [V]	Q_{inp} [J.mm^{-1}]	$t_{8/5}$ [s]	CR [°C.s^{-1}]
Laser	20	1500	-	-	63	0.50	605
TIG	3	-	150	15	304	4.06	43
Laser-TIG	20	1500	60	15	90	0.97	308

The results show that during the laser welding the heat input is about five times lower but the cooling rate is fourteen times higher compared to TIG welding. The key result of laser-TIG combination is halving the cooling rate compared to laser welding due to the additional heat introduced by the electric arc.

The cooling rate is an important variable for the CCT diagram, which states the link between the cooling rate and final structural phases of the weld metal determining its hardness and other mechanical properties. This simulation has shown that the additional heat from the arc discharge can actively modify (by the change of TIG current) the cooling rate during laser welding and thus weld resulting properties. The temperature field from the electric arc develops dynamically over time and is dependent also on material thermal conductivity and its specific heat. However, the primary objective of the arc heating is not the creation of a melt pool. The depth influence of a laser weld is dependent on laser-discharge stand-off distance, welding speed and materials properties.

Combined welding head construction

Precitec YW 30 laser welding head and Fronius TIG machine torch with ceramic nozzle for narrow joints were used for the experiments. A special holder has been designed to fix the torch to the laser head. It allows mutual positioning between the laser beam, tungsten electrode and the material (Fig 1). This holder is patent protected. IPG Photonics YLS2000 fiber laser and Fronius MagicWave 1900 Job power source driven by the robotic arm control system were used.



(a) (b)

Fig. 1. Experimental setup (a) photo and (b) drawing

Arc discharge burning stability

It has been shown experimentally that at welding speeds typical for laser welding, low-current (tens of amperes) TIG arc discharge burning is unstable. It tends to burn against the one point and then jump to another one when the distance increases. However, if the arc discharge burns close to the laser beam impact, where low-density laser induced plasma plume forms, this plasma helps to stabilize the TIG arc discharge burning. This has been investigated experimentally by the side-facing high-speed camera (through gray filter). Fig. 2 presents photographs of arc discharge appearance for three different stand-off distances between the electrode and laser beam axis.

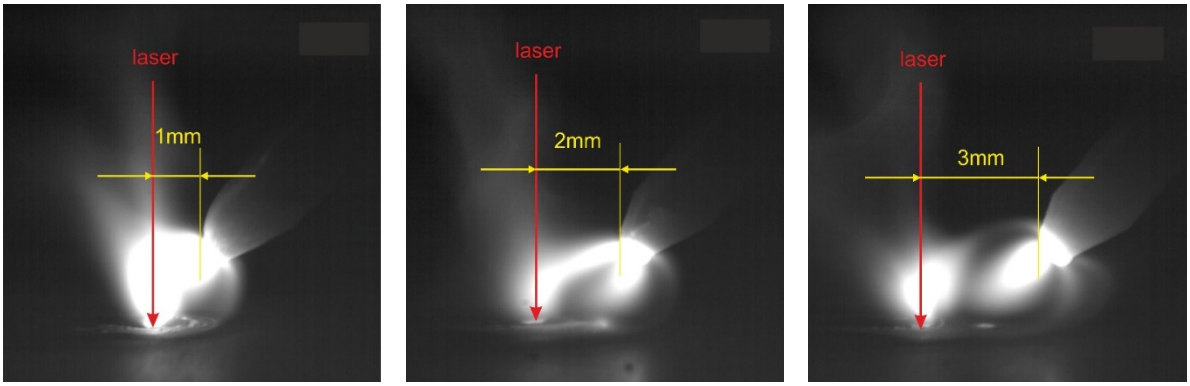


Fig. 2. High-speed camera images of arc discharge for three different stand-off positions

It can be seen that for low stand-off 1 mm the arc burns to the keyhole area. At larger stand-off, a partial anode spot forms but a part of the discharge still aims to the keyhole. It is evident that increasing stand-off distance reduces arc discharge coupling to the keyhole. Exceeding a certain stand-off limit, the discharge is not affected by the laser-induced plasma plume anymore.

In DC mode, the TIG electrode has a negative potential, thus attracting positively charged ions of metals from the keyhole resulting in electrode contamination. For this reason, the AC mode with various settings of amplitude and frequency has been also tested. It has been found that the heat impact on the weld metal and heat affected zone is practically the same irrespective of tested settings. Nevertheless, the electrode contamination is significantly reduced in AC mode. What is more, the arc discharge burning stability is better.

Shielding gas flow

The gas flow of the shielding atmosphere (argon in the region of the weld pool) has been studied. To visualize the gas flow, the schlieren system according to Mrňa et al. 2016 was used. In the basic configuration, there are two gas sources. The first one is a coaxial nozzle on laser welding head from which gas flows perpendicularly to the material surface. The second one is a TIG machine torch producing gas stream inclined towards the material surface. Its function is not only to protect the weld pool but it also protects the tungsten electrode against oxidation, it cools the torch and especially, it provides the environment for arc discharge burning. The gas is heated by the heat of the electric arc and by laser-induced plasma during the welding. A strongly turbulent flow appears. Heated argon flow up from the weld pool despite the original gas flow vector (Fig 3). However, it is evident that the weld pool protection is still assured. The experiments have shown that the use of only the TIG torch gas flow is sufficient enough to protect the weld pool. Therefore, a coaxial nozzle does not have to be used during laser-TIG welding to save gas.

Fig. 3. Schlieren image of gas flow during laser-TIG welding. Red arrow - welding direction

Examples of use

Obviously, the described technology of laser-TIG welding can be applied where high cooling rates leading to brittle structures formation are present. For example, it can be used for welding of martensitic stainless steels with higher carbon content. Such steels are used in the construction of steam turbines. During the conventional welding, both hot and cold cracks can be initiated which is absolutely unacceptable for their safe operation – welding of these steels deals with Comeli et al.2018.

The first example is the welding of steam turbine blades made of X12CrMoV12-1. The material is in quenched and tempered condition before the welding. In the weld line, the blade has a variable shape, thus also the full penetration depth varies. The maximum is 5 mm. Thus, the heat introduced by the electric arc has the influence only to a certain depth (Fig 4a). No cracks were detected in laser-TIG welds.

(a) (b)

Fig. 4. (a) welded pack of steam turbine blades; (b) steam turbine wheel

The second example is the welding of turbine wheel where heterogeneous X12Cr13 – S355 joint is required (Fig 4b) Again, no cracks were detected. This weld joint is under the further technological optimization process these days.

Conclusion

Laser-TIG welding seems to be a promising technology for a specific range of weld joints. For experiments, a hybrid welding head was constructed using commercial parts. The effect of stabilization of the arc discharge due to the near, laser-induced of plasma plume was studied. Using schlieren visualization has been optimized argon flow in the weld pool. The technology Laser-TIG has the following options:

- Active control of the weld metal cooling rate
- Reduction of stress states

These have positive effect on weld defects and final mechanical properties of the weld. In addition, compering to other preheating methods, this method is economically undemanding.

Acknowledgements

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