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HYBRID LASER-MICROPLASMA WELDING OF STAINLESS STEELS*

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Hybrid laser-microplasma welding is one of the modern innovative processes of welding sheet stainless steels, allowing minimization of residual deformations, producing high-quality and durable joints. In this study, basic techniques of hybrid laser-microplasma welding were optimized, mode parameters were précised, and mechanical properties and corrosion resistance of the produced joints of SUS304 steel were assessed. The good prospects for application of laser-microplasma welding for joining thin stainless steels were confirmed experimentally. 6 Ref., 2 Tables, 10 Figures.

Keywords: *laser-microplasma welding, SUS304 stainless steel, filler wire, rate of energy input, strength, elongation, corrosion resistance, hybrid effect*

Welded items from sheet stainless steels are manufactured by modern industry with the purpose of their application in the areas of engineering, associated with the need for operation of sufficiently strong structures, exposed to corrosion and certain mechanical impacts. Examples of such tasks are as follows: manufacturing household structures for conditions of marine climate or higher humidity, elements of hull structures of transport equipment (for instance, railway car bodies), expansion bellows for nuclear engineering, chemical and food industry equipment (for instance, tanks, filters), etc. Here, it is often necessary to perform butt welding of stainless steels up to 3.0 mm thick. As a rule, flash-butt [1] or argon-arc [2], more seldom plasma welding [3], are used to solve such tasks.

However, these welding processes by far not always allow achieving mechanical characteristics of the produced joints maximum close to those of the base metal, and also often do not meet the requirements of minimizing the residual welding deformations of sheet steels. Laser welding is one of the best welding methods today in terms of minimizing residual deformations, producing high-quality and durable welds [4]. However, because of comparatively high cost of laser equipment, this process has not become widely accepted now. One of the ways to lower the cost of laser equipment is reduction of radiation power due to its partial replacement by plasma-arc component in the welding process. Such a process is called hybrid laser-plasma welding [5]. If in this case the welded joint quality close to laser welding quality is preserved, we can get a new promising welding technology. Therefore, this work is devoted to investigation of the capabilities of hybrid laser-microplasma welding of sheet stainless steels in the case of SUS304 steel of thickness δ = 0.3–3.0 mm.

The objective of this work is optimizing the basic techniques of hybrid laser-microplasma welding of sheet stainless steels in the case of welding SUS304 steel, selection of mode parameters for such techniques, as well as checking the mechanical and corrosion properties of the produced joints.

Technological studies of the process of hybrid laser-microplasma welding of stainless steel SUS304 (08Kh18N10 analog) were conducted according to the scheme given in Figure 1. Experiments were performed with application of a disc laser with radiation wave length λ = 1.03 μm, the power of which was varied within 0.3–1.2 kW. The focal spot diameter was of the order of 0.4 mm. In the integrated coaxial direct action plasmatron of original design applied for studies, the laser radiation was combined with constricted low-amperage arc of up to 2.3 kW power [6]. In it the focused laser radiation and constricted arc were guided jointly through a common nozzle of 2.5 mm diameter to the sample being welded, located at the distance of the order of 3 mm from the nozzle edge. The focal plane of laser radiation was located at the depth of the order of 0.5 mm relative to the sample surface. There was a capability of filler wire feeding at the rate

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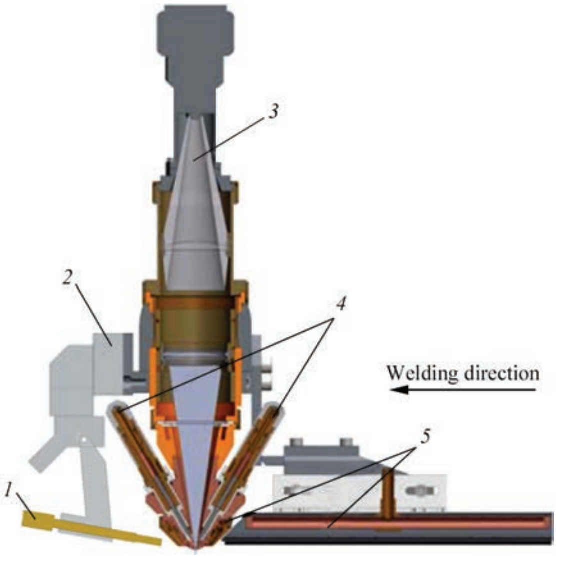


Figure 1. Scheme of integrated plasmatron and conducting the experiments: *1* — filler wire feed; *2* — attachment to the robot arm; *3* — feeding laser radiation of 0.3–1.2 kW; *4* — cathode assemblies; *5* — gas shielding

of 60–600 m/h. A continuous straight polarity electric arc was used in the experiments. Arc current of integrated microplasmatron was smoothly adjustable up to 80 A at arc voltage of up to 28 V. SUS304 steel sheets of (200–300)×100×δ mm size where δ = 0.3; 0.5; 1.0; 1.5; 3.0 mm, were used as samples for butt welding and making penetration beads. ESAB OK Autrod 308L wire (0.8 mm diameter) was applied as filler, which was fed at the rate of 60 m/h. Integrated plasmatron was moved relative to the sample being welded, using anthropomorphous robot KUKA KR30HA (Figure 2).

Conducted experiments showed the high stability of the process of laser-microplasma welding. In the case of hybrid butt welding of SUS304 steel sheets (δ = 3.0 mm) with filler wire, positive results were obtained both with the gap of 0.5 mm between the edges being welded, and without the gap. Positive results by the criterion of formation of the top and reverse beads of the weld were obtained in a broad range of welding speeds from 30 up to 50 m/h. Here, acceptable results of welding without the gap between the edges were observed in the range of speeds of 30–40 m/h, and in welding with the gap — in the range of 40–50 m/h (Figures 3, 4).

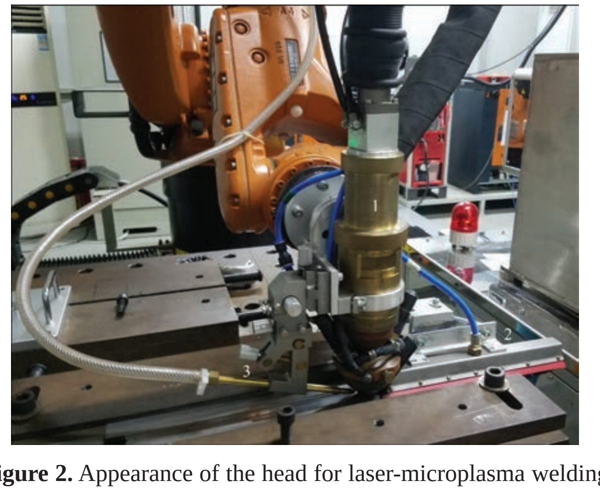


Figure 2. Appearance of the head for laser-microplasma welding in the arm of KUKA KR30HA robot: *1* — integrated plasmatron; *2* — system of formed weld shielding; *3* — nozzle for filler wire feeding

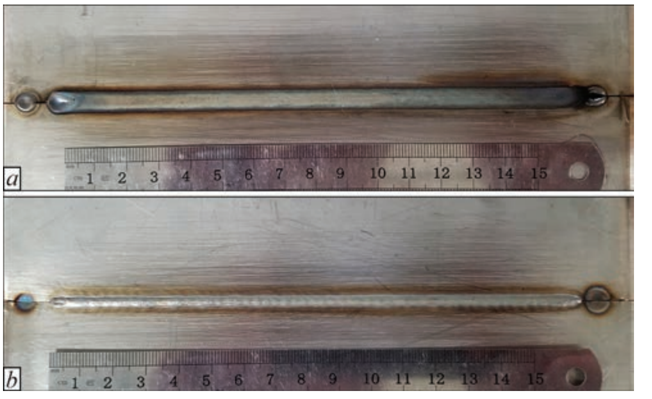


Figure 3. Appearance of SUS304 steel plates (δ = 3.0 mm), butt welded with a gap of 0.5 mm between the edges by laser-microplasma process (radiation power P = 1.2 kW; welding current I = = 80 A; voltage U = 28 V; welding speed v = 30 m/h): face (*a*) and reverse (*b*) sides

Performance of a number of experiments enables determination of the modes of hybrid butt welding of SUS304 steel sheets, both without application of filler wire (Table 1), and with its application (Table 2). These parameters were used for welding joints, from which samples of XIII (XIIIa) type (GOST 6996–66) for performance of mechanical testing and samples of an arbitrary shape for studying the corrosion resistance by weighting procedure were prepared. More over, when studying the process of laser-microplasma welding of SUS304 steel without filler wire application such parameters of the mode were established, which allow performance of sound welded joints without undercuts or weld sagging in the entire range of the considered thicknesses. One of the examples is the result of welding SUS304 steel of thickness δ = 1.5 mm, which is given in below and on Figures 5, 6.

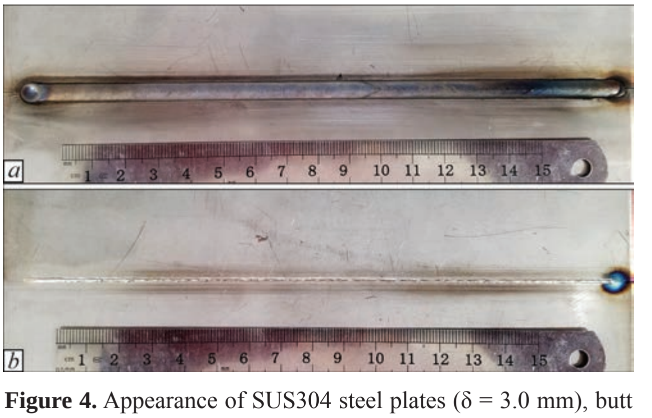


Figure 4. Appearance of SUS304 steel plates (δ = 3.0 mm), butt welded without a gap between the edges by laser-microplasma process (radiation power P = 1.2 kW; welding current I = 80 A; voltage U = 28 V; welding speed v = 40 m/h): face (*a*) and reverse sides (*b*)

Figure 5. Welded sample of SUS304 (δ = 1.5 mm): face (*a*, *b*) and reverse (*c*) sides

Mode and result of hybrid laser-microplasma welding of a defectfree joint of SUS304 steel (δ = 1.5 mm) without filler application

Laser power P, W	1200
Arc current I, A	50
Plasma gas flow rate Q_{pl}, l/min	10
Shielding gas flow rate Q_{sh}, l/min	10
Welding speed v, m/min	2
Gap from part to nozzle, mm	3
Flow rate of additional shielding gas $Q_{ad.sh}$, l/min	20
Flow rate of gas for weld root shielding Q_{rev}, l/min	20
Width of weld face (upper) part, mm	2.1
Face side convexity, mm	0.2
Weld reverse side (root) width, mm	1.0
Weld reverse side (root) convexity, mm	0.25

Two series of three samples each were cut out, in order to obtain the results of comparative mechanical testing of base metal and joint of SUS304 steel (δ = = 1.5 mm), butt welded by laser-microplasma process without filler. One more series of four samples was cut out of welded by hybrid process butt joints of the same steel of thickness δ = 1 and 3 mm (two samples of each type). Tensile testing machine of MTS Criterion 45 type was used to perform static tensile tests of butt welds to determine the ultimate strength δ_t (MPa) and relative elongation δ (%). Results measured for each sample series were averaged. Derived averaged values were used to plot the respective diagrams (Figure 7). As a result, it was established that strength of joints at hybrid laser-microplasma welding of SUS304 stainless steel is equal to about 96 % of that of base metal, relative elongation of samples welded by such a process is 100 % of base metal. The given values are satisfactory for the majority of the welding tasks.

Corrosion resistance testing of butt welded joints of SUS304 steel (δ = 1.0; 1.5 and 3.0 mm), produced by laser-microplasma welding without filler wire, was performed by the weighting procedure. According to this procedure, templates (three samples for each case) of width close to that of the welds, were cut out of the

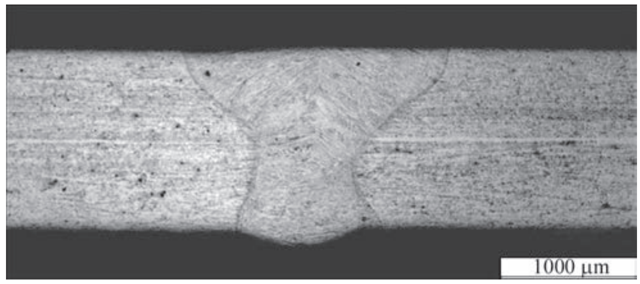


Figure 6. Macrostructure of butt joint of SUS304 steel (δ = 1.5 mm), made by laser-microplasma welding without filler wire

HAZ. Template size was (5–10)×(3–8)×δ mm. Thus, the template contained a certain part of the weld and HAZ at minimum proportion of base metal. Templates of close dimensions (reference samples) were cut out from base metal separately. Ready templates were weighed in analytical balance with the accuracy of up to 0.001 g, which was followed by immersion into the so-called aqua regia — a mixture of $1HNO_3$ + 2HCl acids. After a certain time (usually, 1–2 h), the samples were taken out, thoroughly rinsed and weighed once more. The extent of weight loss allows judging the rate of corrosion. Comparison of weight loss in reference sample from base metal with weight loss of welded sample allows determination of corrosion resistance of the latter.

Results of corrosion testing of the cutout samples are shown as diagrams in Figure 8. These results lead to the conclusion that all the obtained data are within the experimental error, and deviation of the values of weight loss of welded joints from the base metal is in the range of 3–4 %. Sample weight loss is within 0.7–0.8 g/h. Corrosion rate here is equal to $(6–7)\cdot10^{-3}$ g/min. The observed tendency of increase of samples weight loss with increase of their thickness is attributable to grain size growth and increase of the HAZ due to a higher rate of energy input in welding.

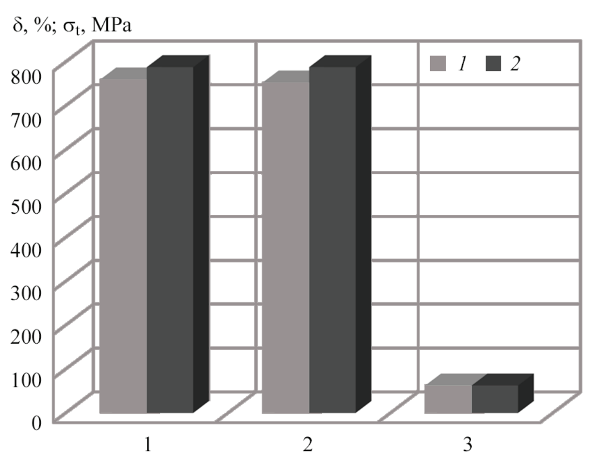
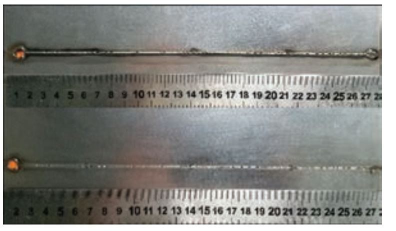
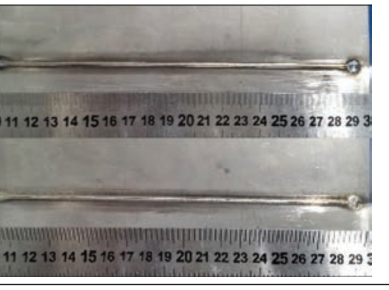
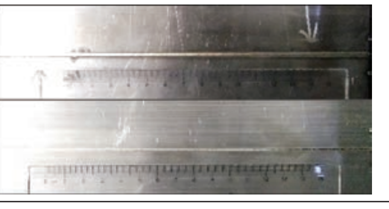
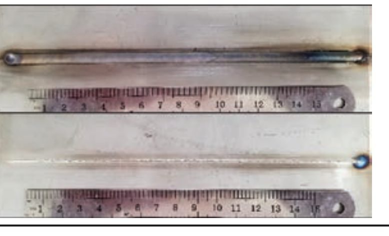


Figure 7. Comparative results of mechanical testing of samples of SUS304 steel (*1*) and base metal (*2*) welded by laser-microplasma process at their static tensile testing: *1* — averaged ultimate strength σ_t (MPa) for 1 and 3 mm thick samples; *2* — averaged ultimate strength σ_t (MPa) for 1.5 mm samples; *3* — relative elongation δ (%) for all the cases

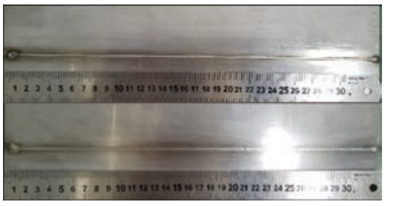
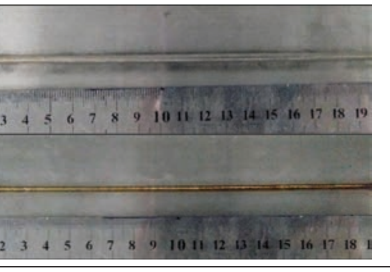
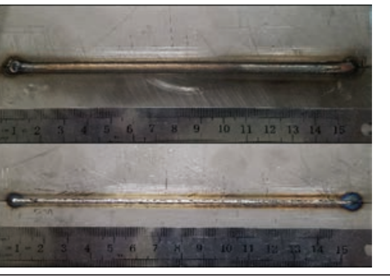
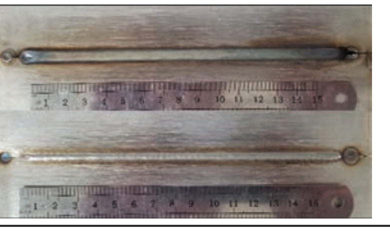
Table 1. Modes and results of hybrid laser-microplasma welding of SUS304 sheet steel without filler wire application

δ, mm	Radiation power, W	Welding current, A	Arc voltage, V	Welding speed, m/h	Result (top and side view of the weld)
0,3	300	15	22	400	
0,5	1000	50	26	360	
1,0	1000	50	26	180	
1,0	1000	70	27	180	
1,5	1200	50	26	120	
3,0	1200	80	28	48	

During analysis of the conducted technological studies, the rate of energy input of the process (E, J/mm) was determined as a sum of powers of laser (P, W) and microplasma (IU, W) components referred to welding speed (v, mm/s). Calculation results were used to plot a dependence of the change of the rate of energy input in the two considered processes of laser-microplasma welding: with filler wire and without it (Figure 9). Comparison of curves *1* and *2*, given in Figure 9, showed that the rate of the process energy input should be increased by 20–40 % in the case of welding with closely abutted edges, and by 15–30 % in the case of welding with a gap between the edges, in order to apply the filler wire. It is desirable for the value of such a gap to be of the order of 15–20 % of the abutted edge thickness.

The following experiment was performed for comparison of the results of laser, microplasma and hybrid laser-microplasma welding. Laser-microplasma process without filler application was used to achieve

Table 2. Modes and results of hybrid laser-microplasma welding of SUS304 sheet steel with filler wire application (0.8 mm diameter), fed at the speed of 60 m/h

δ, mm	Radiation power, W	Welding current, A	Arc voltage, V	Welding speed, m/h	Result (top and side view of the weld)
1,0	1000	70	27	120	
1,5	1200	50	26	90	
3,0	1200	80	28	42	
3,0	1200	80	28	30	

guaranteed penetration in a plate of SUS304 steel δ = = 3.0 mm) in the following mode: P = 1200 W, I = = 80 A; U = 28 V; v = 45 m/h. Then two penetration beads were deposited by laser and microplasma processes (Figure 10) at the same speed and with the same other parameters of the mode. Here the sum of the rates of energy inputs of the component processes corresponded to the rate of energy input in hybrid welding.

Investigation of the cross-sections of these penetration beads showed that the depth of penetration in

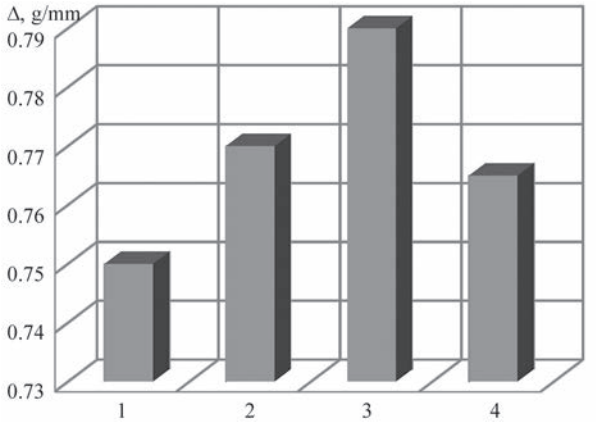


Figure 8. Averaged values of weight loss of samples from SUS304 steel (Δ): *1* — δ = 1.0 mm; *2* — δ = 1.5 mm; *3* — δ = 3.0 mm; *4* — base metal

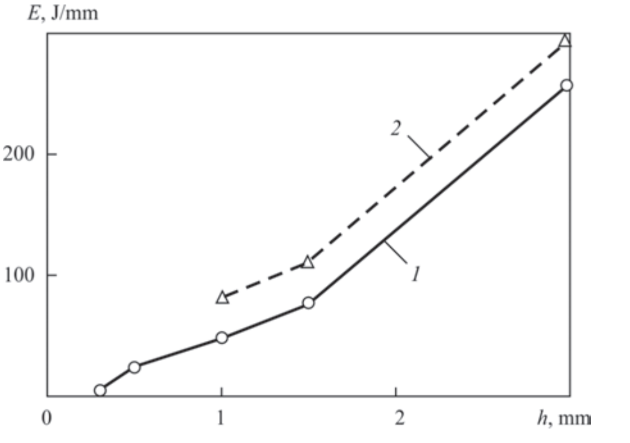


Figure 9. Dependencies of the rate of energy input E (J/mm) of laser-microplasma welding without wire (*1*) and with wire (*2*) on thickness h (mm) of welded SUS304 steel

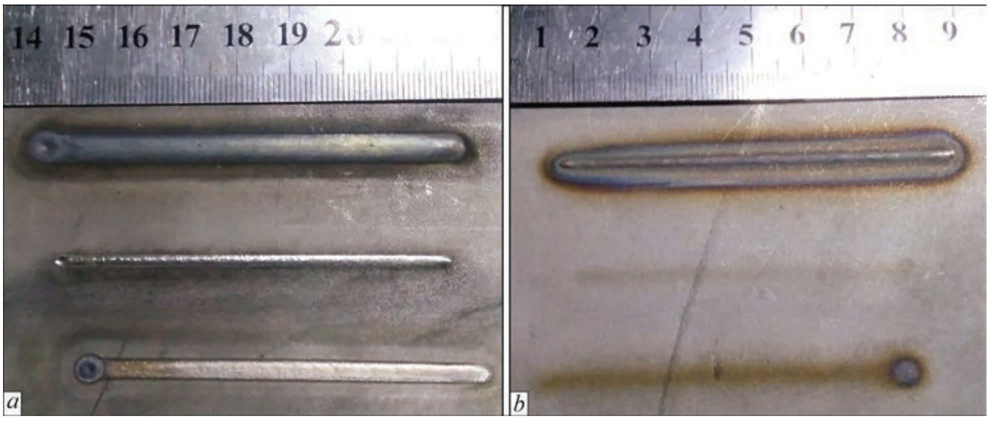


Figure 10. Appearance of face (*a*) and reverse (*b*) sides of penetrations in a plate of SUS304 steel of thickness $\delta = 3.0$ mm (top to bottom), hybrid, laser, microplasma

the hybrid process exceeds by approximately 25 % the sum of penetration depths of laser and microplasma processes. This led to the conclusion about the presence of a pronounced hybrid effect in the case of laser-microplasma welding by the considered method.

Conclusions

1. During this work, hybrid laser-microplasma welding of sheet stainless steels was studied in the case of SUS304 steel without filler wire, and with its application. It was determined that application of filler wire is rational, starting from thicknesses not less than 1.0 mm. Here, in order to achieve complete remelting of 0.8 mm wire in the case of welding with closely abutted edges, the rate of the process energy input should be increased by 20–40 %, and in the case of welding with a gap between the edges — by 15–30 %. The size of the gap should be equal to a value of the order of 15–20 % of the abutted edge thickness.

2. Determination of mechanical properties of the produced by hybrid laser-microplasma welding joints of SUS304 stainless steel showed that their static tensile strength is equal to about 96 % of that of the base metal, and relative elongation is similar to this parameter of the base metal. The given values are acceptable for the majority of welding tasks.

3. Corrosion testing showed that deviation of the values of welded joint weight loss relative to base metal is within 3–4 %. Weight loss of the samples is within 0.7–0.8 g/h. Corrosion rate here is equal to $(6\text{–}7)\cdot 10^{-3}$ g/min. The extent of sample weight loss becomes greater with increase of their thickness that can be attributed to increase of grain size and HAZ, caused by increase of the rate of energy input in welding.

4. Comparative studies of beads made on SUS304 steel by laser, microplasma and hybrid processes showed that the penetration depth in hybrid process is by approximately 25 % greater than the sum of penetration depths in laser and microplasma processes. Here, the sum of the rates of energy inputs of the component processes corresponded to the rate of energy input in hybrid welding. This is indicative of the presence of hybrid effect in the case of laser-microplasma welding.

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