LASER WELDING OF SHEET STAINLESS STEEL BY MODULATED RADIATION

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The effect of power modulation frequency and shape of laser radiation pulses on formation of weld metal structure in welding of austenitic steel of 18-10 type was investigated. It is shown that pulse laser radiation can affect solidification of weld metal and formation of fine-grained structure in it. Optimal range of modulation frequency was determined.

Keywords: *laser welding, thin sheet, stainless steel, solidification, weld, modulated radiation, laser welding parameters, microstructure*

In welding production effective utilization of power and material resources can be achieved by introducing fundamentally new power-saving technologies and equipment.

Known are various methods of controlling the solidification process. Here, the objective is to modify weld structure, in particular, produce fine-grained structure that in the majority of cases essentially improves welded joint properties. Two main methods of controlling weld structure are singled out: metallurgical and technological [1]. Metallurgical method is based on weld pool modification by chemical elements using both filler materials fed into the welding zone, and preliminary preparation of metal before welding (work-hardening, cold-working, application of technological inserts) [2]. Technological method, in addition to optimization of welding modes, envisages an external impact on the weld pool (mechanical, thermal, electromagnetic).

Method of pulsed-periodic impact with application of laser radiation as the heat source became widely accepted recently [3–8]. Studying the physical processes, running in weld pool at such an impact, is extremely complicated [9]. Absence of strict mathematical models of the process, and short duration of thermal processes ensure research performance on the basis of an integrated approach by combining qualitative assessments, experiments, and local simulation with theoretical substantiation.

Achieving high technological strength and mechanical characteristics of welded joints is one of the main objectives in laser welding of thin-walled structures. Here, in order to prevent hot and cold cracks in the weld metal, the possibility of achieving fine-grained primary structure in it becomes important in thin metal welding [10–12].

In this work the influence of parameters of pulsed-periodic laser impact, shape of laser radiation pulses and their repetition rate on formation of weld structure in welding austenitic steel at constant average heat input power was studied.

According to statistical approaches of thermodynamics [13] at metal solidification the probability of formation of nuclei w_1 can be presented as

$$w_1 = M_1 \exp\left(-\Delta G_k/(k_B T)\right), \qquad (1)$$

where k_B is the Boltzmann constant; T is the temperature; ΔG_k is the critical or maximum value of free energy.

Here

$$\Delta G_k = \frac{16\pi s^3 T_m^2}{3\Delta T^2 Q^2}, \qquad (2)$$

where s is the surface tension; T_m is the metal melting temperature; Q is the latent heat of solidification.

However, with increase of overcooling the diffusion process is decelerated, slowing down the approach of new atoms from the liquid to the crystal. The probability of transition from the liquid phase into the solid phase at nucleus formation is

$$w_2 = M_2 \exp\left(-U/(k_B T)\right), \qquad (3)$$

where U is the energy of diffusion self-activation.

Probability w, determining the number of solidification centers n, is equal to the product of probabilities of process components:

$$w = w_1 w_2 = M_3 \exp\left(-(\Delta G_k + U)/(k_B T)\right), \qquad (4)$$

where M_1–M_3 are the constant coefficients, dependent on metal properties.

After substitution of expression (2) into (4), we will obtain the dependence of the number of solidification centers on temperature:

$$w = M_3 \exp\left(-\left(\frac{16\pi s^3 T_m^2}{3\Delta T^2 Q^2} + U\right)\Big/(k_B T)\right). \qquad (5)$$

Dependence of the probability of nuclei initiation on the degree of overcooling is given in Figure 1.

Thus, under the influence of two opposite tendencies there exists the overcooling value, providing optimum conditions for formation of maximum number of nuclei.

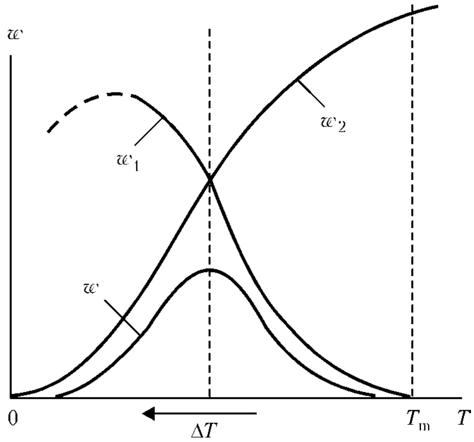


Figure 1. Influence of the degree of overcooling on the conditions of nucleus formation

The forming weld structure is essentially affected also by the solidification rate. Linear rate of crystal face growth is determined as

$$w = M_4 \exp\left(-\left(\frac{\pi s^3 \alpha T_m}{\Delta T\, Q} + U_1\right)\Big/(k_B T)\right). \qquad (6)$$

Increase of the number of solidification centers and slowing down of crystal growth rate promotes crystallite refinement.

To determine the technological parameters, providing optimal conditions of producing the fine-grained structure of weld metal, laser welding was performed by complex-shaped modulated radiation (Figure 2). Pulse shape had a steep leading front and smoothly falling rear front, which contained two regions: melting and solidification. First $(0; t_1)$ provides material melting without intensive evaporation, and the second region $(t_1; t_2)$ has a gradient, the change of angle of which allows changing the solidification rate, while the region length allows determination of the optimum degree of overcooling of the metal being welded.

Using as the model of heat transfer process the moving linear concentrated source in a plate with application of the method of sources, we will obtain a quasi-stationary temperature process (Figure 3).

The objective of modeling is selection of the shape and frequency of repetition of laser pulses, at which the change of weld pool temperature in the region of the zone of liquidus–solidus phase transition is ensured, as well as achieving the calculated values of the degree of welded metal overcooling.

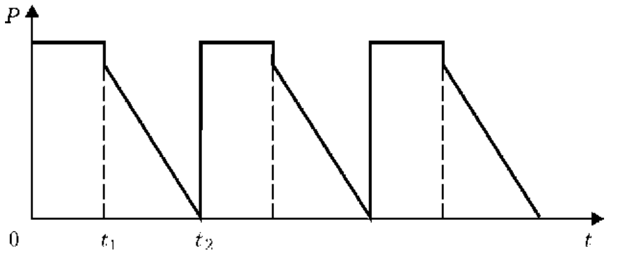


Figure 2. Pulse-periodic law of variation of laser radiation power

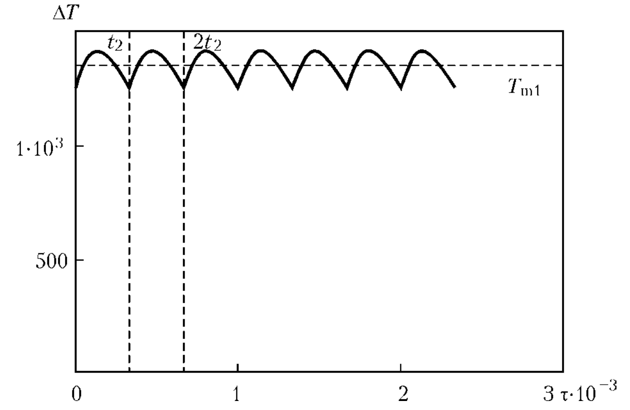


Figure 3. Quasi-steady process of weld pool temperature variation

Materials and equipment. A strip 0.2 mm thick from 1.4541 steel to DIN EN 10028-7:2000, which is an analog of 0818N10T steel, was used.

Samples were welded in a three-coordinate welding complex ARMA-100M (manufactured by PWI) fitted with ytterbium fiberoptic single-mode laser of YLR-100-AC type with radiation power of 100 W (manufacturer is IPG Laser, Germany), in which the generating core is of 10 μm diameter [14]. Laser radiation was focused onto metal in a beam of 40 μm diameter. Argon was used as shielding gas on top and below. Penetration was studied on a whole metal sheet.

Experimental procedure. Samples of stainless steel strip (wt.%: 0.72 Si; 0.25 Ti; 18.8 Cr; 1.68 Mn; 69.65 Fe; 8.9 Ni) were welded by continuous laser radiation of 57 W power and modulated laser radiation. Shape of modulated pulse corresponded to that given in Figure 2. Pulse amplitude was 100 W; modulation frequency was 100, 1000, 2000, 3000, 5000, 10,000 Hz, and calculated values of the degree of overcooling were 151, 143, 136, 125, 106 and 82 K. Average value of input power was 57 W, welding speed was 0.33 cm/s. Samples for metallographic analysis in the form of transverse sections of welded joints were prepared by a standard procedure using polishing-grinding machine of Struers. Microstructure and composition of base metal and welded joints were analyzed using optical microscope Reichert Polyvar Met and scanning microscope CamScan fitted with energy-dispersive system of local analysis Energy 200. Microhardness of welded joints in the weld cross-section was measured with Vickers indenter in Reichert Polyvar Met microscope at 0.2 N load with 50 μm step.

Results and their discussion. Macrostructure of welded joint of stainless steel samples made at different types of laser radiation, distribution of the main components in the weld zone and nature of the change of microhardness in the joint zone are given in Figure 4.

Investigations results show that the proposed method of laser welding provides weld zone composition by the main elements on base metal level both at continuous and at cyclic impact of laser radiation.

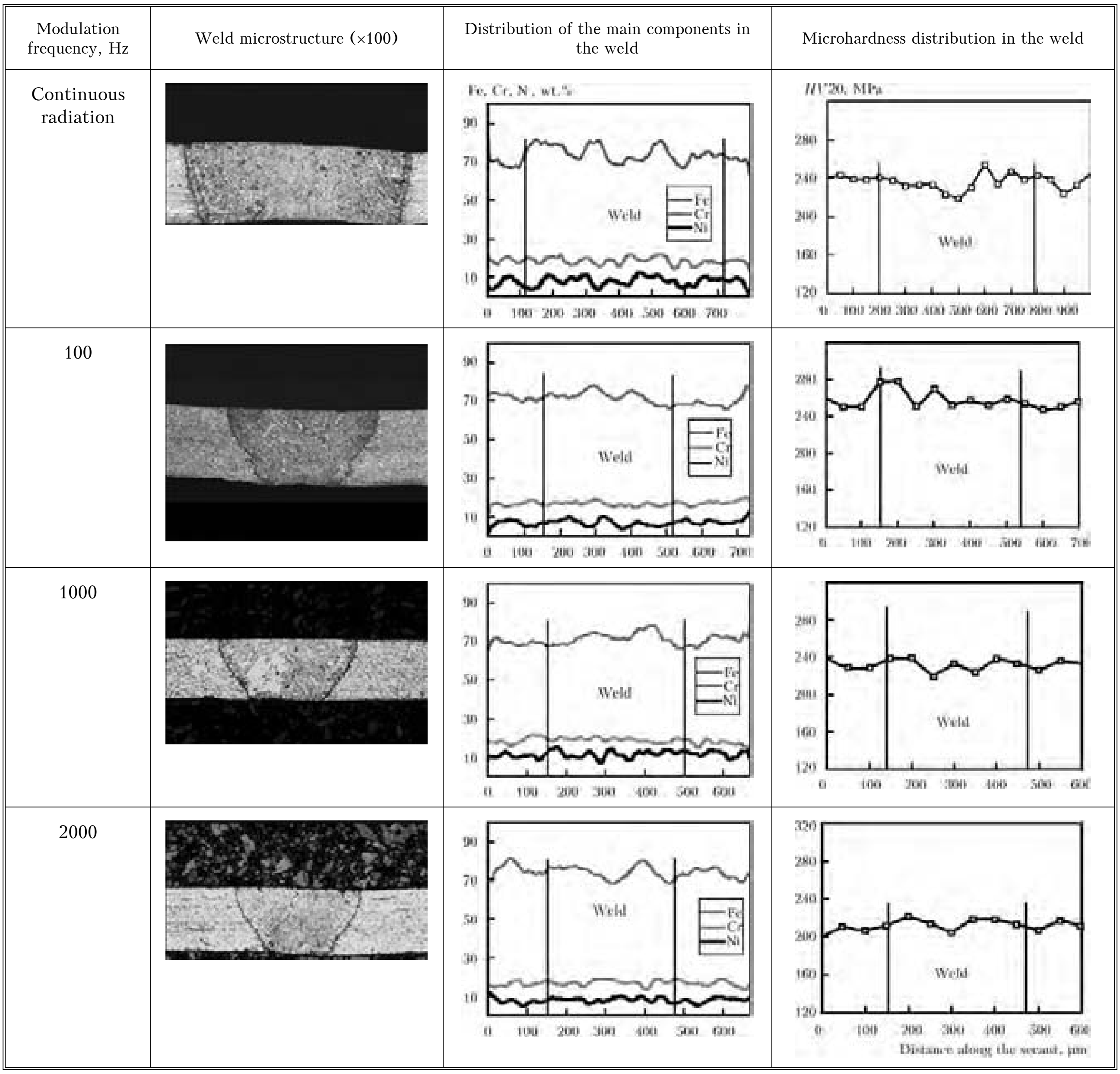


Figure 4. Weld macrostructure, distribution of the main components and microhardness in the transverse section of welded joints made at different frequencies of laser radiation modulation

A certain depletion of the melting zone as to manganese approximately to 1.2 wt.% should be noted. In all the welding modes cracks are absent either in the weld zone, or in the HAZ metal.

At the impact of continuous radiation, a dendritic austenitic structure forms in the weld (Figure 5), which is characteristic for the high solidification rate in laser welding. Coarse equiaxed grains of up to 10 μm size form in the zone adjacent to the fusion line.

Laser processing of stainless steel by modulated radiation with modulation frequency of 100 Hz leads to formation of welding lines in the weld structure that considerably impairs its quality. Weld structure is inhomogeneous because of the mixed form of solidification that causes formation of coarse crystallites with regions of Widmanstaetten structure. Different weld regions have different microhardness, because of structural inhomoneneity (see Figure 4) that may lead to deterioration of the mechanical properties of welded joint.

At 1000 Hz frequency of laser radiation modulation structural homogeneity was not improved, however, regions of cellular form of solidification (see Figure 5) appeared. Weld microhardness was equalized. Increase of modulation frequency of laser impact up to 2000 Hz ensures a predominantly cellular shape of solidification and formation of fine austenitic grains of about 3 μm size with ferrite precipitates along the grain boundaries. At the given welding mode a structurally homogeneous weld forms with different microhardness of the different zones.

Analogous homogeneous microstructure was also observed at modulation frequency of 3000 Hz. Characteristics of distribution of the main components and

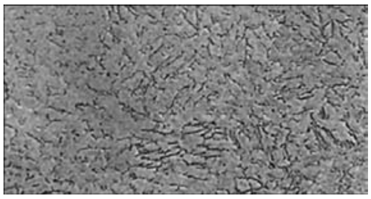
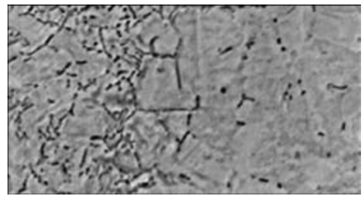
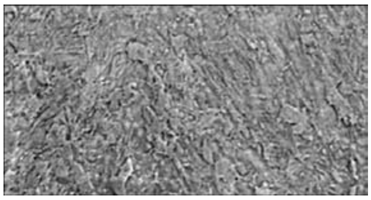
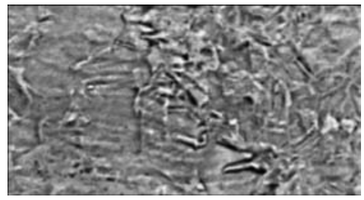
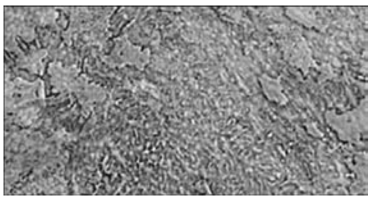
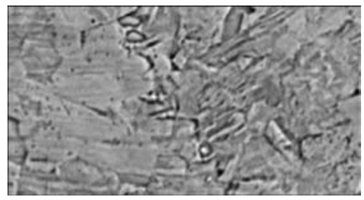
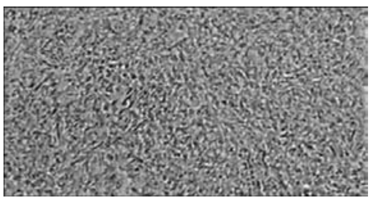
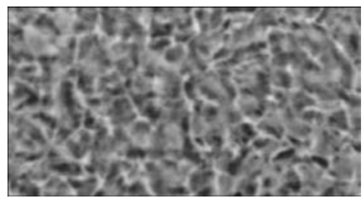
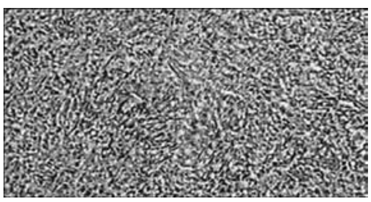
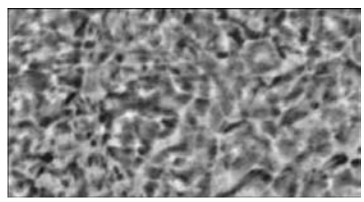
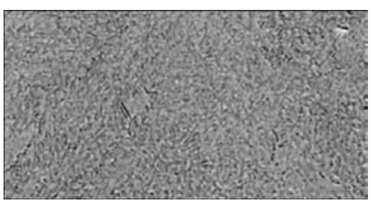
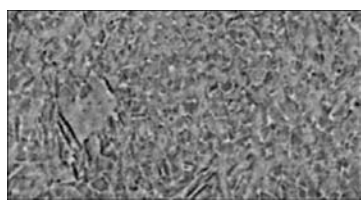
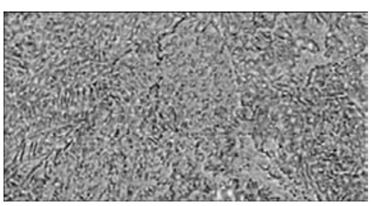
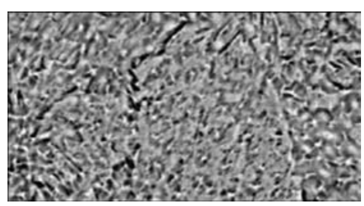
Modulation frequency, Hz	Weld microstructure (×300)	Near-weld zone microstructure (×600)
Continuous radiation		
100		
1000		
2000		
3000		
5000		
10,000		

Figure 5. Microstructure of the weld and near-weld zone in welded joints made at different frequencies of laser radiation modulation

microhardness practically did not differ from the previous experiment. It should be noted that in these cases the fusion line becomes thinner, whereas the austenitic grain becomes smaller that is positive for mechanical properties of the near-weld zone.

Further increase of pulse frequency up to 5000 and 10,000 Hz leads to deterioration of the homogeneity of weld structure formation and its coarsening.

This laser welding process was applied in development of the technology for manufacturing small series of straight-seam thin-walled welded pipes of different diameters from stainless steels, used in manufacture of bellows and bellows assemblies.

CONCLUSIONS

1. Use of modulated laser impact in welding of stainless steel samples affects the morphological features of solidification of structural components of the welded joint.

2. Increase of modulation frequency promotes an increase of the number of solidification centers and formation of a fine-grained cellular austenitic structure.

3. Application of an inclined shape of the rear front of laser radiation pulse provides a slowing down of crystallite growth that also leads to formation of a fine-grained cellular structure of the weld.

4. Influence of modulation frequency on weld structure is of a limited nature. Modulated pulse parameters, optimum for weld metal structure, were determined. Formation of structurally-homogeneous weld with minimum size of austenite grains of about 3 μm occurs at modulation frequency of 2–3 kHz. Here, the calculated values of optimum degree of overcooling are in the range of 125–136 K.

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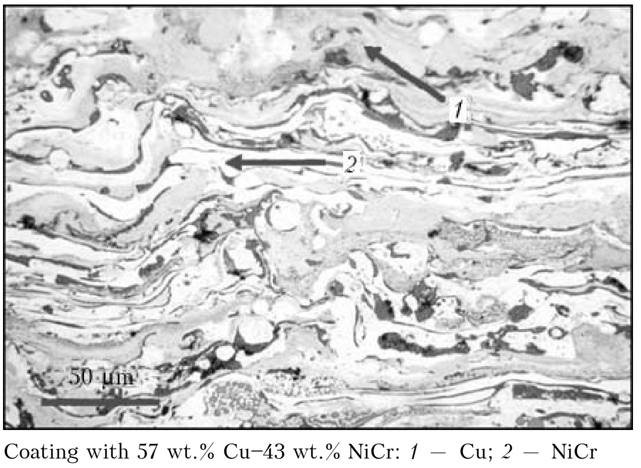
NEWS

WEAR-RESISTANT COATINGS FOR BILLET CCM

Protective Coatings Department of the E.O. Paton Electric Welding Institute is working in the field of thermal spraying of coatings with pseudo-alloy structure, which have high wear-resistant and antifriction properties. For protection of the surface of copper items from abrasive wear, a coating series was developed, which is applied by the method of electric arc metallization, and the structure of which consists of a mixture of copper particles with the second component, ensuring the coating resistance to abrasive wear (for instance, NiCr, Mo, Ti, etc.). One of the objects of these coatings application are plates of CCM mould. Presence of copper in the coating structure (~ 50 wt.%) ensures preservation of a high enough heat conductivity of the coating (up to 200–300 W/(m/deg)), which is an important factor under the conditions of CCM operation. Thickness of coatings, applied for this purpose, is equal to 2 mm. Hot hardness of the coating, for instance, Cu–NiCr, at 20–400 °C exceeds that of copper 3 times, its rupture strength is equal to 240 MPa. Resistance of pseudo-alloy coatings to abrasive wear at 300–350 °C is higher than that of pure copper from 5 up to 100 times, depending on coating composition. Work on testing the developed coatings under the real service conditions of CCM is being conducted.



Coating with 57 wt.% Cu–43 wt.% NiCr: *1* — Cu; *2* — NiCr