NUMERICAL SIMULATION OF TEMPERATURE FIELD OF PLASMA ARC REMELTING ON EN-SGJ-600-3

J. Lu[1]* – B. Sun[1] – F. Tang[1] – T. Ding[2] – L. Zhang[2]

[1]School of Material and chemical Engineering, Zhongyuan University of Technology, Zhengzhou 450007, China
[2]State Key Laboratory of Advanced Brazing Filler Metals & Technology, Zhengzhou Research Institute of Mechanical Engineering, Zhengzhou 450007, China

ARTICLE INFO

***Article history*:**
Received 18.9.2012
Received in revised form 16.11.2012
Accepted 16.11.2012

Keywords:
Plasma arc remelting
Temperature field
Ansys
EN-SGJ-600-3

Abstract:

Plasma arc remelting treatment has been conducted on EN-SGJ-600-3. The microstructure of the melted zone and heat affected zone has been analyzed using an optical microscope. Then in view of the thermal physical parameters of material, latent heat and travelling heat sources, three-D FEA model of the transient temperature field during plasma arc remelting of the surface layer in EN-SGJ-600-3 has been established based on ANSYS software. The APDL (ANSYS Parametric Design Language) has been used to describe the evolvement rules of the temperature field. The results show that the microstructure in the remelted zone is pearlite and ledeburite, whose microhardness reaches 1000~1060 HV. It is worth pointing out that the simulation results of remelted shape are in accordance with the experimental results. The temperature near the surface of the weld pool is the highest, which is up to 1794 °C. This investigation will provide a guide for evaluating the validity of simulation studies.

1 Introduction

Nodular irons which exhibit the advantages of good tensile strength, excellent casting properties and ease of processing, can be widely used as engineering materials for cranks, cylinder bodies, cylinder jackets, etc. Or Nodular irons due to their good tensile strength, excellent casting properties and ease of processing are widely used as engineering materials for cranks, cylinder bodies, and cylinder jackets, etc. However, wear-out failures often occur in the motion process because of lower surface hardness. Surface remelting treatment produces a fine symmetrical microstructure, high surface hardness, reduced overall part distortion not affecting the core performance [1, 2].

Plasma arc remelting is a new approach to surface modification technology. Remelting is a metallurgy process including rapid melting and partial solidification on the surface of metallic materials, characterized by fast temperature rise, high temperature and small action scope. The complex physical and chemical phenomena covering heat transfer, mass transfer, convection, diffusion and phase change during remelting processes have

* Corresponding author. Tel.: + 86 62 506689; fax: + 86 03 7162506689
E-mail address:ljbjohn@163.com .

caused great difficulties in defining technological parameters and establishing a mathematical model [3-5]. The temperature field is a crucial factor in forming of the remelted microstructure, so that an analysis of it is an important aspect for researches into the remelted microstructure. However, the experimental methods for testing the distribution and change of the temperature field during remelting processes have been inadequate so that t finite element simulation with certain experimental verifications of temperature field dynamic distribution in the remelting processing, as well as an analysis of how materials and techniques affect remelting treatment processes have been given. Consequently, it will provide the basis for choosing reasonable technological parameters.

At present, there are a lot of numerical simulations that generate the temperature field induced by laser surface treatment [6-9], but o plasma arc remelting on nodular iron is one of very rare used simulation techniques. This paper has developed a three-dimensional (3-D) double ellipsoid heat source model, taking into consideration the action of plasma arc excavating applied to the weld pool in the remelting process. After having established a three dimensional transient temperature field finite element model for plasma arc remelting based on the APDL language in finite element software Ansys, the change of the temperature field and the formation of the microstructure in the remelting process applied to nodular iron as EN-SGJ-600-3 have been analyzed.

2 The finite element model of temperature field in plasma arc remelting

2.1 Determination of Boundary Conditions

Due to the complexity of remelting process, the analysis should be based on supposition that we have: (1) an isotropic material, (2) ignored the flowing action of the weld pool fluid, (3) ignored the vaporizing effect of material.

Under the action of mobile heat source such as plasma arc, the heat transfer forms on the surface of the material are mainly convection and radiation, while inside the material, they are mainly heat conduction and convection, as is shown in Fig.1. In order to simulate the excavating action of the plasma arc during the remelting process, the three-dimensional double ellipsoid heat source has been used. If the initial temperature of the sample is supposed to be 25 ºC, the heat convection coefficient is supposed to be 10 W/(mK), and plasma arc energy is a self-generating input onto the sample surface remelting layer and that it has subsequently moved at a certain rate in the remelting process, the load parameter matrix form has been established on the basis of Ansys Parametric Design Language (APDL) so that corresponding heat source load input parameters have been provided at different time and different positions, loaded circularly at certain time step.

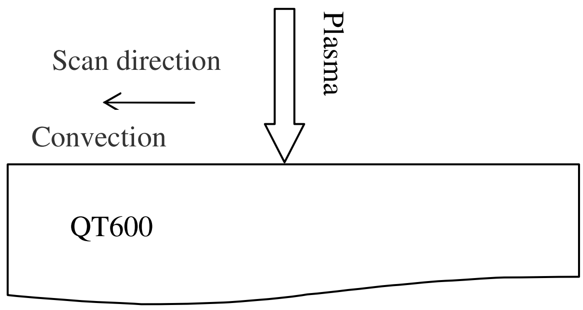

Figure 1. A schematic depiction of the plasma remelting process.

2.2 Geometric Model and the Meshing

Taking into consideration that the action area of plasma arc remelting on the surface of metallic material is small, the established geometric models are also relatively small, being defined as 50 mm×40 mm×10 mm and Solid70 being selected as a thermal solid element. Fine grinding has been used in the plasma-arc scanning region and its adjacent area where 32941 units and 23351 nodes have been formed, as shown in Fig.2.

2.3 The Handling of Non-linear Materials and the Latent Heat of the Phase-change

Thermal properties of engineering materials will change with temperature so that material non-linearity must be taken into account.

There are phase-changes such as melting, solidification etc. in plasma arc remelting processes, and the latent heat from the phase transition will undoubtedly exert certain influence on the temperature field analysis. A phase change is a non-linear transient thermal analysis problem, and the only way to deal with this problem in Ansys is to define the heat enthalpy at different temperatures.

Its mathematic definition is expressed in the equation [5]

$$\Delta H = \int \rho c(T) dT \qquad (1)$$

In the equation (1), the letter ΔH indicates heat enthalpy, the letter ρ is material density, the letter T is absolute temperature, and the letter combination $c(T)$ expresses the specific heat capacity which changes with temperature.

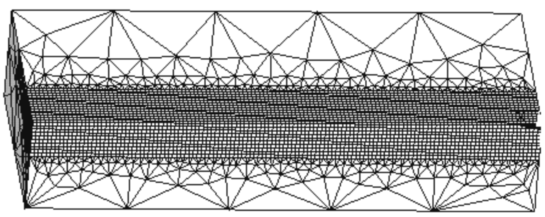

Figure 2. A finite element method model of plasma arc remelting.

3 Calculation Results and Analysis

3.1 Experimental Material and Conditions

The experimental material was EN-SGJ-600-3 whose chemical composition was shown in Table 1. Its microhardness was 260-290 HV0.3, the casting temperature was 1400-1430 ℃, and the sample size was 100 mm×40 mm×10 mm. The remelting was carried out by using self-made plasma equipment after the removal of rust and oil from the sample.

Table 1. The nominal chemical composition of EN-SGJ-600-3 (mass fraction, %)

element	C	Si	Mn	P	S	Mg	Fe
mass fraction	3.7	2.5	0.5	0.07	0.02	0.05	rest

The adoptive technics for parameter estimation were as follows: the operating current was 120, 130, 140, 150, 160A respectively, the working voltage was 19 V, and the scanning velocity was 500 mm/min. Ar was used as the protection and ionized gas. The flux of protection gas was 1.2 m^3/h, and the flux of ionized gas was 0.8 m^3/h. The distance between the nozzle and the workpiece was 5 mm.

3.2 Calculation of Remelting Temperature Field

Using finite element software Ansys, the temperature field was calculated when the remelting processing current was 140 A, voltage was 19 V, and scan velocity was 500 mm/min. The result is shown in Fig.3a whereas Fig.3b expresses the temperature field distribution respectively when remelting time was 0.5 s and 3 s. It could be seen that the maximum temperatures in the two molten pools were 1672 ℃ and 1732 ℃ respectively. So, the surface of nodular iron was melted and the weld pool with the liquid phase was formed. The temperature field is shown in the shape of an ellipse. The temperature gradient measured at the front of molten pool was higher than the one at the end of it, indicating that the temperature equivalent lines at the front were closer than the ones at the rear of the melted region.

a) *b)*

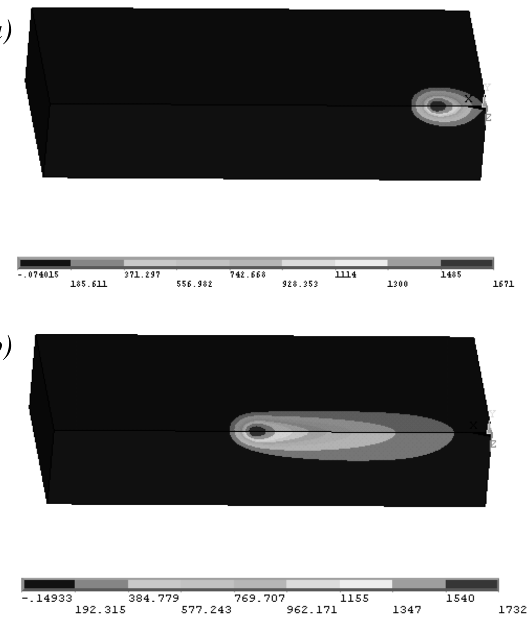

Figure 3. Temperature field distributions at different times (a) remelting time point: 0.5s (b) remelting time point: 3s.

To describe the calculated results clearly, eight calculation spots were set on the sample (as shown in Fig.4), of which four spots (such as A, B, C and D) were distributed on the symmetrical section, and the distances from these spots to the remelting surface of the workpiece were 0, 0.5, 1 and 2 mm respectively, and the other four (such as E, F, G and H) were located on the remelting surface whose distances to the symmetrical section were 1, 2, 3 and 5 mm respectively. The temperature variation curves of these spots are presented in Fig.5 (a) showing that the temperature rose rapidly above 1794 ºC when the plasma arc scanned through the spot as A, and when the rising rate exceeded 4000 ºC/s, while the substrate was still cold with higher temperature gradient relative to the heating zone. After removal of the facula from the action zone, remelting zone would cool down at the rate of 10^3 ºC/s. According to Fe-C-Si phase diagram, the melting point of nodular iron is usually around 1200-1280 ºC, so Fig.5a shows that the depth of remelting zone is about 0.5-0.6 mm. The part which is farther away from the remelting zone has become the heat-affected zone with the approximate temperature above 500 ºC.

Fig.5b shows the temperature curves of the calculation points on the remelting surface of the sample. When the plasma arc moved through the surface, the temperature of each point also rose rapidly, but with the distance to the symmetry plane increasing, the maximum temperature of each point was on the decline, and it could be seen that the distance from the symmetrical plane to the point whose temperature surpassed 1200 ºC was probably 1.85-1.9 mm, therefore the width of remelting region was about 3.7-3.8 mm.

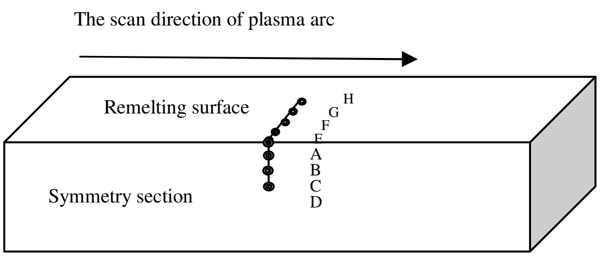

Figure 4. A schematic presentation of the calculation points on the specimen.

3.3 Model Validation

The remelting/remelted specimens obtained by using different currents were cut along the cross-section. Metallographic specimens were ground and the sizes of the remelting/remelted region were observed using an optical microscope, then the results were compared with Ansys calculation results, which is shown in Table 2. As it could be seen in Table 2, the size of remelting zone was increasing with an increase of the current. And the contrasted results show that the calculating data is slightly bigger than the testing data, while the error is within 10%, and the reason might be that the chosen heat source model, material parameters and melting points have changed according to experimental conditions.

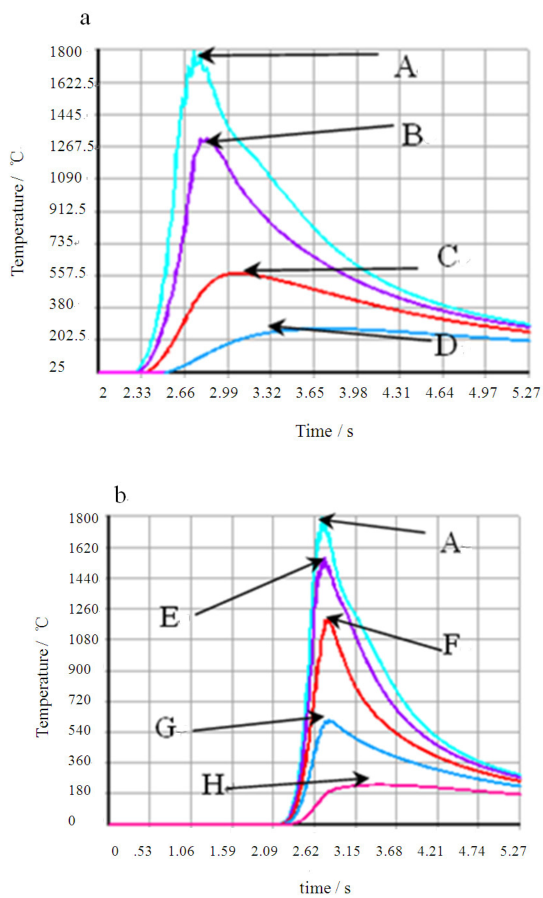

Figure 5. Temperature circulation curves of the different points. (a) on symmetrical section (b) on remelting surface.

3.4 Microstructure of Plasma Arc Remelting

EN-SGJ-600-3 was processed by plasma arc remelting using the technological parameters as follows: the current of 140 A, with a voltage of 19 V, and scanning speed of 500 mm/min. The specimens were first sawed in vertical cross-section, for the purpose of grinding and polishing, then corroded with 4% nitric acid alcohol, and subsequently their microstructures were tested and shown in Fig.6, Fig.7 and Fig.8 respectively. Fig.6 shows the microstructure of the remelted zone. It could be seen that graphite of the original microstructure was completely dissolved and apparent dendrite was produced. Its forming process was as follows: in the solidification process with cooling, firstborn austenite dentrite is assumed to be first separated along the direction of thermal diffusion, and then followed by an eutectic reaction which produced eutectic ledeburite microstructures in which the crystalline firstborn austenite would change into pearlite in the cooling process, and eventually branch crystalline pearlite and eutectic ledeburite would be formed.

Fig.7 shows the transition part from the remelting zone to the heat-affected zone. The above part was remelting zone, and the following part was heat-affected zone. The interface between them is assumed to be relatively clear. Nevertheless, there was a lot of ferrite and spherical graphite on the chip underside the remelting zone. Fig.8 shows the microstructure of the heat-affected zone. The microstructure is said to contain spherical graphite, high-carbon martensite and residual austenite.

Table 2. Comparison between the measured and calculated results

Sample sign	Working current /A	Remelting width (measured)/mm	Remelting width (calculated)/mm	Remelting depth (measured)/mm	Remelting depth (calculated)/mm
1	120	2.77	2.9	0.45	0.48
2	130	3.56	3.6	0.53	0.61
3	140	3.76	3.8	0.61	0.65
4	150	3.79	4.0	0.67	0.71
5	160	4.16	4.3	0.71	0.78

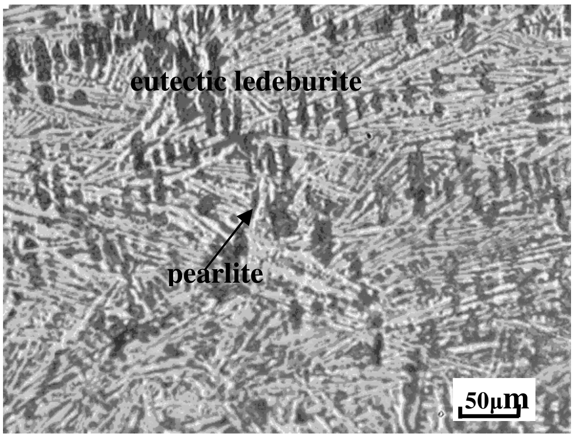

Figure 6. Microstructure of the remelted zone in EN-SGJ-600-3.

3.5 Microhardness of Plasma Arc Remelting

HXD-1000TC microhardness tester was used for testing the microhardness values of the specimen with the load of 300g. The results are shown in Fig.9. As could be seen from Fig.9, the hardness values of the remelting zone are steadily rising from the outside to the inside surface, while the hardness values of the junction between remelting/remelted and solid-state phase transition zone has a relatively large drop, which means that there is a softening belt between them. The hardness values of the solid-state phase transition zone are fluctuant, whereas the total tendency shows a downward trend.

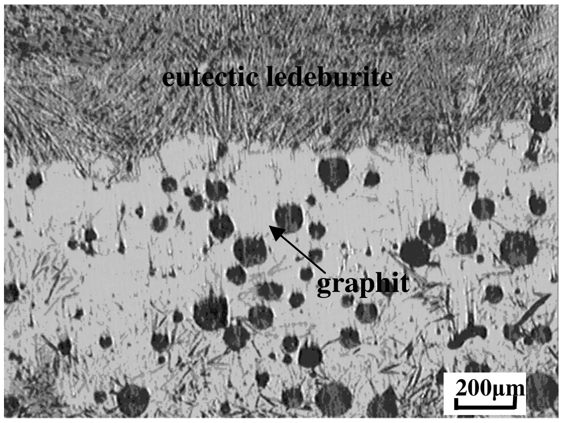

Figure 7. Microstructure of the transitional area in EN-SGJ-600-3.

In the remelted zone near the surface, due to fast heating with the plasma beam followed by cooling, the microstructure is relatively dense, and is mainly made up from pearlite and ledeburite, and its hardness has reached 800~1060 HV0.3. Because of the burning away of the base metal generated by plasma arc, the surface microhardness has been slightly reduced. . In the middle, between the remelted and heat-affected zone, due to high temperatures, the C element mostly spread to graphite ball and eventually formed the microstructure consisting of the ferrites and graphite, and as a result hardness declined greatly.

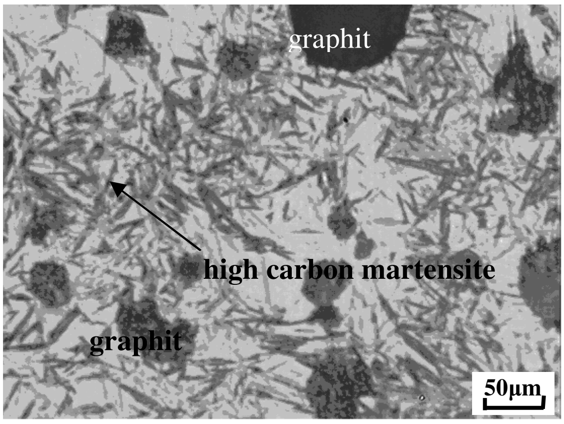

Figure 8. Microstructure of the heat-affected zone in EN-SGJ-600-3.

In the heat affected zone, with the heating temperature gradually decreasing, its microstructure should be an austenized zone, a semi-austenitized zone and a tempering zone, forming the quenching microstructure, semi-quenching microstructure and tempering microstructure respectively so that its microhardness has gradually declined till close to the one of the original microstructures.

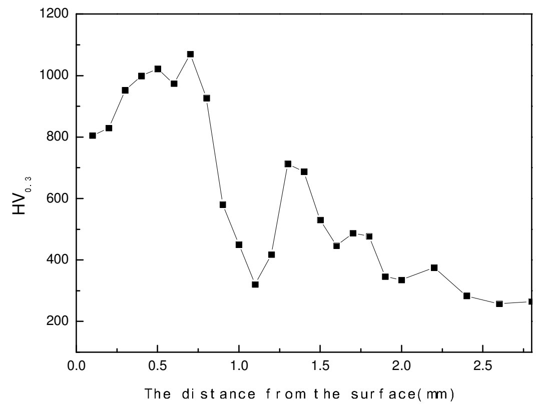

Figure 9. Microhardness distribution of the remelted layer.

4 Conclusion

1) According to the heat transfer theory and the numerical simulation method, the distribution rule of plasma arc remelting temperature field has been studied, and a finite element model of three-D transient temperature field about EN-SGJ-600-3 processed by plasma arc remelting has been established using the APDL of Ansys software.
2) In the process of plasma arc remelting on EN-SGJ-600-3, the area of remelting zone was enlarging with the current increasing, which was basically consistent with the computed result of finite element.
3) When EN-SGJ-600-3 was processed by plasma arc remelting, the hardness values in the remelted layer were about 1000~1060 HV0.3, which were obviously higher than the ones of the substrate.

Acknowledgments

This work was supported by the Opening Project of State Key Laboratory of Advanced Brazing Filler Metals & Technology (Zhengzhou Research Institute of Mechanical Engineering (contract no SKLABFMT201003).

References

[1] De Lima, M. S. F., Goia, F. A., Riva, R., do Espírito Santo, A. M.: *Laser Surface Remelting and Hardening of an Automotive Shaft Sing a High-power Fiber Laser,* Materials Research, 10 (2007), 461-467.
[2] Y. Li.: *Influence of Plasma Beam Hardening Operating Current on Microstructure and Performance on Surface of Nodular Cast Iron*, Hot Working Technology, 38 (2009), 147-150. (in Chinese)
[3] Ma, W., Fei, Q. X., Pan, W. X., Wu, C. K.: *Investigation of laminar plasma cladding processing*, Applied Surface Science. 252 (2006), 3541-3546.
[4] Crowe, C. T.: *Review-Numerical Models for Dilute Gas-Particle Flows,* Journal of Fluids Engineering – ASME, 104 (1982), 297-303
[5] Toyserkani, E., Khajepour A., Corbin, S.: *3-D finite element modeling of laser cladding by powder injection: Effects of laser pulse shaping on the process,* Optics and Lasers in Engineering, 41 (2004), 849-867.
[6] Obergfell, K., Schulze V., Voehringer, O.: *Classification of microstructural changes in laser hardened steel surfaces,* Material Science and Engineering: A., 355(2003), 348-356.
[7] Liu, Z. D., Chen Y., Huang, Y. H.: *Numerical Simulation of the Temperature Field on Laser*

Remelted Ni-Coating Oriented by Jet Electroforming, China Mechanism Engineering, 18 (2007), 2884-2886.

[8] Fu, Y. C., Loredo, A., Martin B., Vannes, A. B.: *A theoretical model for laser and powder particles interaction during laser cladding*, Journal of Material Processing Technology, 128(2002), 106-112.

[9] Tian, Z. J., Wang D. S., Huang, Y. H.: *Numerical simulation of temperature field of laser remelting on 45 steel,* Transactions of Materials and Heat Treatment, 29(2008), 173-178. (in Chinese)