Problems of Tribology*, V. 26, No 1/99-2021,59-65*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2021-99-1-59-65

High-carbon steel: microstructure and abrasive wear resistance of heat affected zone after welding with fast cooling

M.N.Brykov[1*], V.G.Efremenko[2], M.Yu.Osipov[1], A.E.Kapustyan[1], T.A.Akrytova[1], Yu.A.Kalinin[3]

[1]"Zaporizhzhya Polytechnic" National University, Ukraine,
[2]Priazovskyi State Technical University, Ukraine
[3]PrJSC "Zaporozhtransformator", Ukraine

**E-mail: brykov@zntu.edu.ua*

Abstract

The goal of this work is to estimate the abrasive wear resistance of heat affected zone (HAZ) after welding high-carbon low-alloy steel 120Mn3Si2 with fast cooling. The following benchmark data were used: microstructures of HAZ of 120Mn3Si2 steel after welding with cooling in water; abrasive wear resistance of different microstructure constituents of 120Mn3Si2 steel in two-body abrasive wear conditions. It is shown that high abrasive wear resistance of material in HAZ is provided in the vicinity of fusion line. The reason is unstable retained austenite which appears in HAZ as a result of quenching at fast cooling right after welding. The wear resistance of material in HAZ is altered by microstructural changes from austenite to austenite+martensite and finally martensite. The martensitic zone is about 0.5 mm wide and it is followed by zone of tempering of initial structure of steel. Zone of tempering is 1.5-2.0 mm wide and is the only zone of low abrasive wear resistance in HAZ of 120Mn3Si2 steel welded with fast cooling. Welding of 120Mn3Si2 steel with fast cooling in water results in welding joints which have as high wear resistant as the base material or even higher. This enables manufacturing flat welded elements with high wear-resistance and large surface area.

Key words: high-carbon steel, welding, fast cooling, austenite, martensite, bainite, abrasive wear resistance, microstructure.

Introduction

Protection against abrasive and other kinds of wear requires materials with specific properties. For example, high abrasive wear resistance of steels is attributed to high carbon content (1.0 wt. % of carbon or even more) and specific thermal treatment to obtain certain microstructure. The problem may arise if such thermally treated machine parts are to be welded. Heat input during thermal welding cycle changes the initial wear resistant microstructure inside heat affected zone (HAZ). Special efforts are needed to minimize HAZ and provide quality welding joints while welding heat treated high-carbon wear resistant steels. Anyway, the width of HAZ in any case would not be less than approximately 5 mm from the fusion line. Therefore, if two plates of high-carbon steel are welded, a zone of changed wear resistance appears to be 10 mm wide. It is necessary to know the wear resistance of this zone because local low wear resistance may negatively affect the overall lifetime of machine part. In this study the attempt is made to estimate the abrasive wear resistance in HAZ of high-carbon low-alloy steel 120Mn3Si2 after welding with fast cooling.

Literature review

Friction and wear are estimated to cause approximately 20% of the world energy consumption [1]. Wear is responsible for short lifetime of many critical machine parts and even for their sudden catastrophic failures. Abrasive wear is the most aggressive form of wear. Generally it appears during operation in mining sector [2, 3] and other industries where hard particles of natural or artificial abrasives are in direct contact with metallic surfaces. Losses connected to abrasive wear are estimated as 4% of the GNP of industrially developed countries

[4]. Extensive investigations have been made on abrasive wear resistance of steels and cast irons during last century. Important results were obtained by I.N.Bogachev and R.I.Mints, B.A.Voinov, V.I.Dvoruk, V.G.Kaplun and P.V.Kaplun, V. N. Kashcheev, M.V. Kindrachuk, L.G.Korshunov, A.V.Makarov, L. S. Malinov, V.S.Popov and N.N.Brykov, M.M.Tenenbaum, V.M.Tkachev, M. M. Khrushchev and M. A. Babichev, A.P.Cheiliakh, V.V.Shevelya, A.Fisher, I.I.Garbar, A.Misra и I.Finnie, R.C.D.Richardson, G.W.Stachoviak, A.A.Torrance, J.H.Tylczak, K.-H. Zum Gahr. Main attention of researchers has been concentrated on wear resistance of martensite and austenite. Abrasive wear resistance of austenite depends on its degree of hardening during friction and the ability of the wear medium to provide such hardening. I.M.Bogachev and R.I.Mints have discovered the phenomenon of deformation transformation of austenite to martensite during mechanical load [5]. Since then this effect was widely used to increase wear resistance of machine parts under conditions of abrasive wear. Researches of L. S. Malinov [6], A.P.Cheiliakh [7], M. A. Filippov [8] should be mentioned among the works devoted to the study of the properties of steels with the structure of unstable residual austenite. V.S.Popov and N.N.Brykov [9, 10] have made extensive research on abrasive wear resistance of retained austenite in numerous applications in refractory industry. In [10] the range of optimal chemical composition for wear resistant austenitic alloys was proposed. It was shown that high carbon content, i.e. 1.0 mass.% or higher, is responsible for high abrasive wear resistance. According to [11] maximal wear resistance in Fe-C alloys is achieved at 2 mass.% of carbon. As a result of studying the effect of alloying on the wear resistance of steels with the structure of unstable austenite during abrasive wear, it was found that the level of alloying of wear-resistant alloys should be maintained at the lowest possible level [12]. Thus, the requirements for the chemical composition of abrasive wear resistant steels are specified as follows: approximately 3% of alloying elements (e.g. Mn, Cr) in total, the carbon content should provide the martensite start temperature at 20 ^{o}C. The simplest example is the steel containing 1.2% C and 3% Mn. After quenching from 1000 ^{o}C (single-phase γ-region) austenite retains almost completely and is capable to deformation martensitic transformation in the course of abrasive wear. This provides high wear resistance for steel after above mentioned thermal treatment, much higher than the one of high-carbon untempered martensite. High ability of austenite to deformation martensitic transformation is useful in the case of impactless-abrasive wear. But if the machine part is subjected not only to wear but also to impacts, the instability of austenite is also a disadvantage. In the initial stages of the impacts, when the crack is not yet formed, the initial plastic deformation takes place. But after the formation of the first crack, a stress concentration occurs at its tip. Under the large local stresses near the crack tip, a deformation martensitic transformation occurs, and the crack actually propagates in brittle high-carbon martensite during repeated shocks. Thus, low resistance to shock loads is the price for high abrasive wear resistance. This significantly narrows the potential range of possible successful usage of high-carbon low-alloy steels as a wear-resistant material in conditions of mechanical wear. In [13, 14] it is proposed to use isothermal treatment of residual austenite of high-carbon low-alloy steels in order to reduce the susceptibility to brittle fracture while maintaining abrasive wear resistance at a sufficiently high level. High-carbon low-alloy steels, for example, 120Mn3 steel, allow to obtain up to 100% of residual austenite after quenching from a single-phase region. Therefore, such steels do not require baths with liquid media for the isothermal treatment of austenite. It is enough to quench them in water, to heat further in a conventional air furnace and to hold at a constant temperature for the required time. During isothermal holding of quenched 120Mn3 steel, bainite transformation of austenite takes place. If silicon content is high enough (1.5-2.0%), cementite is not formed during bainite transformation. After isothermal transformation the structure contains bainitic ferrite and austenite, which is carbon supersaturated [15, 16]. Due to increasing the carbon content the austenite stabilizes and its susceptibility to deformation martensitic transformation is reduced. Thus, it is possible to eliminate the catastrophic fragility of unstable residual austenite due to a small loss of abrasive wear resistance [13, 14]. In order to accelerate the bainite transformation, it is necessary to quench 120Mn3Si2 steel from such a temperature that after cooling, martensite was present in the structure in small amount. Martensite acts as a catalyst for bainite transformation [17], which begins less than in 1 hour if the steel 120Mn3Si2 is hardened from 900 ^{o}C [18]. Welding of previously quenched 120Mn3Si2 steel may be needed for large-part manufacturing. In order to minimize influence of welding heat on initial microstructure of steel it is proposed to use fast cooling of just-welded joints in water [19]. It was shown that due to rapid cooling it is possible to minimize dimensions of heat affected zone (HAZ) and obtain welding joints of acceptable quality. The width of HAZ was about 5 mm from fusion line from each side of a welding joint. This results in a 10 mm wide zone of altered microstructure and hence altered wear resistance at the location of welding joint on a produced large-scale part.

The goal of this work is assessing the abrasive wear resistance of a material inside HAZ of 120Mn3Si2 welding joint after welding with fast cooling in water.

Methods

The assessment of the abrasive wear resistance of the material in HAZ of 120Mn3Si2 steel was carried out according to the known experimental data. The authors have performed numerous experiments on abrasive wear of steels with different microstructures in two-body abrasive wear conditions and reported the results in [11-14, 20- 22]. The microstructure of HAZ in welding joints of 120Mn3Si2 after welding with fast cooling in water has been investigated and reported in [19, 23]. Hence, it is possible to accurately predict the abrasive wear resistance of each point in HAZ depending on the microstructure. For the sake of this research, wear mode was assumed to be two-body abrasive wear of cylindrical specimen 2 mm in diameter sliding against fresh surface of abrasive cloth under load of 300 g. The assumed abrasive is 0.6…0.8 mm grits of Al_2O_3. The ability of material to resist abrasive wear is expressed as relative wear resistance ε. The assumed reference sample is pure iron having ε = 1,0.

Results and discussion

According to [19] optimal heat treatment of 120Mn3Si2 steel includes quenching from 900 °C and subsequent isothermal treatment at 250 °C. After quenching from 900 °C microstructure is preliminary austenitic with nearly 30% of martensite. Certain amount of undissolved carbides is present as well. Subsequent isothermal treatment leads to appearance of fine lamellas of bainitic ferrite. The amount of bainitic ferrite depends on isothermal holding time. The very first lamellas are observed even after 1 hour of isothermal holding [18]. Decarburized layer inevitably appears when 120Mn3Si2 steel is exposed to quenching heat. The depth of decarburized layer depends on holding time at quenching temperature and may reach 1 mm. Because of decrease in carbon content, martensite start temperature (Ms) significantly increases. Therefore the martensitic layer appears after quenching in the near surface regions where significant decarburization had happened [22]. 5 mm thick plates of 120Mn3Si2 steel where quenched from 900 °C, held isothermally at 250 °C and then were welded with fast cooling in water. The microstructure of welding joint from 120Mn3Si2 side is shown on Fig.1, a. Because of fast cooling after welding the material in HAZ is quenched. Therefore HAZ consists of several zones of microstructures depending on peak temperatures during heating cycle in each particular point.

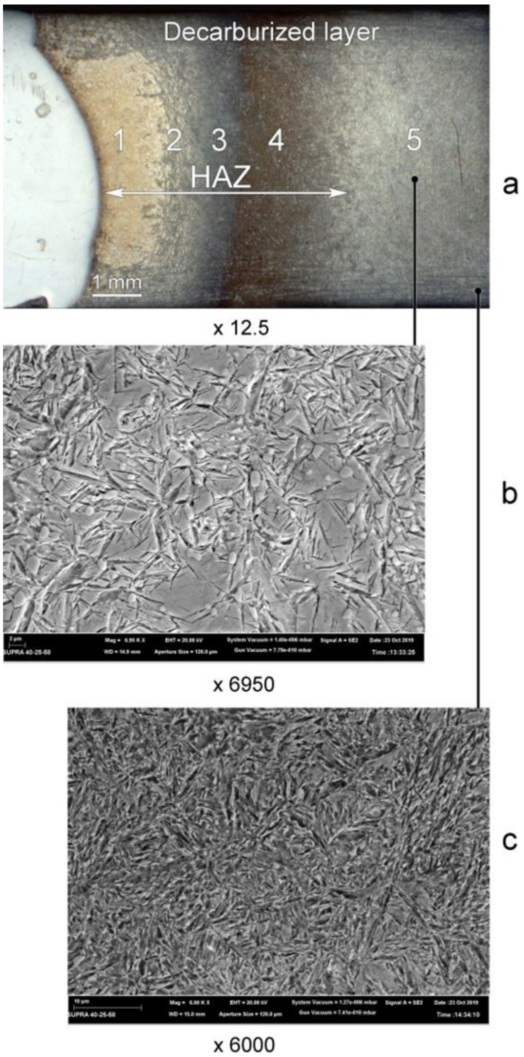

Fig. 1. Macro- and microstructure of welding joint of thermally treated 120Mn3Si2 steel: a – macrostructure of welding joint with different zones of HAZ, 1 – austenite, 2 – austenite + martensite, 3 – martensite, 4 – zone of high tempering of initial microstructure, 5 – thermally unaffected core; b – microstructure of thermally unaffected core: austenite + tempered martensite + bainitic ferrite + carbides; c – microstructure of decarburized layer: tempered martensite + austenite

Four different zones may be distinguished in HAZ. Zone 1 appears as a result of heating the material to the temperatures between Acm critical point and solidus temperature (single-phase γ-region). The structure in zone 1 is almost fully austenitic because the Ms temperature is near 30 ^{o}C [13]. The more the distance from fusion line is, the less is the peak temperature. Zone 3 is preliminary martensitic and is equivalent to classic quenching for maximal hardness of hyper-euthectoid steels. It corresponds to quenching from temperatures slightly above Ac_1 critical point. Zone 2 corresponds to quenching from a range of temperatures between Ac_1 and Acm. The structure is austenite + martensite. The closer to fusion line in the zone 2, the more amount of austenite is present in the structure.

If heating temperature doesn't exceed Ac_1, then no phase transformation takes place during welding cycle (zone 4). The structure in this zone right at the border with zone 3 contains products of diffusional decomposition of initial microstructural constituents. The more the distance to zone 3 is, the less is the peak temperature in the welding cycle in zone 4. Thus, microstructure gradually changes from products of high tempering to products of low tempering and further to zone 5 where initial microstructure is not changed at all.

Having the information on microstructures of different zones in HAZ it is possible to determine changes in relative wear resistance of material on different distance to fusion line (Fig. 2). Relative wear resistance of preliminary austenitic structure in zone 1 of HAZ is at the level of 4.0. This value corresponds to wear resistance of 120Mn3Si2 steel quenched from 1000 ^{o}C as reported in [14]. If quenching temperature decreases to 900 ^{o}C then some amount of martensite appears after quenching. This is due to less carbon content in austenite before quenching and rising the Ms. Retained austenite becomes even more unstable, therefore relative wear resistance of 120Mn3Si2 steel after quenching from 900 ^{o}C is slightly higher than that after quenching from 1000 ^{o}C [20]. This microstructure corresponds to zone 2. Relative wear resistance gradually increases to some maximum due to gradual alteration in content of retained austenite. This maximum corresponds to microstructure which is equivalent to those obtained after quenching from 900 ^{o}C. The expected value of relative wear resistance at the point of maximum is 4.2-4.3.

Further increasing of distance from fusion line leads to decreasing of peak temperatures in welding cycle. Consequently, the amount of martensite gradually increases until zone 3 is reached. Relative wear resistance of untempered martensite (eutectoid composition) is 2.9 [21]. Therefore the same relative wear resistance is provided in zone 3.

Sharp drop in relative wear resistance takes place upon transition from zone 3 to zone 4. The structure of zone 4 in the vicinity of zone 3 is equivalent to that after recrystallization annealing, i.e. pearlite. Relative wear resistance of pearlite is 1.4 [21], so that is the value to which ε is decreased on the border of zones 3 and 4. The more is the distance from zone 3, the finer is the pearlite. The microstructure gradually changes to sorbite, troostite, and finally the thermally unaffected zone 5 is reached. Relative wear resistance increases respectively from 1.4 to the level that is specific for the base preliminary treated material. In the case of quenching 120Mn3Si2 steel from 900 ^{o}C and subsequent isothermal treatment at 250 ^{o}C the structure is austenite+tempered martensite+bainitic ferrite+carbides. Relative wear resistance of such microstructure is slightly higher than that of untempered high-carbon martensite [14].

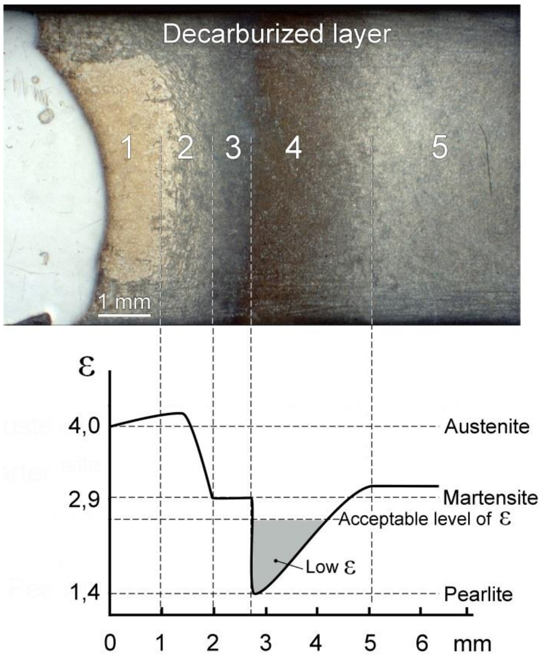

Fig. 3. Relative wear resistance of different zones of HAZ of 120Mn3Si2 steel after quenching from 900 ^{o}C, isothermal treatment at 250 ^{o}C and welding with fast cooling in water

Steels with martensitic microstructure are widely used as abrasive wear resistant material. Because of high brittleness of untempered martensite this microstructure is not acceptable for majority of machine parts. At least low temper is needed to get lower brittleness of material after quenching. Low tempering decreases hardness and hence abrasive wear resistance. Thus, relative wear resistance of tempered martensite is the lowest level that is practically acceptable. This level of ε is designated as “Acceptable level of ε” on Fig. 2. All points in HAZ with higher values of ε should be considered as zone with high relative wear resistance to abrasive wear.

It is evident, that the only zone of low wear resistance is that designated in gray on Fig. 2 (“Low ε”). The width of this zone is 1.5-2.0 mm. The rest of HAZ possesses wear resistance that is above acceptable level. Relative wear resistance in zones 1 and 2 is even higher than the one of the base material.

All considerations expressed above allow to claim that welding of 120Mn3Si2 steel with fast cooling in water enables HAZ with wear resistance that is the same or even higher than the one for base thermally treated material. The only zone with low wear resistance is 1.5-2.0 mm wide and corresponds to heating the material to high but subcritical temperatures. This zone cannot be eliminated since it is not possible to avoid places in HAZ that are heated to subcritical temperatures. This zone also cannot be made less wide since cooling is as fast as possible.

Conclusions

Abrasive relative wear resistance of heat affected zone of 120Mn3Si2 steel after welding with fast cooling in water is assessed in this research. The only zone with low wear resistance is 1.5-2.0 mm wide. This zone cannot be neither avoided nor narrowed. It corresponds to heating material to subcritical temperatures during welding cycle. The relative wear resistance of material in this zone corresponds to that for pearlite.

The relative wear resistance of the rest of HAZ appears to be higher or at the same level as for previously heat treated steel. Thus, welding 120Mn3Si2 steel with fast cooling in water enables obtaining welding joint with high abrasive wear resistance of heat affected zones.

The research shows that welding of 120Mn3Si2 steel with fast cooling in water results in welding joints which have as high wear resistance as the base material or even higher. This enables manufacturing flat welded elements of high wear-resistance and large surface area.

References

1. Holmberg, K., Erdemir, A. Influence of tribology on global energy consumption, costs and emissions. Friction 2017, 5, 263–284.

2. Holmberg, K., Kivikytö-Reponen, P., Härkisaari, P., Valtonen, K., Erdemir, A. Global energy consumption due to friction and wear in the mining industry. Tribology International 2017, 115, 116–139. https://doi.org/10.1016/j.triboint.2017.05.010

3. Terva, J., Kuokkala, V.-T., Valtonen, K., Siitonen, P. Effects of compression and sliding on the wear and energy consumption in mineral crushing. Wear 2018, 398–399, 116–126.

4. Totten, G.E. (Ed.). Friction, Lubrication, and Wear Technology. ASM International 2017.

5. Bogachev I.N., Mincz R.I. Kavitaczionnoe razrushenie zhelezouglerodistykh splavov. M., Sverdlovsk : Mashgiz, 1959. 111 s.

6. Malinov L. S., Malinov V. L. Ekonomnolegirovannye splavy s martensitnymi prevrashheniyami i uprochnyayushhie tekhnologii : monografiya. Khar`kov : NNCz KhFTI, 2007. 346 s.

7. Chejlyakh, A. P. Ekonomnolegirovannye metastabil`nye splavy i uprochnyayushhie tekhnologii : monografiya. Mariupol` : PGTU, 2009. 483 s.

8. Filippov M. A., Litvinov V. S., Nemirovskij Yu. R. Stali s metastabil`nym austenitom. M. : Metallurgiya,1988. 257 s.

9. Popov V. S., Brykov N. N., Dmitrichenko N. S. Iznosostojkost` pressform ogneupornogo proizvodstva. M. : Metallurgiya, 1971. 160 s.

10. Schastlivczev V. M., Filippov M. A. Rol` princzipa metastabil`nosti austenita Bogacheva-Mincza pri vybore iznosostojkikh materialov. Metallovedenie i termicheskaya obrabotka metallov. 2005. # 1, S.6-9.

11. Brykov M. N. Abrazivnoe iznashivanie zhelezouglerodistykh splavov. Trenie i iznos. 2006. # 1, S. 105-109.

12. Brykov M. N., Andrushhenko M. I., Kulikovskij R. A. Vliyanie legirovaniya na iznosostojkost` zhelezouglerodistykh splavov pri abrazivnom iznashivanii. Novi materiali i tekhnologiyi v metalurgiyi ta mashinobuduvanni. 2006. # 2, S. 59-62.

13. Hesse O., Liefeith J., Kunert M., Kapustyan A., Brykov M., Efremenko V. Bainit in Stählen mit hohem Widerstand gegen Abrasivverschleiß. Tribologie + Schmierungstechnik. 2015. V 63. № 2, S. 5-13.

14. Brykov M. N. Iznosostojkost` bejnita pri abrazivnom iznashivanii. Problems of Tribology. 2015. # 1, S.113-118.

15. Bhadeshia H. K. D. H. Nanostructured bainite. Proc. R. Soc. A. 2010. V 466, P. 3-18.

16. Gabarello F. G., Miller M. K., Garcia-Mateo C. Opening previously impossible avenues for phase transformation in innovative steels by atom probe tomography. Materials Science and Technology. 2014. V 30, P. 1034-1039.

17. Jellinghaus W., Anregung der Zwischenstufen-Umwandlung des Stahles durch kleine Mengen von a-Eisen. Arch. Eisenhütt. 1952. V 23, P. 459-470.

18. Kalinin Yu. A., Petrishinecz I., Efremenko V. G., Kapustyan A. E., Brykov M. N. Vliyanie izotermicheskoj obrabotki na mikrostrukturu zakalyonnoj na austenit vysokouglerodistoj nizkolegirovannoj stali. Visnik KhNADU. 2020. T 1. vip. 88, S. 58-66.

19. Microstructure and properties of heat affected zone in high-carbon steel after welding with fast cooling in water / M.N. Brykov, I. Petryshynets, M. Džupon, Yu. A. Kalinin, V. G. Efremenko, N.A. Makarenko, D. Yu. Pimenov, F. Kováč // Materials. 2020. 13(22). 5059.

20. Efremenko V.G. Two-body abrasion resistance of high-carbon high-silicon steel: Metastable austenite vs nanostructured bainite / V.G. Efremenko, O. Hesse, T. Friedrich, M. Kunert, M.N. Brykov, K. Shimizu, V.I. Zurnadzhy, P. Šuchmann // Wear. 2019. V. 418-419, P. 24-35.

21. Brykov M.N., Efremenko V.G., Efremenko A.V. Iznosostojkost` stalej i chugunov pri abrazivnom iznashivanii : Nauchnoe izdanie / M.N.Brykov, V.G.Efremenko, A.V.Efremenko. Kherson : Grin` D.S., 2014. 364 s.

22. Khesse O. Iznosostojkost` obezuglerozhennogo sloya vysokouglerodistoj nizkolegirovannoj stali v ekstremal`nykh usloviyakh treniya / O. Khesse, M. Kunert, V.G. Efremenko, K. Shimiczu, M.N. Brykov, A.E. Kapustyan // Naukovi notatki. 2017. Vip. 58, S. 301-307.

23. Struktura okoloshovnoj zony zakalyonnoj vysokouglerodistoj stali posle svarki s uskorennym okhlazhdeniem / Yu. A. Kalinin, A. A. Shumilov, I. Petrishinets, V. G. Efremenko, M. N. Brykov // Novi materiali i tekhnologiyi v metalurgiyi ta mashinobuduvanni. 2019. # 1, S. 31-36.

Бриков М.М., Єфременко В.Г., Осіпов М.Ю., Капустян О.Є., Акритова Т.О., Калінін Ю.А. Високовуглецева сталь: мікроструктура і абразивна зносостійкість зони термічного впливу після зварювання із швидким охолодженням у воді.

Метою роботи є оцінювання абразивної зносостійкості зони термічного впливу (ЗТВ) після зварювання високовуглецевої низьколегованої сталі 120Г3С2 із швидким охолодженням. Було використано такі вихідні дані: мікроструктура ЗТВ сталі 120Г3С2 після зварювання з охолодженням у воді; абразивна зносостійкість різних мікроструктурних складових сталі 120Г3С2 в умовах абразивного зношування закріпленими частинками. Показано, що в ЗТВ у безпосередньої близькості до границі сплавлення забезпечується висока абразивна зносостійкість матеріалу. Причиною є структура нестабільного залишкового аустеніту, який утворюється в ЗТВ в результаті гартування під час швидкого охолодження одразу ж після зварювання. Зносостійкість матеріалу в ЗТВ змінюється із зміною мікроструктури від аустеніту до аустеніт+мартенсит і, нарешті, мартенситу. Ширина мартенситної зоні становить приблизно 0,5 мм. За мартенситною зоною утворюється зона відпуску вихідної мікроструктури сталі завтовшки 1,5-2,0 мм. Ця зона є єдиною зоною зі зниженою зносостійкістю. Зварювання сталі 120Г3С2 із швидким охолодженням у воді дозволяє отримати зварні з’єднання із зносостійкістю, що дорівнює зносостійкості вихідного матеріалу, або навіть перевищує її. Це дає можливість виготовляти пласкі зварні елементи з високою зносостійкістю і великою площею поверхні.

Ключові слова: високовуглецева сталь, зварювання, швидке охолодження, аустеніт, мартенсит, бейніт, абразивна зносостійкість, мікроструктура.