ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2015, № 5 (59)

МАТЕРІАЛОЗНАВСТВО

UDC 691.87:691.714

I. A. VAKULENKO[1*], A. G. LISNYAK[2], O. N. PERKOV[3], XU XIAO HAI[4]

[1*]Dep. «Technology of Materials», Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryana, Lazaryan St., 2, Dnipropetrovsk, Ukraine, 49010, tel. +38 (056) 373 15 56, e-mail dnuzt_texmat@ukr.net, ORCID 0000-0002-7353-1916
[2]Dep. «Technology of Mining Machinery», Dnipropetrovsk National Mining University, K. Marks Av., 19, Dnipropetrovsk, Ukraine, 49027, tel.+38 (0562) 46 99 81, e-mail aleklisn@gmail.com, ORCID 0000-0001-6701-5504
[3]Iron and Steel Institute named after Z. I. Nekrasova, NAN Ukraine, Starodubov Sq., 1, Dnipropetrovsk, Ukraine, 49107, +38 (056) 373 15 56, e-mail dnuzt_texmat@ukr.net, ORCID 0000-0002-8101-1654
[4]Chinese Machine-Building Investment Group of Ltd, Anli St., 60, Beijing, Chinese Folk Republic, 100101, tel. 86 10 64827530, e-mail xxhai2004@163.com, ORCID 0000-0002-0338-5976

INFLUENCE OF SHOCK VOLTAGE FROM THE ELECTRIC DISCHARGE ON THE FATIGUE ENDURANCE OF CARBON STEEL IN WATER

Purpose. The research supposes the explanation of influence of stress impulses from an electrical discharge in water on the level of the limited endurance at a cyclic loading of the thermally work-hardened carbon steel. **Methodology**. Material for research was steel 45 (0,45 % carbon) with concentration of chemical elements within the limits of steel composition. Specimens for tests are made as plates in 1 thick, width 15 and length 120-180 mm. The structural state of steel corresponded to quenching on a martensite from the normal temperatures of annealing and tempering at 300 °C, duration of 1 h. Microstructure was investigated with the use of electronic microscopy, the density of dislocations was estimated on the methods of X-ray analysis. Hardness was measured on the method of Rockwell (scale of «C»). A cyclic loading was carried out in the conditions of symmetric bend on a tester «Saturn-10» at a temperature +20 °C. The treatment by shock voltage from the electrical discharge was carried out in water on setting of bath type «Iskra-23», used for cleaning of castings manufactures. Electric impulses were formed at 15-18 kV with energy of 10-12 kJ and amplitude of 1-2 GPa. **Findings.** As a result of processing pulses of a pressure wave of heat-strengthened steel 45 found the increase of endurance under the cyclic loading corresponds to an increased amount of accumulated dislocations on the fracture surface. The use of Coffin–Manson Equation allowed finding the decrease of deformation per cycle of loading as a result of arising stress from an electrical discharge in water. On the fracture surface (after pulse exposure) was found the increased number of dislocations, located in different crystallographic systems, that is a testament to the rather complicated development of dislocation transformations in the structure of steel, which provide an increase of endurance at a fatigue. The increase of the limited endurance became as a result of impulsive treatment largely related with the number change of mobile dislocations. For the area of low-cyclic fatigue the growth of amplitude of loading is accompanied with the decrease of distinction in the values of the limited endurance (before and after the treatment of shock voltage). **Originality.** For the field of high-cycle fatigue, the result of shock voltage of carbon steel with the structure of the improvements, the increase of limited endurance is accompanied with a decrease in deformation per cycle. As far as growth of amplitude of stress cycle the effect of increase of endurance from treatment of metal by the shock voltage declines. **Practical value.** Treatment of metal by the impulses of pressure waves from an electrical discharge in water can be used for the time extending of exploitation details of the rolling stock, which are subjects of the cyclic loading.

Keywords: hardness; distribution; impulse of pressure; electric discharge; limited endurance

doi: 10.15802/stp2015/53162

Introduction

Regardless of the circuit loading, the observed changes of the internal structure of metal materials are determined largely by the conditions of deformation. At a constant temperature and the appearance of the loading cycle, depending on the magnitude of amplitude exceeding the endurance limit, the qualitatively different structural changes in metallic materials are observed [2]. For the fields of little or a high cycle fatigue the increase in the dislocation density and their redistribution, the number keeping of dislocations in a non-blocking state are among the major factors that determine stock endurance metal [14]. On this basis, the use of external influences such as the introduction of additional harmonics in the loading cycle, or intermediate treatments, for example by passing an impulse of electric current [6,10], can significantly change the processes course of structure formation development under the cyclic loading.

The state of the question

The technology of processing metal materials using a shock wave, with relative ease of implementation, was widely adopted. [4]. This technology allows to solve difficult tasks, such as deformation in the manufacture of large-size products, their hardening or welding of the individual elements construction. The achieved effect has an explicit dependence on the threshold voltage with the passage of the shock wave in the metal, depending on the level of disposable energy input, or pulse resulting voltage [7, 13], their amount, the achieved effect has an explicit dependence on the threshold voltage with the passage of the shock wave in the metal. Moreover, as the experience of use said the impulse treatment to harden metal, the achieved result in several times may exceed the effect of equivalent plastic strain [4, 12].

Known experimental results [4, 5] indicate that the process of hydraulic shock encountered when forming an electric discharge in the liquid the achieved effect for most of metal materials is adequate hardening. On this basis it is quite natural to expect the increase in the number of crystalline structure defects. The results of studies that indicate a qualitatively different influence of the parameters of the specified impulsive loading have a particular scientific and practical interest. Thus, in [4] it is shown that the increase of the amplitude of the emerging pressure wave largely determines the increase in the number of dislocations and increase the pulse duration at constant amplitude mainly affects on the process of displacement.

There is almost no information on the influence of energy and number of pulses on several properties, including enduring quality of metal under the cyclic loading, except the known restrictions on the use of the technology shock pulse processing in the manufacture of certain products [5].

Purpose

Explanation of the effect of the resulting voltage pulses from electric discharge in water on the magnitude of the limited endurance of thermally hardened carbon steels under cyclic loading.

Methodology

The research material was steel 45 (0.45% of carbon) with the concentration of chemical elements within the grade composition. The test specimen produced in the form of plates thickness 1, width 15 and a length 120-180 mm. Structural state of steel corresponded to quenching on martensite from the normal heating temperatures and annealing at 300 C, with duration of 1 h. The microstructure was investigated using the electron microscopy; the dislocation density was evaluated by the methods of x-ray structural analysis [1]. The hardness was measured with Rockwell method (scale «C»). Cyclic loading was performed under conditions of symmetrical bending on a testing machine «Saturn-10» at a temperature of +20 C. Treatment of shock voltage (SV) from the electric discharge in water was performed with the installation of bath type «Iskra-23» used for cleaning of foundry products. The electrical pulses formed at a voltage of 15 to 18 kV with energy of 10-kJ and the amplitude of 1-2GPa. Metal processing consisted in the set of pulses number up to 15 thousand, at a frequency of 2-3Hz.

Findings

In the present research when choosing a structural condition of carbon steel as a result of tempering on martensite and annealing 300 C the authors were guided primarily by the need to achieve the simultaneously a high density of crystal structure defects and sufficient endurance under the cy-

doi: 10.15802/stp2015/53162

clic loading metal. The analysis of the microstructure showed that as a result of the treatment (Fig.1) the signs of the initial stages of emission of finely dispersed carbide particles on the dislocations, situated in the middle of the martensite strips and at their boundaries were found. Moreover, as it shown in [9], the evidence of the dislocations recombination beginning, which can result in a decrease of the dislocations density and formation of dislocation nonmonotonicity in the distribution, is the reduction of the contrast image of the microstructure. The observed loss of contrast of an image in separate places of the wide walls of dislocations (Fig.1) with simultaneous decoration of carbon atoms can be regarded as evidence of the almost total absence of mobile dislocations. On this basis, it can be assumed that the majority of dislocations introduced into the metal during the formation of martensite crystal, after the following holidays are not able to move under cyclic loading.

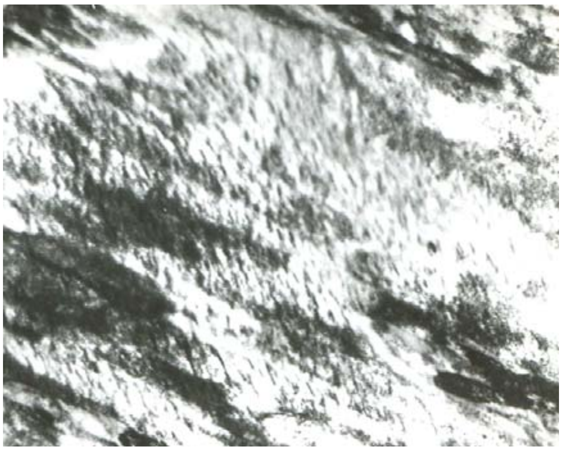


Fig. 1. Structure of steel 45 after tempering and annealing at 300 $^{\circ}$ C. Magnification is $14000 \times 1{,}3$.

To analyze the degree of compliance of the obtained results with known experimental data of the investigated steel after annealing and tempering without cyclic loading was exposed by SV. In state after annealing and tempering the steel 45 had a hardness HRC of 46.6. The obtained values are in fairly good agreement with the known data [3, 11]. After treatment of SV it was found that the hardness increase of 11% (to 51.8 HRC), that does not contradict to data [10, 12]. Thus, the impact impulse from the pressure wave by the nature of its influence on the heat-treated carbon steel should be attributed to the hardening effect.

In Fig. 2 the areas graphs of cyclic loading that correspond to low cycle and the transition region to high-cycle fatigue are shown.

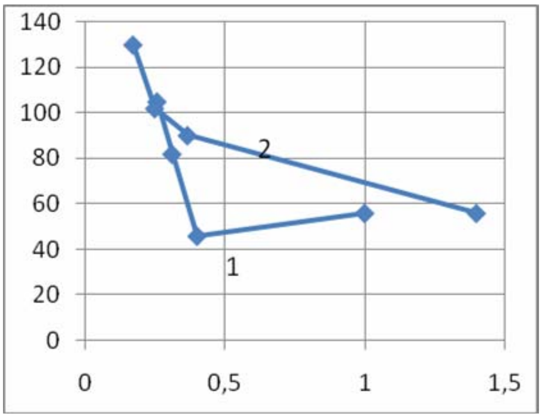


Fig. 2. The diagrams of cyclic loading steel 45 after tempering and annealing at 300 $^{\circ}$ C (1) and after treatment of SV (2).

Firstly, the curve of cyclic loading steel 45 after tempering and annealing of 300 (curve 1, Fig. 2) was received. Further, knowing the number of cycles that a metal can withstand before failure at a certain value of amplitude (σ_a), the samples loading to about 0,6-0,65 limited endurance was carried out, they were exposed by SV and after that the samples were brought to failure. The value of the limited endurance was estimated as the sum of the number of cycles before the SV and after the final decay at a particular amplitude (curve 2). Comparative analysis of progress curves indicates the possible qualitative differences in the internal structure of the metal with different structural condition under the cyclic loading. For example, for a field of low-cycle fatigue the increases of the loading amplitude is accompanied by a decrease of differences in values of finite life (before and after SV), when σ_a=100 kg/mm^2 is practically absent. Further extrapolation of the curves of cyclic loading in the field of amplitudes exceeding 100 kg/mm^2 indicates the achieving of the opposite effect: the impulse of the shock wave treatment helps to reduce the limited endurance (Fig. 2). On the other hand, the reduction σ_a regardless of previous processing, is accompanied by a corresponding increase in the number of cycles before failure,

doi: 10.15802/stp2015/53162

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2015, № 5 (59)

and the observed more gently sloping curve run of metal fatigue after SV indicates a fairly effective impact on endurance. Indeed, exposing the carbon steel to the action of pulses of a pressure wave in water, the amplitude of the cyclic loading while achieving the same endurance increases significantly. This is especially noticeable for the transition curves of fatigue. On the other hand, for the same amplitude of the cyclic loading, for example, at 56 kg/mm^2 , the increase in endurance may exceed 30% (Fig. 2).

The analysis of changes in the dislocation density after reaching a certain level of limited endurance of metal was conducted with the aim to explain the mechanism influencing the metal of the voltage pulse from the passage of electrical discharge in water. In Fig. 3 the change in the density of dislocations depending on the number of loading cycles and previous treatment is presented. Regardless of the structural state of the metal (without or after SV) a decrease in the amplitude of cyclic loading is accompanied by increase of the accumulated dislocation density in the studied interferences ($\rho_{(hkl)}$). Considering that the dislocation density was determined on the fracture surface of the samples, the nature of the change and absolute values should correspond to flat deformed state of the metal formed under the conditions of accelerated fatigue crack growth [2].

On the other hand, given the increasing role of the static component with increase the degree of overload under the cyclic loading (adequate growth σ_a) [8], the number of dislocations on the fracture surface should decrease. One explanation of given position is increased with the increase σ_a in the proportion of the metal under the conditions of volumetric stress state near the surface of the fracture. On the basis of this the greater extent enrichment of near-surface dislocations of specified amounts of metal should be occurring and, as a consequence, there is a decrease in the dislocation density determined on the fracture surface.

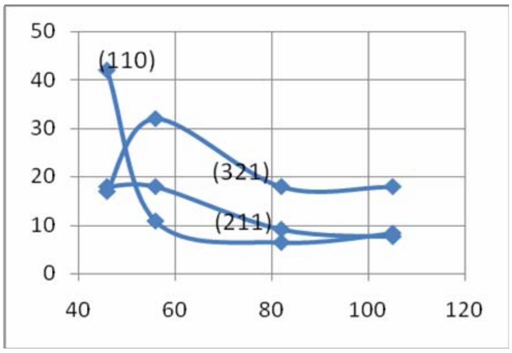
Given the dislocation propagation mechanism of plastic deformation, the assessment of its value during the loading cycle will provide the additional evidence regarding the nature of structural changes with increasing toughness of the metal as a result of SV effect. The ratio of the magnitude of plastic strain per cycle of loading (ε_i) and the achieved number of cycles to failure (N_i) is subject to the famous Coffin–Manson Equation [2]:

$$\varepsilon_i \cdot (N_i)^a = b, \quad (1)$$

where a and b – are taken as constant and equal to carbon steel of 0.5 and 1 respectively [2]. After conversion of (1), it was received for the dependence assessment of ε_i:

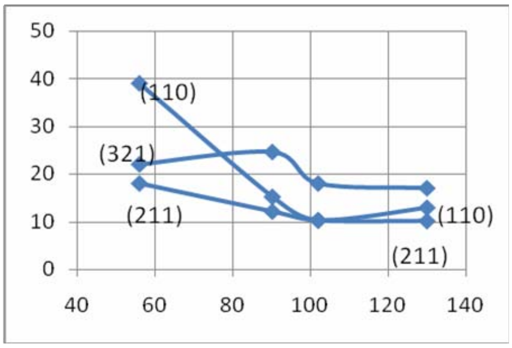
$$\varepsilon_i = 1/\sqrt{N_i} \quad (2)$$

– a $\rho_{(hkl)}, \times 10^{10} sm^{-2}$



$\sigma_a, kg/mm^2$

– b $\rho_{(hkl)}, \times 10^{10} sm^{-2}$



$\sigma_a, kg/mm^2$

Fig. 3. The change of dislocations density, estimated on interferences (110), (211) and (321) depending on amplitude of cyclic loading and preliminary treatment: without SV *(a)* and after SV *(b)*.

Substituting in (2), for the same σ_a corresponding values N_i, it was found the decrease of deformation per cycle of loading by approximately 20% as a result of processing metal by SV. On this basis, it can be assumed that the process of introducing of additional dislocations in thermally

doi: 10.15802/stp2015/53162

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)
Наука та прогрес транспорту. Вісник Дніпропетровського національного університету залізничного транспорту, 2015, № 5 (59)

hardened steel from pulse pressure wave is not accompanied by the annihilation events apparently. Moreover, the implementation of the deformation per cycle for the region of high-cycle fatigue is possible and it is ensured by the participation of a smaller number of dislocations. Thus, either the process of SV has the vast number of dislocations that remain mobile and able to interact only at the subsequent cyclic loading, or there is an additional unlock of previously immobile dislocations after the heat strengthening. In general, the detected on the fracture surface after pulsed effect the increased number of dislocations, located in different crystallographic systems can be regarded as evidence of the development rather complicated dislocation reactions, which has provided the increase in endurance of the metal during the cyclic loading process of thermally hardened carbon steel.

Originality and practical value

1. For the transition field to high-cycle fatigue, the result of machining voltage pulses of carbon steel with structure improve the limited endurance increase is accompanied by a decrease in deformation per cycle.
2. With the increase of the amplitude of the voltage cycle, the effect of metal endurance increase from processing of SV reduced.

Metal working by pulses of pressure waves from an electric discharge in water can be used to extend the lifetime of rolling stock parts, which are subjected to cyclic loading.

Conclusions

1. As a result of processing by pulses of the pressure wave of heat-strengthened steel 45 it was found the increase of endurance under cyclic loading corresponds to the increased amount of accumulated dislocations on the fracture surface.
2. The increase of steel endurance under the cyclic loading after pulse treatment is largely associated with the change in the number of mobile dislocations.

LIST OF REFERENCE LINKS

1. Гинье, А. Рентгенография кристаллов / А. Гинье. – Москва : Государств. изд-во физико-матем. лит., 1961. – 604 с.
2. Нотт, Дж. Ф. Основы механики разрушения / Дж. Ф. Нотт. – Москва : Металлургия, 1978. – 256 с.
3. Совершенствование состава и термической обработки сталей для ножей холодной резки листового проката / В. Г. Ефременко, А. В. Мурашкин, Е. П. Иванченко [и др.] // Сталь. – 2007. – № 1. – С. 75–77.
4. Ударные волны и явления высокоскоростной деформации металлов / под ред. М. А. Мейерса и Л. Б. Мурра. – Москва : Металлургия, 1984. – 510 с.
5. Чачин, В. Н. Электрогидравлическая обработка машиностроительных материалов / В. Н. Чачин. – Минск : Наука и техника, 1978. – 184 с.
6. A research on electroplastic effects in wire-drawing process of an austenitic stainless steel / K-F. Yao, J. Wang, M. Zheng [et al.] // Scripta Materialia. – 2001. – Vol. 45. – Iss. 15. – P. 533–539. doi: 10.1016/s1359-6462(01)01054-5.
7. Comparison of the structural properties and residual stress of AIN films deposited by dc magnetron sputtering and high power impulse magnetron sputtering at different working pressures / K. Ait Aissa, A. Achour, J. Camus [et al.] // Thin Solid Films. – 2014. – Vol. 550. – P. 264–267. doi: 10.1016/j.tsf.2013.11.073.
8. Conrad, H. Effects of electric current on solid state phase transformations in metals // Materials Science and Engineering : A. – 2000. – Vol. 287. – Iss. 2. – P. 227–237. doi: 10.1016/s0921-5093-(00)00780-2.
9. Dhadeshia, H. K. D. H. Bainite in Steels / H. K. D. H. Dhadeshia. – Cabridge : The University Press, 2001. – 454 p.
10. Electric pulse treatment of welded joint of aluminum alloy / I. A. Vakulenko, Yu. L. Nadezdin, V. A. Sokirko [et al.] // Наука та прогрес трансп. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. – 2013. – № 4 (46). – P. 73–82. doi: 10.15802/-stp2013/16584.
11. Experimental study of electroplastic effect on stainless steel wire 304L / G. Tang, J. Zhang, M. Zheng [et al.] // Materials Science and Engineering : A. – 2000. – Vol. 281. – Iss. 1–2. – P. 263–267. doi: 10.1016/s0921-5093(99)00708-x.
12. Morgan, W. L. Surface electrical discharges and plasma formation on electrolyte solutions / W. L. Morgan, L. A. Rosocha // Chemical Physics of Low-Temperature Plasmas. – 2012. – Vol. 398. – P. 255–261. doi: 10.1016/j.chemphys.2011.06.-037.
13. Numerical simulation of high voltage electric pulse comminution of phosphate ore / S. M. Razavian, B. Rezai, M. Irannajad [et al.] // Intern.

doi: 10.15802/stp2015/53162

J. of Mining Sci. and Tech. – 2015. – Vol. 25. – Iss. 3. – P. 473–478. doi: 10.1016/j.ijmst.2015.-03.023.

14. Vakulenko, I. A. The Influence Mechanism of Ferrite Graine Size on Strength Stress at the Fatigue of Low-Carbon Steel / I. A.Vakulenko, S. V. Proydak // Наука та прогрес трансп. Вісн. Дніпропетр. нац. ун-ту залізн. трансп. – 2014. – № 1 (49). – P. 97–104. doi: 10.15802/stp-2014/22668.

І. О. ВАКУЛЕНКО[1*], А. Г. ЛІСНЯК[2], О. М. ПЕРКОВ[3], СЮ СЯ ХАЙ[4]

[1*]Каф. «Технологія матеріалів», Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпропетровськ, Україна, 49010, тел. +38 (056) 373 15 56, ел. пошта dnuzt_texmat@ukr.net, ORCID 0000-0002-7353-1916
[2]Каф. «Технологія гірничого машинобудування», Дніпропетровський національний гірничий університет, пр. К. Маркса, 19, Дніпропетровськ, Україна, 49027, тел.+38 (0562) 46 99 81, ел. пошта aleklisn@gmail.com, ORCID 0000-0001-6701-5504
[3]Інститут чорної металургії імені З. І. Некрасова, НАН України, пл. Стародубова, 1, Дніпропетровськ, Україна, 49107, тел. +38 (056) 373 15 56, ел. пошта dnuzt_texmat@ukr.net, ORCID 0000-0002-8101-1654
[4]Китайська машинобудівна інвестиційна група Лтд, вул. Анлі, 60, Пекін, Китайська народна республіка, 100101, тел. 86 10 64827530, ел. пошта xxhai2004@163.com, ORCID 0000-0002-0338-5976

ВПЛИВ ІМПУЛЬСУ НАПРУЖЕННЯ ВІД ЕЛЕКТРИЧНОГО РОЗРЯДУ У ВОДІ НА ВИТРИВАЛІСТЬ ПРИ ВТОМІ ВУГЛЕЦЕВОЇ СТАЛІ

Мета. Дослідження передбачає пояснення впливу імпульсів виникаючого напруження від електричного розряду у воді на величину обмеженої витривалості при циклічному навантаженні термічно зміцненої вуглецевої сталі. **Методика**. Матеріалом для дослідження була сталь 45 (0,45 % вуглецю) із концентрацією хімічних елементів у межах марочного складу. Зразки для випробувань виготовляли у вигляді пластин завтовшки 1, шириною 15 і завдовжки 120-180 мм. Структурний стан сталі відповідав гартуванню на мартенсит від нормальних температур нагріву й відпуску при 300 $^\circ$C, тривалістю 1 год. Мікроструктуру досліджували з використанням електронної мікроскопії, густину дислокацій оцінювали за методиками рентгенівського структурного аналізу. Твердість вимірювали за методом Роквелла (шкала «С»). Циклічне навантаження здійснювали в умовах симетричного вигину на випробувальній машині «Сатурн-10» при температурі +20 $^\circ$C. Обробку імпульсами напружень від електричного розряду здійснювали у воді на установці ванного типу «Іскра-23», яку використовують для очищення ливарних виробів. Електричні імпульси формувалися при напрузі електричного струму 15−18 кV, з енергією 10−12 кДж та амплітудою 1−2 ГПа. **Результати.** У результаті обробки імпульсами хвилі тиску термічно зміцненої сталі 45 виявленому збільшенню витривалості при циклічному навантаженні відповідає підвищена кількість накопичених дислокацій на поверхні руйнування. Використання рівняння Кофіна–Менсона дозволило виявити зниження деформації за цикл навантаження в результаті виникаючого напруження від електричного розряду у воді. Виявлена на поверхні руйнування (після імпульсної дії) підвищена кількість дислокацій, розташованих у різних кристалографічних системах, є свідченням розвитку достатньо складних дислокаційних перетворень у структурі сталі, які забезпечили приріст витривалості при втомі. Приріст обмеженої витривалості сталі в результаті імпульсної обробки в значній мірі пов’язаний зі зміною числа рухомих дислокацій. Для області малоциклової втоми зростання амплітуди навантаження супроводжується зниженням різниці в значеннях обмеженої витривалості (до і після обробки імпульсами напружень). **Наукова новизна**. Для області багатоциклової втоми, в результаті обробки імпульсами напружень вуглецевої сталі зі структурою поліпшення, приріст обмеженої витривалості супроводжується зниженням деформації за цикл. По мірі зростання амплітуди напруження циклу ефект приросту витривалості від обробки металу імпульсами напружень знижується. **Практична значимість.** Обробка металу імпульсами хвиль тиску від електричного розряду у воді може бути використана для продовження терміну експлуатації деталей рухомого складу, які піддаються циклічному навантаженню.

Ключові слова: твердість; дислокація; імпульс тиску; електричний розряд; обмежена витривалість

doi: 10.15802/stp2015/53162

ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського
національного університету залізничного транспорту, 2015, № 5 (59)

И. А. ВАКУЛЕНКО[1*], А. Г. ЛИСНЯК[2], О. Н. ПЕРКОВ[3], СЮ СЯ ХАЙ[4]

[1*]Каф. «Технология материалов», Днепропетровський национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днепропетровськ, Украина, 49010, тел. +38 (056) 373 15 56, эл. почта dnuzt_texmat@ukr.net, ORCID 0000-0002-7353-1916
[2]Каф. «Технология горного машиностроения», Днепропетровський национальный горный университет, пр. К. Маркса, 19, Днепропетровск, Украина, 49027, тел. +38 (0562) 46 99 81, эл. почта aleklisn@gmail.com, ORCID 0000-0001-6701-5504
[3]Институт черной металлургии имени З. И. Некрасова, НАН Украины, пл. Стародубова, 1, Днепропетровск, Украина, 49107, +38 (056) 373 15 56, эл. почта dnuzt_texmat@ukr.net, ORCID 0000-0002-8101-1654
[4]Китайская машиностроительная инвестиционная группа Лтд, ул. Анли, 60, Пекин, Китайская народная республика, 100101, тел. 86 10 64827530, эл. почта xxhai2004@163.com, ORCID 0000-0002-0338-5976

ВЛИЯНИЕ ИМПУЛЬСА НАПРЯЖЕНИЯ ОТ ЭЛЕКТРИЧЕСКОГО РАЗРЯДА В ВОДЕ НА ВЫНОСЛИВОСТЬ ПРИ УСТАЛОСТИ УГЛЕРОДИСТОЙ СТАЛИ

Цель. Исследование предполагает объяснение влияния импульсов возникающего напряжения от электрического разряда в воде на величину ограниченной выносливости при циклическом нагружении термически упрочненной углеродистой стали. **Методика.** Материалом для исследования являлась сталь 45 (0,45 % углерода) с концентрацией химических элементов в пределах марочного состава. Образцы для испытаний изготавливали в виде пластин толщиной 1, шириной 15 и длиной 120-180 мм. Структурное состояние стали соответствовало закалке на мартенсит от нормальных температур нагрева и отпуска при 300 °С, длительностью 1 ч. Микроструктуру исследовали с использованием электронной микроскопии, плотность дислокаций оценивали с использованием методик рентгеноструктурного анализа. Твердость измеряли по методу Роквелла (шкала «С»). Циклическое нагружение осуществляли в условиях симметричного изгиба на испытательной машине «Сатурн-10» при температуре +20 °С. Обработку импульсами напряжения от электрического разряда осуществляли в воде на установке ванного типа «Искра-23», используемой для очистки литейных изделий. Электрические импульсы формировались при напряжении 15−18 кV, с энергией 10-12 кДж и амплитудой 1−2 ГПа. **Результаты.** В результате обработки импульсами волны давления термически упрочненной стали 45 обнаруженному увеличению выносливости при циклическом нагружении соответствует повышенное количество накопленных дислокаций на поверхности разрушения. Использование уравнения Кофина–Менсона позволило обнаружить снижение деформации за цикл нагружения в результате возникающего напряжения от электрического разряда в воде. Обнаруженное на поверхности разрушения (после импульсного воздействия) повышенное количество дислокаций, расположенных в различных кристаллографических системах, является свидетельством развития достаточно сложных дислокационных преобразований в структуре стали, которые обеспечили прирост выносливости при усталости. Увеличение ограниченной выносливости стали в результате возникающего напряжения от импульсной обработки в значительной степени связано с изменением числа подвижных дислокаций. Для области малоцикловой усталости возрастание амплитуды нагружения сопровождается снижением различия в значениях ограниченной выносливости (до и после обработки импульсами напряжения). **Научная новизна**. Для области многоцикловой усталости, в результате обработки импульсами напряжения углеродистой стали со структурой улучшения, прирост ограниченной выносливости сопровождается снижением деформации за цикл. По мере возрастания амплитуды напряжения цикла эффект прироста выносливости от обработки металла импульсами напряжения снижается. **Практическая значимость**. Обработка металла импульсами волн давления от электрического разряда в воде может быть использована для продления срока эксплуатации деталей подвижного состава, которые подвергаются циклическому нагружению.

Ключевые слова: твердость; дислокация; импульс давления; электрический разряд; ограниченная выносливость

doi: 10.15802/stp2015/53162

REFERENCES

1. Gine A. *Rentgenografiya kristallov* [Roentgenography of crystals]. Moscow, Gosudarstvennoye izdatelstvo fiziko-matematicheskoy literatury Publ., 1961. 604 p.
2. Nott Dzh.F. *Osnovy mekhaniki razrusheniya* [Fundamentals of fracture mechanics]. Moscow, Metallurgiya Publ., 1978. 256 p.
3. Yefremenko V.G., Murashkin A.V., Ivanchenko Ye.P. Sovershenstvovaniye sostava i termicheskoy obrabotki staley dlya nozhey kholodnoy rezki listovogo prokata [Improvement of composition and heat treatment of steels for knives for cold cutting of sheet metal]. *Stal – Steel*, 2007, no. 1, pp. 75-77.
4. Meyers M.A., Murr L.B. *Udarnyye volny i yavleniya vysokoskorostnoy deformatsii metallov* [Shock waves and phenomena of high-rate deformation of metals]. Moscow, Metallurgiya Publ., 1984. 510 p.
5. Chachin V.N. *Elektrogidravlicheskaya obrabotka mashinostroitelnykh materialov* [Electro-hydraulic processing of engineering materials]. Minsk, Nauka i tekhnika Publ., 1978. 184 p.
6. Yao K-F., Wang J., Zheng M. A research on electroplastic effects in wire-drawing process of an austenitic stainless steel. *Scripta Materialia,* 2001, vol. 45, issue 15, pp. 533-539. doi: 10.1016/s1359-6462(01)01054-5.
7. Ait Aissa K., Achour A., Camus J. Comparison of the structural properties and residual stress of AIN films deposited by dc magnetron sputtering and high power impulse magnetron sputtering at different working pressures. *Thin Solid Films*, 2014, vol. 550, pp. 264-267. doi: 10.1016/j.tsf.2013.11.073.
8. Conrad H. Effects of electric current on solid state phase transformations in metals. *Materials Science and Engineering : A,* 2000, vol. 287, issue 2, pp. 227-237. doi: 10.1016/s0921-5093(00)00780-2.
9. Dhadeshia H.K.D.H. Bainite in Steels. Cabridge, The University Press Publ., 2001. 454 p.
10. Vakulenko I.A., Nadezdin Yu.L., Sokirko V.A. Electric pulse treatment of welded joint of aluminum alloy. *Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu – Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport*, 2013, no. 4 (46), pp. 73-82. doi: 10.15802/stp2013/16584.
11. Tang G., Zhang J., Zheng M. Experimental study of electroplastic effect on stainless steel wire 304L. *Materials Science and Engineering: A,* 2000, vol. 281, issue 1-2, pp. 263-267. doi: 10.1016/s0921-5093(99)00708-x
12. Morgan W.L., Rosocha L.A. Surface electrical discharges and plasma formation on electrolyte solutions. *Physics of Low-Temperature Plasmas*, 2012, vol. 398, pp. 255-261. doi: 10.1016/j.chemphys.2011.06.037.
13. Razavian S.M., Rezai B., Irannajad M. Numerical simulation of high voltage electric pulse comminution of phosphate ore. *Intern. Journal of Mining Sci. and Tech.,* 2015, vol. 25, issue 3, pp. 473-478. doi: 10.1016/j.ijmst.2015.03.023.
14. Vakulenko I.A., Proydak S.V. The Influence Mechanism of Ferrite Graine Size on Strength Stress at the Fatigue of Low-Carbon Steel. *Nauka ta prohres transportu. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu – Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport*, 2014, no. 1 (49), pp. 97-104. doi: 10.15802/stp2014/22668.

Prof. V. O. Zabludovskyi, D. Sc. (Tech.) (Ukraine); Ass. Prof. O. O. Chaikovskyi, PhD (Tech.) (Ukraine) recommended this article to be published

Accessed: July 15, 2015
Received: Sep. 25, 2015

doi: 10.15802/stp2015/53162