ACTA METALLURGICA SLOVACA
2022, VOL. 28, NO. 1, 5-9

RESEARCH PAPER

INVESTIGATION OF THE EFFECT OF NITROCARBURIZING TREATMENT ON TRIBOLOGICAL PROPERTIES OF AISI 1045 MEDIUM CARBON STEEL

Elhadj Ghelloudj [1]*

[1] *Department of industrial mechanics, SH/DP Regional Direction Haoud Berkaoui, Ouargla 30000, Algeria*

* Corresponding author: hadjhadj105@gmail.com, tel.: +213676407456, *Department of industrial mechanics, SH/DP Regional Direction Haoud Berkaoui, Ouargla 30000, Algeria*

Received: 01.09.2021
Accepted: 05.01.2022

ABSTRACT

In this paper, the effect of nitrocarburizing treatment on tribological properties of AISI 1045 steel was investigated. This medium carbon steel was used in automotive industry, especially in the manufacture of machine components due to the good mechanical properties and lower cost. Characterization of the surface layer of treated samples was made by optical microscopy (OM), Vickers microhardness test, scanning electron microscope (SEM), surface profilometer and pin-on-disk wear machine. Experimental results showed that the surface layers formed through nitrocarburizing processing at 580 °C (compound layer and diffusion zone) increased the microhardness. It was found also that the nitriding treatment reduced the friction coefficient and improved the wear resistance, where the specific wear rate were decreased to 1/9 was noticed after 10 hours of nitriding time.

Keywords: Nitrocarburizing treatment; AISI 1045 steel; Compound layer; Friction coefficient; Wear resistance

INTRODUCTION

AISI 1045 steel is a type of steel that is commonly used in the automobile industry for the manufacture of machine components that require high strength and durability [1–8]. Due to its properties, it has been regarded as a good choice for various engineering projects [9]. This steel has good machinability, good weldability, high strength [10-12], and can provide engineers with a reliable and effective solution when subjected to various service conditions [13-14]. In order to improve the tribological and mechanical properties of AISI 1045 steel, it must undergo several thermochemical techniques such as carburizing [15], plasma nitriding [16-19], gas nitriding [20-21] and, nitrocarburizing [22-30]. Nitrocarburizing is a superficial thermochemical process that hardens steel by using nitrogen to improve their surface hardness [31-33], mechanical properties, as well as wear [34-36], and corrosion resistance [37-41], as well as fatigue life [42-44], and high dimensional stability. It is similar to the process of creating nitriding. Nitrocarburizing is distinguished from nitriding because it uses nitrogen and carbon, instead of nitrogen. It should also be noted that the nitrocarburizing treatment has the greatest performance and less expensive comparing the other thermochemical technologies [45]. Recent studies have shown that the tribological properties of the steel can be improved by surface layers consisting of ε-$Fe_{2-3}N$ and γ'-Fe_4N phases [46-50]. However, there is no available information and sufficient studies about the effect of nitrocarburizing treatment on the microstructure and triboligical properties of AISI 1045 medium carbon steel. Therefore, the aim of the current research is to make an attempt to investigate the effect of nitrocarburizing treatment on the microstructure, phases compositions, tribological properties, and the microhardness before and after the treatment by using optical microscopy (OM), scanning electron microscopy (SEM), Surface profilometer, pin-on-disk wear test and testing machine Digital Micro Vickers Hardness Tester.

MATERIALS AND METHODS

The steel used in this research paper was AISI 1045 steel with the following chemical compositions (wt. %): C: 0.49, Si: 0.32, Mn: 0.74, Cr: 0.15, Ni: 0.13, Mo: 0.04, S: 0.002, P: 0.002 and Fe balance. The specimens of 16 mm diameter and 4 mm thick were cut for this research work. Before surface treatments, the specimens were subjected to a normalizing heat treatment. Fig. 1 represents the microstructure of AISI 1045 steel before nitrocarburizing and after heat treatment (martensitic). The mechanical properties of the AISI 1045 steel used are summarized in **Table 1**. In order to know the behavior of tribological properties of AISI 1045 steel, the specimens were subjected to a nitrocarburizing treatment, the conditions and parameters of this process are shown in **Table 2**.

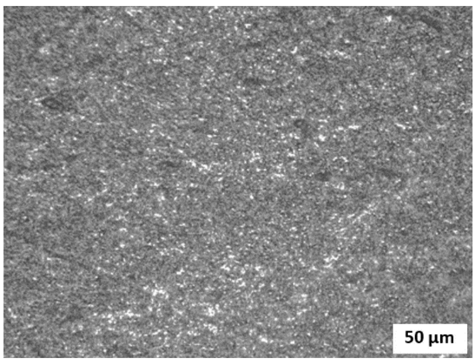


Fig. 1 Microstructure of specimen of AISI 1045 steel after heat treatment

Table 1 Mechanical properties of AISI 1045 steel

Rm (MPa)	Re (MPa)	A%	Hardness (HV)
700	550	10	287

Table 2 Parameters of nitrocarburizing treatment

Process	Chemicals	Temperature	Time	Cooling type
Nitrocarburizing	Cyanates, carbonates	580ºC	5h , 10h	Oil cooling

The cross-sectional microstructure and the surface appearance were observed with GA-120 type optical microscope (OM), the nitrided layers were revealed at room temperature by chemical etching with 2% NITAL (2% HNO_3 in ethanol). According to the ASTM E384-99 standard, the microhardness and the surface hardness of AISI 1045 steel specimens before and after nitrocabonized treatment were tested using a microhardness tester (machine digital micro vickers hardness tester, model: HVS-1000Z) with a load of 300 g. The surface roughness of AISI 1045 steel samples before and after nitrocarburizing was measured using a surface profilometer. According to the ISO 4287:1997 standard, surface roughness was defined by measuring the average roughness Ra. The wear tests were carried out with a pin-on-disk tester, during the test, a 5 mm diameter steel ball rotated at a speed of 60 revs/min at a load of 5 N. After the wear tests, the worn regions of the samples surfaces of AISI 1045 steel were examined with Jeol type scanning electron microscope (SEM). The weight of the samples before and after wear test was evaluated using an electronic balance accurate to 0.1 mg to calculate the weight loss. The specific wear rate is determined using the (Archard, 1953) equation (Eq. 1) [51-52]:

$$k = \frac{V}{F.S} \qquad (1.)$$

where:
k [$m^3.N^{-1}.m^{-1}$] - specific wear rate coefficient
V [m^3] - wear volume
F [N] - applied normal load
S [m] - sliding distance

RESULTS AND DISCUSSION

Microstructure

The morphology and microstructure of treated specimens of AISI 1045 steel by nitrocarburizing at a temperature of 580 °C for 5 h and 10 h is shown in **Fig. 2**. It can be clearly seen that two distinct layers were formed at the samples surface during nitrocarburizing.

One can see an outermost layer well-known as compound layer of a few microns thickness (also called white layer), and below it there is a modified region a relatively thick also known as diffusion layer. The white layer on the surface of the sample treated for 10 h (as shown in **Fig. 2**) was much thicker compared to the sample treated for 5 h as shown in **Fig. 2**, this indicates that the treatment times affects the microstructure during the nitrocarburizing process. There are many previous studies, which highlighted the microstructure of AISI 1045 steel during nitriding treatment, and it proved that the latter has a direct impact on the surface layer of the studied steel. It has also been proven through these studies that the white layer consisted by ε-$Fe_{2\text{-}3}N$ and γ'-Fe_4N, while the diffusion layer consisted by α-Fe [47, 50, 53].

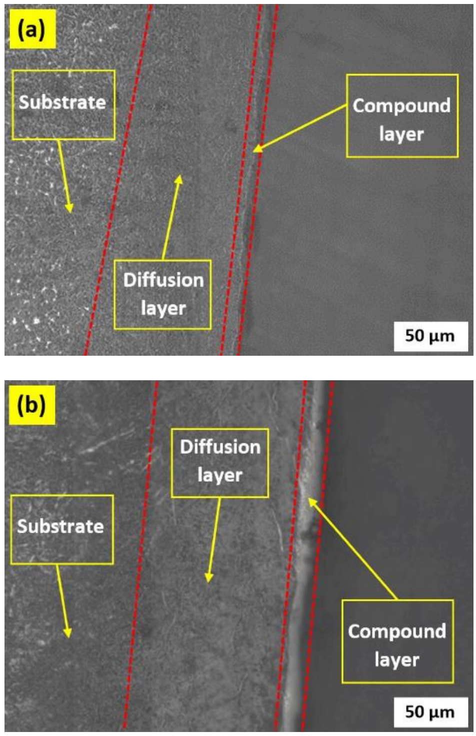


Fig. 2 Cross-sectional microstructures of samples during nitrocarburizing at 580 °C, (a) for 5h, (b) for10h

Microhardness profile

Fig. 3 shows microhardness profile of AISI 1045 steel samples before and after nitrocarburizing under different conditions (at 580 °C for 5 h, 10h of treatment time). The surface hardness reaches the maximum of 418 $HV_{0.3}$ when nitrided for 10 h, representing a 46 per cent increase in surface hardness value of untreated sample, which was 286 $HV_{0.3}$. On the other hand, the surface hardness value of treated sample for 5h increased by up to 38 per cent, which amounted to 393 $HV_{0.3}$. Through the **Fig. 3** also can be seen that the hardness values in the core of the sample before nitrocarburizing were 286 $HV_{0.3}$, which remained relatively constant even after being treated, whether the treatment time was 5 hours or 10 hours (287 $HV_{0.3}$).

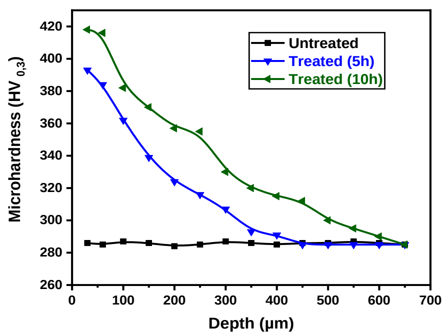


Fig. 3 The cross-sectional hardness profile of the samples untreated and treated at 580 °C for 5h, 10h

This result confirms that the core of AISI 1045 steel samples is not subject to the influence of the nitrocarburizing process. The hardness gradients indicate that the hardness gradually decreases with increasing distance from the surface to core, that is due to the presence of ε-phase ($Fe_{2-3}N,C$) and γ'-phase (Fe_4N,C) in the surface layers, with the concentration of the latter decreasing towards the core of AISI 1045 steel treated. These results agreed with those of studies on the effect of the nitrocarburizing process on the mechanical properties of AISI 1045 steel they clearly showed that the microhardness could be significantly increased by nitrocarburizing treatment [47-49].

Surface roughness

The results of the average roughness Ra of the treated specimens of AISI 1045 steel compared to the untreated specimen were obtained using a surface profilometer in accordance with the ISO 4287:1997 standard. As shown in **Fig. 4**, the average roughness Ra of the untreated AISI 1045 steel specimen is clearly lower than that of the samples after nitrocarburizing at 580 °C, which reaches about 1.06 µm. However, after nitriding treatment, the average roughness Ra of the specimens increased significantly, reaching 1.325 µm and 1.695 µm for 5 h and 10 h of treatment time, respectively.

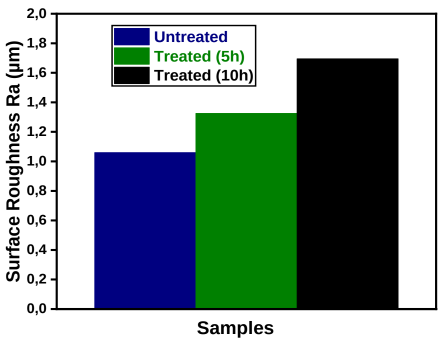


Fig. 4 Average roughness Ra of the samples of AISI 1045 steel before and after nitrocarburizing for different time

Tribological behavior

In this study, the friction coefficient on the sample surface of AISI 1045 steel before nitrocarburizing were compared with those on the surface after she underwent nitrocarburizing treatments at 580 °C for 5 h, 10h . **Fig. 5** represents the friction coefficient of the specimens treated for different duration and untreated one. It can be seen that the friction coefficient of the specimens of AISI 1045 steel treated by nitrocarburizing was lower than that of the untreated specimen. The average friction coefficient value for the sample before treatment was 0.72, while decreasing significantly after nitrocarburizing, approximately corresponding to 0.45, 0.23 for nitriding time of 5 h, 10 h, respectively. According to the results, the friction coefficient of the AISI 1045 steel sample was reduced as much as possible because of the high surface hardness during nitrocarburizing treatments at 580 °C.

Fig. 6 illustrates the results of the specific wear rate coefficient of the treated specimens of AISI 1045 steel compared to the untreated specimen were measured using a tribometer under various dry sliding conditions. It can be clearly seen that the specific wear rate of the untreated specimen of AISI 1045 steel is much higher than those of the samples after nitrocarburizing at 580 °C, which reaches about 19.10^{-13} $m^3.N^{-1}.m^{-1}$. Whereas, the specific wear rate of specimens after nitriding treatment decreased dramatically, 6.10^{-13} $m^3.N^{-1}.m^{-1}$, 2.10^{-13} $m^3.N^{-1}.m^{-1}$ were obtained when nitride for 5 h, 10 h, respectively.

From these results, it can be said that the AISI 1045 steel after nitrocarburizing presents the lowest specific wear rates. This behavior can be explained by the results obtained from previous studies, which confirmed that the wear resistance is related to the surface hardness, the higher the surface hardness of the materials, typically has better wear resistance [45, 52].

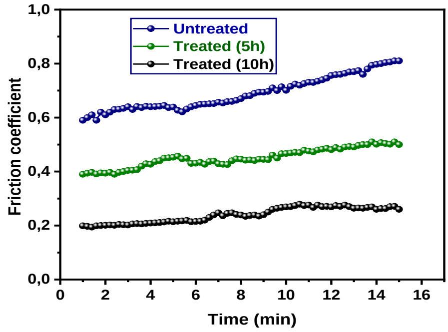


Fig. 5 Friction coefficient of the samples of AISI 1045 steel before and after nitrocarburizing for different time

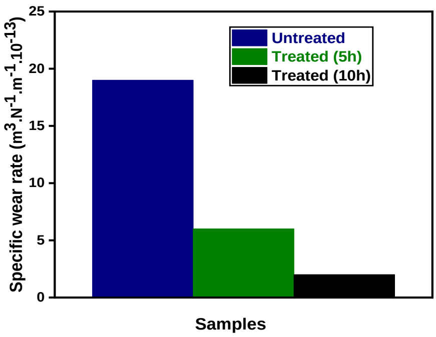
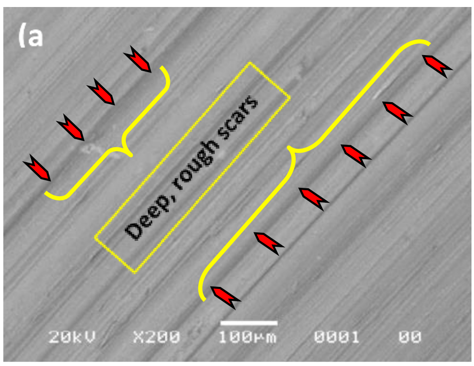
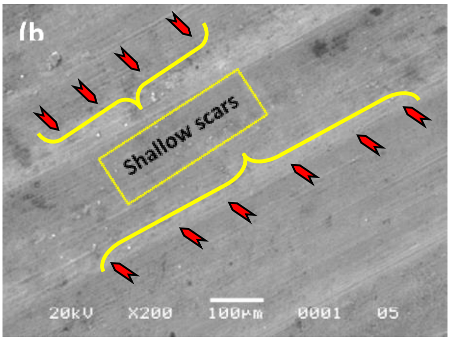


Fig. 6 Specific wear rate of the samples of AISI 1045 steel before and after nitrocarburizing for different time





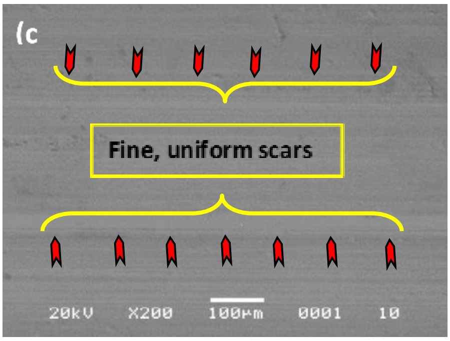


Fig. 7 SEM images of the wear track of the specimens of AISI 1045 steel, (a) untreated specimen, (b) treated specimen for 5 h at 580 °C, (c) treated specimen for 10 h at 580 °C

SEM images of the wear track of the specimens of AISI 1045 steel before and after nitrocaburizing treatment at 580 °C are presented in **Fig. 7**. Fig. 7a illustrates the worn surface of untreated specimen. Figures 7b and 7c shown the worn surface of the specimens nitrided for 5 and 10 h, respectively. It can be seen the worn surfaces of the untreated specimen were clearly different from the worn surfaces of the treated specimens, where we it was observed that the worn surface of the untreated specimen of AISI 1045 steel has numerous abrasion grooves (Deep, rough wear scars), while on the surface of the specimens treated for 5 and 10 h the abrasion grooves are lower and, in general, was more homogeneous and smoother (Fine, uniform wear scars).

CONCLUSION

In this work, the tribological properties behaviour of AISI 1045 medium carbon steel has been studied according to the nitrocarburizing treatment at 580 °C. The most significant results obtained are the compound layer (ε-$Fe_{2\text{-}3}N$,C and γ′-Fe_4N,C) and diffusion layer were formed after nitriding on surface of samples. The thickness of the compound layer is directly proportional to the nitriding time. The surface hardness of AISI 1045 steel was significantly increased after nitrocarburizing, reaching a maximum of 418$HV_{0.3}$ for 10 h, which was 2 times higher than the untreated specimen's 286 $HV_{0.3}$. The surface hardness increased as the nitriding treatment time of increased. The surface roughness is increased by nitrocarburizing. The nitrocarburizing process is most effective for increasing the wear resistance of AISI 1045 steel. The specific wear rate decreased to 1/9 in treated sample compared to untreated sample. The coefficient of friction exhibited the same behavior, where has been reduced by the nitrocarburizing to a large degree.

Acknowledgments: This research was supported by National company tractors ETRAG, Algeria and department of mechanical engineering, University Abbes Laghrour, Khenchela, Algeria

REFERENCES

1. R.P. Verma, D.S. Shwetank Avikal: International Journal of Engineering and Advanced Technology, 8(4s), 2019, 42-44. https://doi.org/10.35940/ijeat.d1013.0484s19.
2. G.L. Leite et al.: International Journal of Engineering Technologies and Management Research, 5(6), 2018, 15-23. https://doi.org/10.29121/ijetmr.v5.i6.2018.242.
3. D.D. Trung: Tribology in Industry, 42(4), 2020, 658-665. https://doi.org/10.24874/ti.969.09.20.11.
4. Q. G. Wu, X. D. Chen, Z. C. Fan, D. F. Nie: Fatigue & Fracture of Engineering Materials & Structures, 40(2), 2017, 245-253.
https://doi.org/10.1111/ffe.12492.
5. I. Akhyar, M. Sayuti: Advanced Materials Research, 1119, 2015, 575-579.
https://doi.org/10.4028/www.scientific.net/amr.1119.575.
6. X. P. Zhang, S. B. Wu, Z. Q. Yao, L. F. Xi: Materials Science Forum, 861, 2016, 63- 68.
https://doi.org/10.4028/www.scientific.net/msf.861.63.
7. W. Gong, Y. Chen, M. Li, R. Kang: Wear, 418-419, 2019, 75-85.
https://doi.org/10.1016/j.wear.2018.10.019.
8. D. Nie, X. Chen, Q. Wu: Engineering Failure Analysis, 110, 2020, 104406.
https://doi.org/10.1016/j.engfailanal.2020.104406.
9. H. R. Ghazvinloo, A. Honarbakhsh-Raouf: Materials Science, 56(2), 2020, 210 -213.
https://doi.org/10.1007/s11003-020-00417-x.
10. M. Murugesan, D. W. Jung: Heliyon, 5(4), 2019, e01347.
https://doi.org/10.1016/j.heliyon.2019.e01347.
11. R. Karimbaev, S. Choi, Y.S. Pyun, A. Amanov: Materials, 13(4), 2020, 859-874.
https://doi.org/10.3390/ma13040859.
12. D.A. Lesyk, S. Martinez, B.N. Mordyuk, V.V. Dzhemelinskyi, A. Lamikiz, G.I. Prokopenko: Optics & Laser Technology, 111, 2019, 424-438.
https://doi.org/10.1016/j.optlastec.2018.09.030.
13. A. Abdul-Ameer, A. Hussein: University of Thi-Qar Journal, 13(1), 2018, 74-83.
https://doi.org/10.32792/utq/utj/vol13/1/6.
14. E. Abedi, S. Daneshmand, I. Karimi, A.A.L. Neyestanak: Journal of Electrochemical Science and Technology, 6(4), 2015, 131-138.
https://doi.org/10.5229/jecst.2015.6.4.131.
15. P. Cheng et al.: Journal of Materials Engineering and Performance, 29(2), 2020, 8340-8347.
https://doi.org/10.1007/s11665-020-05257-z.
16. A. Habibolahzadeh, F. Haftlang: Journal of Tribology, 140(2), 2018, 021602.
https://doi.org/10.1115/1.4037465.
17. M. Gushchina, T. Carstensen, H.J. Maier, T. Hassel: Materials Today: Proceedings, 30, 2020, 694- 699.
https://doi.org/10.1016/j.matpr.2020.01.524.
18. L. N. Araújo et al.: Engineering Reports, 2(12), 2020, 1-9.
https://doi.org/10.1002/eng2.12279.
19. H. Kovacı, A.F. Yetim, Ö. Baran, A. Çelik: Materials Science and Engineering: A, 672, 2016, 257-264.
https://doi.org/10.1016/j.msea.2016.07.002.

20. Y. Yamada, E. Hirohito, K. Takahashi: Metals, 9(12), 2019, 1352-1361.
https://doi.org/10.3390/met9121352.
21. J.A. Díaz-Elizondo et al.: Materials Research, 24(4), 2021, 1-9.
https://doi.org/10.1590/1980-5373-mr-2021-0025.
22. S. Hamann, K. Börner, I. Burlacov, H.J. Spies, J. Röpcke: Contributions to Plasma Physics, 55(10), 2015, 689-700.
https://doi.org/10.1002/ctpp.201510019.
23. Z. Pokorny, D. Dobrocký: ECS Transactions, 91(1), 2019, 443- 449.
https://doi.org/10.1149/08701.0443ecst.
24. L. Jiang, H. Luo, C. Zhao: Surface Engineering, 34(3), 2018, 205-210.
https://doi.org/10.1080/02670844.2016.1253268.
25. V. Tandon, A.P. Patil, R.C. Rathod: Protection of Metals and Physical Chemistry of Surfacesr, 56(4), 2020, 772-779.
https://doi.org/10.1134/s2070205120040243.
26. L. Xiliang, M. Changjun, W. Meihong, C. Wei, D. Mingyang, H. Jing: Acta Metallurgica Slovaca, 26(1), 2020, 4-6.
https://doi.org/10.36547/ams.26.1.458.
27. M. Opaliński, P. Mazuro, A. Klasik, E. Rostek: Archives of Metallurgy and Materials, 61(4), 2016, 1881-1888.
https://doi.org/10.1515/amm-2016-0303.
28. S.K. Singh, C. Naveen, Y.V Sai, U. Satish, C. Bandhavi, R. Subbiah: Materials Today: Proceedings, 18, 2019, 2717-2722.
https://doi.org/10.1016/j.matpr.2019.07.134.
29. W. Mei, J. Wu, M. Dai, K. Wei, J. Hu: Acta Metallurgica Slovaca, 25(2), 2019, 130-135.
https://doi.org/10.12776/ams.v25i2.1271.
30. A.S. Biro, E. Szabo, M. Tisza: Materials Science Forum, 812, 2015, 253-258. https://doi.org/10.4028/www.scientific.net/msf.812.253.
31. H. Sun, J. Zheng, Y. Song, J. Chi, Y. Fu: Surface and Coatings Technology, 362, 2019, 234- 238.
https://doi.org/10.1016/j.surfcoat.2019.01.079.
32. İ. Çelikyürek: Transactions of the Indian Institute of Metals, 70(5), 2017, 1209-1214.
https://doi.org/10.1007/s12666-016-0918-4.
33. Q. Feng, D. Zhang, X. Gao, S. Liu: AIP Conference Proceedings, 1820(1), 2017, 040024-1-040024-7.
https://doi.org/10.1063/1.4977296.
34. G. Prakash, S.K. Nath: Journal of Materials Engineering and Performance, 27(7), 2018, 3206-3216.
https://doi.org/10.1007/s11665-018-3424-5.
35. D. Caliari, G. Timelli, F. Vanzo: Surface Engineering, 34(7), 2018, 536-546.
https://doi.org/10.1080/02670844.2017.1346034.
36. C. Du, J. Zhang, L. Zhang, Y. Lian, M. Fang: Surface Engineering, 37(6), 2020, 764-774.
https://doi.org/10.1080/02670844.2020.1802545.
37. V. Tandon, A.P. Patil, R.C. Rathod: Anti-Corrosion Methods and Materials, 66(4), 2019, 439-445.
https://doi.org/10.1108/acmm-10-2018-2013.
38. J. Alphonsa, S. Mukherjee, V.S. Raja: Corrosion Engineering, Science and Technology, 53(Sup 1), 2018, 51-58.
https://doi.org/10.1080/1478422x.2017.1396648.
39. A.M Prasad et al.: International Journal of Mechanical and Production Engineering Research and Development, 9(4), 2019, 57-62.
https://doi.org/10.24247/ijmperdaug20196.
40. L. Longyi et al.: Metallurgical and Materials Transactions A, 51(8), 2020, 4242-4256.
https://doi.org/10.1007/s11661-020-05802-4.
41. T. Borowski: Materials, 14(12), 2021, 3320-3333.
https://doi.org/10.3390/ma14123320.
42. A. Campagnolo, M. Dabalà, G. Meneghetti: Metals, 9(12), 2019, 1306-1324.
https://doi.org/10.3390/met9121306.
43. S. Xiang, S. Jonsson, P. Hedström, B. Zhu, J. Odqvist: International Journal of Fatigue, 143, 2021, 105984.
https://doi.org/10.1016/j.ijfatigue.2020.105984.
44. V. Bhavsar et al.: Transactions of the Indian Institute of Metals, 73(10), 2020, 2471-2479. https://doi.org/10.1007/s12666-020-02054-z.
45. E.R.S. Sran, E.G.R. Sharma: International Journal for Research in Applied Science and Engineering Technology, 8(10), 2020, 104-109.
https://doi.org/10.22214/ijraset.2020.31812.
46. E. Badisch et al.: Key Engineering Materials, 674, 2016, 325-330.
https://doi.org/10.4028/www.scientific.net/kem.674.325.
47. M. Dai, C. Li, Y. Chai, J. Hu: Metal Science and Heat Treatment, 60(7-8), 2018, 454-456.
https://doi.org/10.1007/s11041-018-0300-8.
48. E. Ghelloudj, H. Djebaili, M. T. Hannachi, A. Saoudi, B. Daheche: Acta Metallurgica Slovaca, 22(3), 2016, 188-194.
https://doi.org/10.12776/ams.v22i3.756.
49. S. Lu, B. Miao, L. Song, R. Song, K. Wei, J. Hu: Vacuum, 145, 2017, 153-157.
https://doi.org/10.1016/j.vacuum.2017.08.026.
50. T. Peng, M. Dai, W. Cai, W. Wei, K. Wei, J. Hu: Applied Surface Science, 484, 2018, 610- 615.
https://doi.org/10.1016/j.apsusc.2019.04.134.
51. V. Popov: Facta Universitatis, Series: Mechanical Engineering, 17(1), 2019, 39-45.
https://doi.org/10.22190/fume190112007p.
52. F. Haftlang, A. Habibolahzadeh: Acta Metallurgica Sinica (English Letters), 32(10), 2019, 1227-1236.
https://doi.org/10.1007/s40195-019-00874-7.
53. M. Dai, Y. Chen, Y. Chai, J. Hu: Surface Review and Letters, 23(6), 2016, 1650049(1)-1650049(5).
https://doi.org/10.1142/s0218625x16500499.