ACTA METALLURGICA SLOVACA
2022, VOL. 28, NO. 4, 197-202

RESEARCH PAPER

DECREASING MECHANICAL PROPERTIES OF THE SUPERHEATER STEEL GRADE P22 HEATED AT ELEVATED TEMPERATURE UNDER CONSTANT STRESS

Cao-Son Nguyen[1], Thu-Hien Nguyen[1], Anh-Hoa Bui[1,]*

[1] School of Materials Science and Engineering, Hanoi University of Science and Technology, No. 1, Dai Co Viet Road, Hai Ba Trung District, Hanoi, Vietnam

*Corresponding author: hoa.buianh@hust.edu.vn, tel.: +84 24 38680409, School of Materials Science and Engineering, Hanoi University of Science and Technology, No. 1, Dai Co Viet Road, Hai Ba Trung District, Hanoi, Vietnam

Received: 11.10.2022
Accepted: 23.10.2022

ABSTRACT

This paper investigated the change in the mechanical properties of the superheater pipe steel grade P22 (ASTM A335) under the constant stress of 9.68 MPa and various temperatures of 500-700 ºC. The steel specimens were prepared from the unused steel pipe P22, then heated to the given temperature, and held for the predetermined time as 24, 48, and 72 hours in the atmosphere. The results showed that the mechanical properties of the steel P22 decreased with the increased temperature and time. This deterioration of the steel strength was caused by the redistribution of the carbide in the steel subjected to elevated temperature and constant stress. Although the change in the microstructure including phase and grain size was not observed, the SEM micrographs showed that the carbide of the heated steel accumulated on the grain boundaries and the triple regions when the temperature and holding time increased. This phenomenon was attributed to the reduced number of the carbide in the steel, resulting in a decrease in the mechanical properties. The obtained results indicated that a decrease in the mechanical properties of the steel pipe P22 can occur in the early period of working time in the practice.

Keywords: mechanical properties, superheater steel, microstructure, redistribution of carbide, grain boundaries

INTRODUCTION

High chromium (Cr) and low molybdenum (Mo) alloy steel, e.g., 9Cr-1Mo usually used for thickness section components of steam generators operating at high temperatures [1-4]. Meanwhile, demand for the increase of thermal efficiency in power plants has been the main driving force for the development of low alloy steels used to produce the superheater pipe [5-8]. These steel grades mostly contain alloys of low Cr and Mo, but they can attain high strength and stainless properties at the working condition of high temperature and pressure. Since the steel grade P22 (ASTM A335) has good characteristics and a reasonable price, this grade is widely used for operating temperature up to 600 °C. This steel pipe is designed to work with a steam pressure of about 15 MPa and a temperature of 540-570 °C [7]. The superheater pipe of the steel P22 was used in many coal-fired power plants in Vietnam, however, those plants have been facing a lot of pipeline failures involving the degradation of steel grade P22, i.e., the loss of steel's strength in service, evenly the trouble can occur at the early period of working time. Therefore, investigation and understanding of this degradation are helpful for using the steel pipe P22 effectively.

Such pipes in the power plants have a determined lifetime because of prolonged exposure to high temperatures, stress, and an aggressive environment. Recently, the remaining life assessment of the pipeline in the industrial condition has become necessary for both economic and safety reasons for all the power plants. It is acknowledged that some components can have a shorter life than expected because the steel subjected to the creep stress at elevated temperatures has a tight relationship between microstructure evolution and mechanical properties [6-9]. Identification of the steel degradation in service is necessary for the improvement of operation and maintenance to keep the plants in reliability, availability, and profitability. Some studies have paid attention to the decrease of mechanical properties of the steel so that an evaluation of the lifetime can be proposed by deploying the factors affecting the mechanical properties of the steel in the working condition [10-12]. For example, Fujibayashi et al. [10] carried out an experiment in the condition of high temperature and pressure to determine the service life of the 1.25Cr-0.5Mo pipe steel and concluded that the change in carbide morphology during the creep exposure was the most pronounced. Lima et al. [11] studied the microstructural changes of commercial Cr-Mo steel products due to the impact of stress, temperature, and time which could be used to evaluate the damage and as life assessment tools for the individual component. Liu et al. [12] investigated the effects of stress, time, steel hardness, and heat treatment schedule on the room temperature creep; and concluded that the increased creep strains had been attributed to higher applied stresses, longer creep times, lower hardness, and the existence of an inhomogeneous microstructure. On the other hand, the creep strength of the pipe steel was evaluated via measurement of the mechanical properties, then the lifetime of the steel could be

predicted; the effect of carbide distribution on the mechanical properties of steel pipe was considered to correlate [13-15].
Even though the previous studies revealed that the reason for the damage of the low alloy pipe steel was due to the obvious decline of mechanical properties and microstructure, the authors have mentioned the deterioration of the steel and, the role of the carbide after long service time. Thus, this paper focuses on and explains the change in the mechanical properties of the steel P22 in the early period of working time. The relation between this change and the microstructure of the steel is also discussed.

MATERIAL AND METHODS

Specimens of the steel P22 were cut from the unused superheater pipe (inner diameter: 30 mm, outer diameter: 40 mm) of a coal-fired power plant in Vietnam. The chemical composition of the steel was analyzed using the optical emission spectrometer (Metal LAB 75/80J MVU-GNR) and given in **Table 1** where the contents of Cr and Mo were consistent with the standard ASTM A335.

Table 1 Compositions of the steel P22 (wt.%)

C	Mn	Si	Cr	Mo	S	P	Fe
0.09	0.47	0.23	2.27	0.89	0.015	0.005	Bal.

The tensile test specimens which the shape and dimensions are shown in **Fig. 1**, were cut according to the standard ASTM E8.

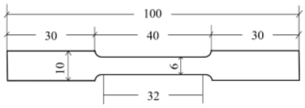


Fig. 1 Tensile test specimen according to the standard ASTM E8 (unit: mm)

After that, the specimen was set up in the resistance furnace under the stress of 9.68 MPa (Fig. 2) equivalent to the withstanding pressure of the pipe in the working condition. The heating rate was selected as 10 ºC/min for all experiments. The holding temperature remained at 500, 600, and 700 °C for different times (24, 48, and 72 hours respectively). Finally, the specimen was cooled down to room temperature together with the furnace, removed from the load, and then subjected to the tensile test or microstructural investigation. The mechanical properties were measured by the tensile tester (INTRON). All measurements with a strain rate of 10^{-2} mm/s were carried out at room temperature. The microstructure was observed by optical microscopy (Axioplan 2) and scanning electron microscopy (JEOL JSM-7600F).

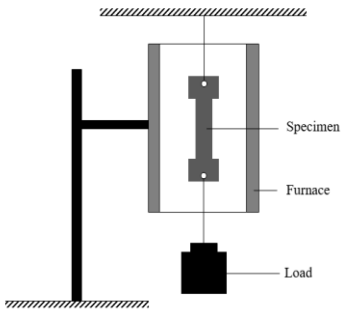


Fig. 2 Experimental setup for heating the specimen under constant stress

RESULTS AND DISCUSSION

Results of the tensile tests are shown in **Fig. 3** and **4** in which ultimate tensile strength (UTS) and yield strength (YS) have degraded with the increase of the heating temperatures or the increase of the holding time. For example, the UTS and YS were found to be decreased from 465 to 353 MPa and from 292 to 200 MPa respectively when the temperature was raised from 500 to 700 ºC. At 700 ºC, the UTS and YS were reduced from 396 to 353 MPa and from 233 to 200 MPa respectively when the time increased from 24 to 72 hours. However, the total elongation (EL) did not have a significant change for all experimental conditions. In comparison with the initial mechanical properties (UTS = 510 MPa, YS = 360 MPa, EL = 36 %), there was a decline in the strength of the steel P22 which was heated at elevated temperature under constant stress. This phenomenon was in similarity to the results of several researchers who concluded that the strength of the pipe steel was degraded after working at high temperatures for a certain time [6,16-18]. In addition, the practical operation reveals that the steel pipe has been deformed plastically due to the impact of high temperature and pressure of the steam, resulting from the creep failure which has been explored in the case of steel under different conditions.

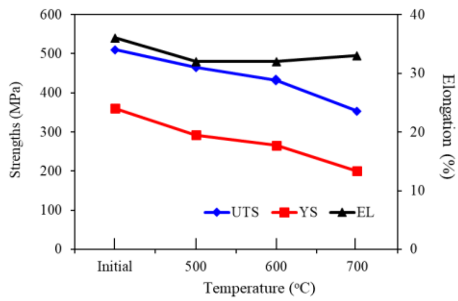


Fig. 3 Variation of the mechanical properties with the temperature after 72 hours

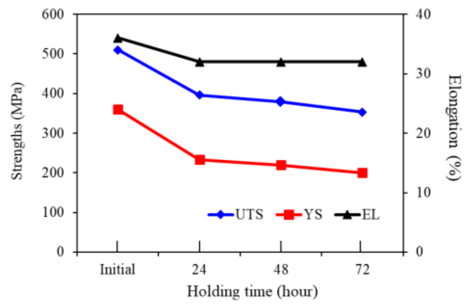


Fig. 4 Variation of the mechanical properties with the holding time at 700 ºC

In general, high strength and/or low ductility are good for the steel to against plastic deformation. The elongation and tensile strength of the steel are usually contrary, i.e., high strength and low elongation, or low strength and high elongation. Thus, it is important to compromise the strength and the elongation of the steel to attain good working performance. In some cases, the ratio of YS/UTS is used to roughly evaluate the ductility of the

DOI: 10.36547/ams.28.4.1610

steel. Table 2 showed the calculated ratio of YS/UTS which decreased slightly with increasing the temperature from 500 to 700 ºC, but this change was trivial in the time range of 24 to 72 hours. This indicated that not only the strength (UTS and YS) but also the ductility of the steel P22 reduced with increasing temperature. The plasticity may have occurred during the investigated conditions because of changes in the microstructure of the steel.

Table 2. The ratio YS/UTS of the steel corresponded to the different conditions

Ratio	**Initial**	**For the time of 72 hours**			**At the temperature of 700 ºC**		
		Temperature (ºC)			**Time (hour)**		
		500	600	700	24	48	72
YS/UTS	0.78	0.63	0.61	0.57	0.59	0.58	0.57

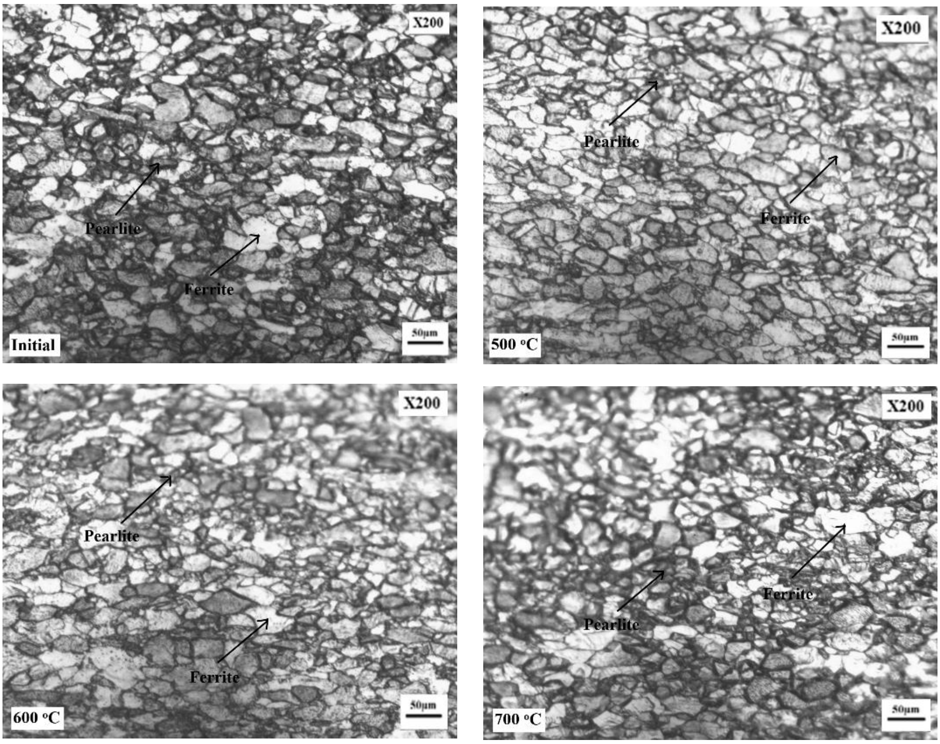


Fig. 5 Microstructure of the initial and heated steels for 72 hours

Carbide is known to affect the dislocation movement and play an important role in the improvement of the mechanical properties of steel [7,19,20]. Therefore, the above decrease in the mechanical properties of the heated steel P22 can be explained by changes in the microstructure. The optical micrographs of the steels are shown in Fig. 5 where the microstructure is predominantly ferrite, and pearlite is precipitated at the ferritic grain boundaries. These microstructures and grain sizes were almost the same for all steel specimens. In this case, the carbide of the steel was thought to relate to the decrease in the mechanical properties of the steel P22. According to Pramanick *et al.* [19], the carbide distribution was a reason for decreasing the mechanical properties of the low alloy steel worked at high temperatures for a long time. Therefore, it is necessary to investigate the distribution of the carbide in the present steel specimens.

The carbide particles in the steel P22 heated for different times at the temperature of 700 ºC were shown in Fig. 6. Figure 6a showed the carbide particles that distributed homogeneously in the matrix of the initial steel P22. According to previous studies, this carbide distribution was desirable for good mechanical properties of the pipe steel [4-6,19]. However, the size and distribution of the carbide particles were observed to be changed when the steel specimens were heated at high temperatures under constant stress (Fig. 6b-d). The carbides were observed in the boundaries, inside the grain, or at the triple point of the grain boundaries. At the temperature of 700 ºC, the number of carbide particles in the steel was seen to be fewer in comparison with those at temperatures of 500 and 600 ºC. In similarity with the other literature, it could be confirmed that the carbide coarsening process proceeded with the increased temperature [5-7,14]. In this study, carbides of the steel P22 heated at 700 ºC tended to grow, and the coarsen carbides precipitated in the grain boundaries and the triple area. Redistribution of the carbides in the alloy steel worked at high temperatures was also revealed in the research of Zhang et al. [21]. Bendick *et al.* [16] who focused on new low alloy heat-resistant steels for power plant application remarked that the

DOI: 10.36547/ams.28.4.1610

growth of carbide was dependent on the diffusion rate of C and Cr, but Cr diffusion along grain boundary was more preferential. Apparently, the carbide was an advantage to grow and redistribute at a higher temperature because of the decrease in the surface energy; resulting in the replacement of the small particles by the bigger ones, i.e., the redistribution of the carbides occurred. Consequently, there was a long distance between carbides and a fewer number of carbide particles at high temperatures [22,23]. For the present steel P22, the optical micrographs showed an unchanged microstructure; thus, the reason for the decrease in the mechanical properties would be the redistribution of carbide which caused a more preferential movement of dislocation that decreased the creep resistance of the pipeline steel.

Figure 7 showed the SEM-EDS results of the steel heated at 700 ºC at different times. For the heating time of 24 hours, the carbides were found to distribute homogeneously on both the matrix and grain boundaries; however, once the heating time was 72 hours, there was a significantly increased grain size of the carbides, the number of the particles reduced, resulting an increase of the distance among carbide particles. Also, the EDS analysis revealed that the chemical compositions of the carbides containing Fe (majority), Cr, and Mo (minority) were mostly unchanged with the increased temperature. This result indicated that the compositions of the carbides did not affect the decrease of the mechanical properties of the steel P22 in the investigated conditions.

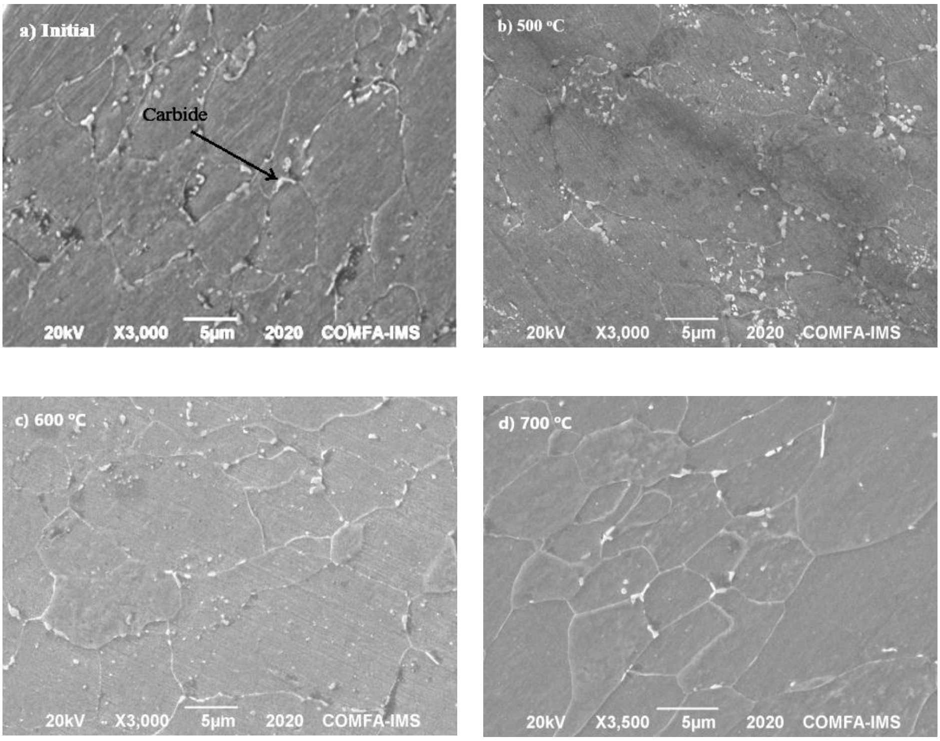
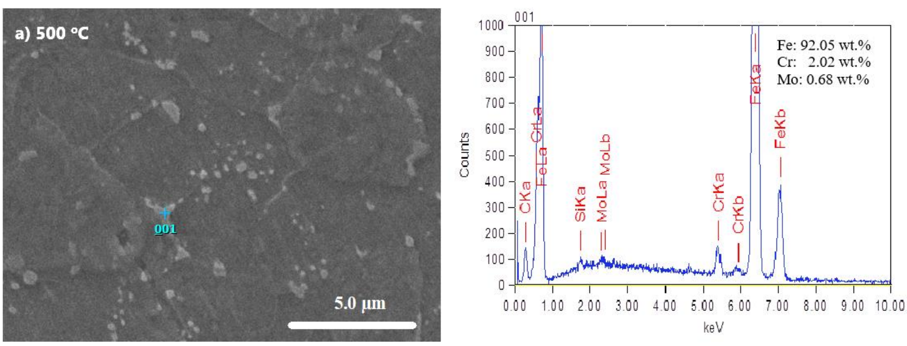


Fig. 6 Carbides distribution in the initial steel and the steel heated at different temperatures for 72 hours



DOI: 10.36547/ams.28.4.1610

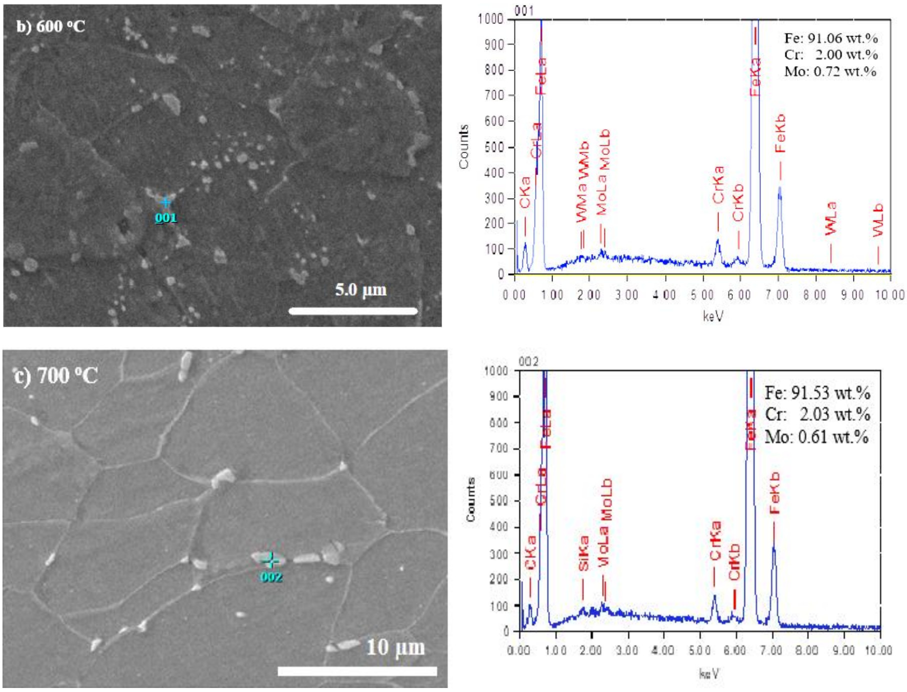


Fig. 7 Carbides distribution in the steel P22 heated for 72 hours for various temperatures: (a) 500 ºC, (b) 600 ºC, (c) 700 ºC

Instead of that, the mechanical properties of the steel decreased due to the microstructural change such as coarsening and redistribution of the carbide. Jones [6] explained the carbide redistribution that the pearlite was thermodynamic unstable because of the interfacial energy of the carbide-ferrite boundaries; the carbide plates gradually broke down with time and the iron carbide reformed; eventually, the coarsening of the carbide particles occurred themselves. The larger particles grew at the expense of the smaller ones, and the distribution gradually changed from large numbers of small particles to a small number of large ones. The obtained result was consistent with the reported creep mechanism, by which the growth and redistribution of carbides resulted in decreasing the steel performance [24,25]. However, the SEM observation did not find any cavities because the time may not be sufficient for the formation of cavities occurring at grain boundaries, as the creep failure, caused damage in the pine steel worked at elevated temperatures for a long time.

CONCLUSIONS

Deterioration of mechanical properties of the superheater steel P22 (ASTM A335) occurred in the early period time when the specimens were heated at the temperature range of 500-700 ºC under the constant stress of 9.68 MPa. The results showed that the UTS and YS of the steel P22 decreased from 465 to 353 MPa and from 292 to 200 MPa, respectively once the temperature increased from 500 to 700 ºC after 72 hours. At the temperature of 700 ºC, the increased time from 24 to 72 hours decreased the UTS from 405 to 396 MPa and YS from 233 to 200 MPa. This was attributed to the creep phenomenon that occurred in the early period of the heating time. The distribution of carbide in the matrix of steel P22 was concluded to be the main reason for the deterioration of the strength. For the initial steel specimen, the carbides were confirmed to distribute homogeneously in the matrix and at the grain boundaries. Once the temperature and the time increased, the number of the carbide increased and concentrated on the boundaries and the triple point of the grain boundaries. It can be noted that the distribution of the carbide in the early period of working time is crucial, these changes may accelerate the failure of the steel pipe during the operation of the coal-fired power plant. The kinetic of carbide transformation in the steel heated or worked at high temperatures for a long period must be paid attention to.

REFERENCES

1. L. Falat, V. Homolova, J. Kepic, M. Svoboda, A. Vyrostkova: Journal of Mining and Metallurgy, Section B - Metallurgy, 48(3), 2012, 461-469. https://doi.org/10.2298/JMMB120701057F.
2. A. Fedorikova, T. Kvackaj, R. Kocisko, R. Bidulsky, P. Petrousek, J. Bidulska, L. Domovcova: Acta Metallurgica Slovaca, 22(2), 2016, 102-110. https://doi.org/10.12776/ams.v22i2.616.
3. H. S. Bao, S. C. Cheng, Z. D. Liu, S. P. Tan: Journal of Iron and Steel Research - International, 17(2), 2010, 67-73. https://doi.org/10.1016/S1006-706X(10)60062-3.
4. M. Mazaheri, F. Djavanroodi, K. M. Nikbin: International Journal of Pressure Vessels and Piping, 87, 2010, 746-752. https://doi.org/10.1016/j.ijpvp.2010.08.013.
5. J. N. Dupont, J. A. Siefert, J. P. Shingledecker: International Materials Reviews, 62(1), 2016, 32-56. https://doi.org/10.1080/09506608.2016.1207008.
6. D. R. H. Jones: Engineering Failures Analysis, 11(6), 2004, 873-893.

https://doi.org/10.1016/j.engfailanal.2004.03.001.
7. A. K. Ray, Y. N. Tiwari, P. K. Roy, S. Chaudhuri, S. C. Bose, R. N. Ghosh, J. D. Whittenberger: Materials Science and Engineering A, 454-455, 2007, 679- 684. https://doi.org/10.1016/j.msea.2006.11.019.
8. K. Singh, M. Kamaraj: Procedia Engineering, 55, 2013, 394-401. https://doi.org/10.1016/j.proeng.2013.03.270.
9. S. Mrozinski, Z. Lis, H. Egner: Materials, 15(4), 2022, 1-12. https://doi.org/10.3390/ma15144917.
10. S. Fujibayashi, T. Endo: ISIJ International, 43(5), 2003, 790-797. https://doi.org/10.2355/isijinternational.43.790.
11. W. F. Lima, G. Rigueira, H. C. Furtado, M. B. Lisboa, L. H. Almeida: Materials Research, 2017, 1-5. http://dx.doi.org/10.1590/1980-5373-MR-2016-0596.
12. C. Liu, P. Liu, Z. B. Zhao, D. O. Northwood: Materials and Design, 22(4), 2001, 325-328. https://doi.org/10.1016/S0261-3069(00)00074-1.
13. A. Raj, B. Goswami, A. K. Ray: High Temperature Materials and Processes, 33(1), 2014, 1-12. https://doi.org/10.1515/htmp-2012-0177.
14. C. Y. Chi, H. Y. Yu, J. X. Dong, W. Q. Liu, S. C. Cheng, Z. D. Liu, X. S. Xie: Progress in Natural Science: Materials International, 22(3), 2012, 175-185. https://doi.org/10.1016/j.pnsc.2012.05.002.
15. P. Duan, Z. D. Liu, B. Li, J. Y. Li, X. Q. Tao: High Temperature Materials and Processes, 39, 2020, 545-555. https://doi.org/10.1515/htmp-2020-0087.
16. W. Bendick, J. Gabrel, B. Hahn, B. Vandenberghe: International Journal of Pressure Vessels and Piping, 84(1-2), 2007, 13-20. https://doi.org/10.1016/j.ijpvp.2006.09.002.
17. P. C. Dsilva, S. Bhat, J. Banappanavar, K. G. Kodancha, S. R. Hegde: Engineering Failure Analysis, 121(2), 2021, ID 230530919. https://doi.org/10.1016/j.engfailanal.2020.105152.
18. F. Abe: Engineering, 1(2), 2015, 211-224. https://doi.org/10.15302/J-ENG-2015031.
19. A. K. Pramanick, G. Das, S. K. Das, M. Ghosh: Case Studies in Engineering Failure Analysis, 9, 2017, 17-26. https://doi.org/10.1016/j.csefa.2017.06.001.
20. P. J. Maziasz: Journal of The Minerals, Metals, and Materials Society, 70, 2018, 66-75. https://doi.org/10.1007/s11837-017-2642-x.
21. Y. T. Zhang, L. D. Miao, X. J. Wang, H. Q. Zhang, J. F. Li: Materials Transactions, 50(11), 2009, 2507-2511. https://doi.org/10.2320/matertrans.M2009172.
22. B. S. Prasad, V. B. Rajkumar, H. Kumar: Materials Science, 36(3), 2017, 1-7. https://doi.org/10.1016/j.calphad.2011.10.006.
23. H. J. Sung, S. J. Kim: ISIJ International, 58(11), 2018, 2142-2146. https://doi.org/10.2355/isijinternational.ISIJINT-2018-265.
24. K. Kucharova, V. Sklenicka, M. Kvapilova, M. Svoboda: Materials Characterization, 109, 2015, 1-8. https://doi.org/10.1016/j.matchar.2015.08.008.
25. V. C. Igwemezie, C. C. Ugwuegbu, J. U. Anaele, P. C. Agu: Journal of Engineering Science and Technology Review, 8(5), 2015, 84-94. https://doi.org/10.25103/jestr.085.12.