International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XII, No. 1 / 2020

INCREASING THE TOOL LIFE OF FORGING DIE INSERTS

Brenda Castaños[1], Laura Peña-Parás [1], Demófilo Maldonado-Cortés[1], Marta Kitala[2], Szymon Sliwa[2], Maciej Węglarz[2], Dariusz Mierzwiński[2]

[1] Departamento de Ingeniería, Universidad de Monterrey, San Pedro Garza García, Nuevo León, México, 66238
[2] Institute of Materials Engineering, Faculty of Mechanical Engineering, Cracow University of Technology, al. Jana Pawła II 37; 31-864 Cracow, Poland

Corresponding author: Laura Peña-Parás, laura.pena@udem.edu

Abstract: In the metal-mechanic industry, wear and friction highly affect the useful life of forging dies, leading to economic losses and poor product quality. In this study, the tribological behavior of AISI H13 and Thermodur E40K Superclean hot-work tool steels with and without a nitriding thermochemical treatment were investigated for die inserts. Forging tests of brass pieces were performed under industrial conditions in order to validate the results obtained in the laboratory and to determine the optimal combination of conditions for the forging die inserts. The laboratory tests results showed that nitrided E40K had the best tribological performance. For the forging tests the application of the nitriding thermochemical treatment was detrimental to the performance of die inserts. Tool steel E40K presented the best results in the number of manufactured parts (+67%), fewer rejected parts (-67%) and equipment downtime during forging tests (-73%) compared to H13 tool steel. The novelty of this work consists on the application of a methodology based on the abstraction of a tribological system and the study of one of its most important response variables, wear, through laboratory testing. After this, technological decisions can be made in order to improve a complex manufacturing processes, such as forging of non-ferrous materials, which would be very costly if tested directly in the manufacturing process without prior laboratory study.

Key words: Forging, wear, die inserts, tribotesting

1. INTRODUCTION

During forging processes die inserts present high friction and wear, which reduces their durability, generating high costs for repairs and/or replacements, as well as productivity losses due to equipment downtime [1, 2]. Tooling wear also results in poor quality of the forged pieces with defects such as cracks, scratches, splits, or not meeting the required dimensions; therefore, these pieces are rejected.

It has been reported by Bayramoglu et al. [3] that die cost represents approximately 30% of the forging process and by increasing the die life by 100% a reduction of 15% in the total cost of the forging process could be obtained. According to Hawryluk et al. [4] forging tools, especially those used in hot forging processes, are characterized by a relatively short and unstable lifetime, which significantly affects the quality and costs of the manufactured products.

About 70% of failures in the metal-mechanic industry are caused by the tribological aspects of mechanical components [5], and approximately one third of the world's energy resources results in waste due to friction and wear [6]. As discussed by Fradinho et al. [7], sustainability in manufacturing process is of great importance to save materials, energy, waste and reduce overall pollution to the environment. For these reasons, several approaches have been followed in order to improve the durability of tooling materials [8] and forging tools [4, 9].

Forging processes are commonly performed at elevated temperatures, approximately ranging from 250-700°C. Therefore, general requirements for tooling materials in forging applications are high strength and toughness at high temperatures, uniform hardening, mechanical and thermal shock resistance, and wear resistance [4]. Hence, appropriate material selection under these conditions is essential for prolonging the die inserts tool life.

Common materials in die inserts that meet these requirements are tool steels with medium carbon content containing chromium, nickel, molybdenum, tungsten, and vanadium [4, 10]. Particularly, AISI H13 chromium-molybdenum hot-work tool steel has been selected for insert dies and tooling for forging processes due to its high toughness, hardness, thermal fatigue and wear resistance, and mechanical strength [1,11]. Recently, a hot-work tool steel, namely Thermodur E40K Superclean steel has been developed and applied for die inserts for forging processes due to their better temperature stability and toughness compared to H-type steels [12].

Surface engineering techniques may also be used to improve die inserts tool life [3, 4, 9, 13, 14]. In a study by Suchánek & Kuklík [15] a comparison of different surface treatments was made. They found that by applying a nitriding thermochemical treatment to the die inserts a higher surface hardness was obtained, extending overall tool life. Castro et al. [13] studied the influence of nitriding time on the wear behavior of AISI H13 hot-work steel and found that larger nitride layer thicknesses affected the number of forged parts. Finally, Bayramoglu et al. [3] found that the nitriding treatment increased their service life by 119% attributed to the higher hardness of the surface under high temperature conditions.

In this research the performance of an AISI H13 hot-work tool steel and a Thermodur E40K Superclean steel with and without a nitriding thermochemical treatment to be used for forging die inserts was investigated. Laboratory tests were done to characterize the materials´ wear behavior. Performance tests of forging die inserts under industrial conditions of brass forgings were done in order to validate the laboratory results and to determine the optimal combination of conditions for achieving higher tool life and productivity.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

The selected materials used in this research were hot-work tool steels AISI H13 and Thermodur E40K Superclean. These materials were quenched and tempered by the supplier providing similar hardness for both materials of HRC 53.2 (H13) and HRC 52.4 (E40K). The chemical composition of these materials is presented in Table 1, showing very similar content of elements. Slight differences in Cr, Mo, Si, Ni and Mn content; however, even these small differences can impact the performance of tool steels, as discussed by Higuera et al., [16].

A nitriding thermochemical treatment was applied to the materials with the purpose of enhancing their tribological behaviour, namely, wear resistance. Particularly, an ionic nitriding at 490-530°C with a duration of 50h was performed by *Tratamientos Térmicos Avanzados*. The thickness of the nitrided layer for all samples was 0.1778-0.254 mm. The nomenclature of the materials used in this study with and without nitriding is shown in Table 2, where H1 and E1 represent H13 and E40K, respectively, and H2 and E2 represent H13 and E40K tool steels with a nitriding thermochemical treatment, respectively. Finally, hardness of all materials was measured with a Rockwell C hardness test.

Table 1. Chemical composition of the materials

	C %	**Cr %**	**Mo %**	**Si %**	**V %**	**Ni %**	**Mn %**
H13	0.38	5.15	1.22	0.97	0.94	0.21	0.32
E40K	0.38	4.63	1.88	0.34	0.85	0.09	0.22

Table 2. Combination of materials used in the laboratory and field tests

H1	H13
H2	H13 + Nitriding
E1	E40K
E2	E40K + Nitriding

2.2 Experimental methods

Laboratory studies were performed on blocks with dimensions of 6.35 x 10 x 15.75mm, fabricated of the selected tool steels with and without nitriding treatment. Tribological properties were characterized with a T-05 block-on-ring tribotester following the ASTM G77-05 standard [17]. This test is used to characterize the anti-wear properties of a pairs of materials according to their sliding wear characteristics under various conditions. The tribosystem consists of a stationary block of the material to study pressed against a D2 steel ring in lubricated conditions. The ring rotates at a constant speed of 300rpm, with a constant load of 900N, during a testing time of 4500 seconds. The lubricant used for the tests was a Deltaforge, forging die lubricant. Wear loss was obtained from the displacement of the tribosystem, that is, the wear of both the block and the ring materials, as shown in Figure 1.

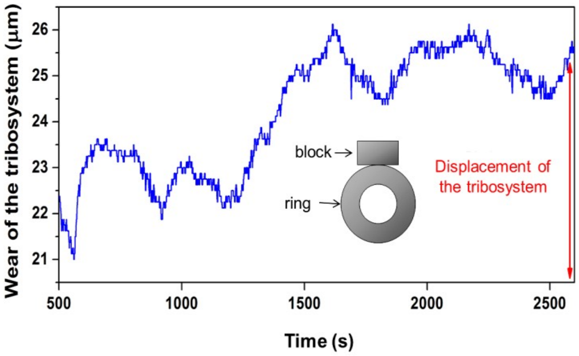

Fig. 1.Wear loss obtained from the displacement of the tribosystem (block and ring materials)

2.3 Forgings tests

In order to validate the results obtained from the laboratory tests die inserts were fabricated from the materials and thermochemical treatments shown in Table 2. These tests were performed under real operating conditions at a company that forges brass products. The results recorded from the forging tests were: the number of manufactured brass forgings, the number of rejected parts, and the downtime of the forging press during the lifetime of each insert. The die inserts' wear was analyzed with an Alicona IF-EdgeMaster optical 3D measuring system by measuring the insert die´s edge radius as shown in Figure 2(a). Figure 2(b) shows the graph generated by the instrument, where the red circle indicates where the edge radius was measured. This equipment allows for automatic tool measurement such as cutting edges of inserts or and other edges of tools regardless of the material or surface finish.

It should be noted that in this case, sharper radii of insert dies are indicative of higher wear resistance that may affect the number, quality of manufactured products, number of equipment downtime, and overall productivity by the forging process.

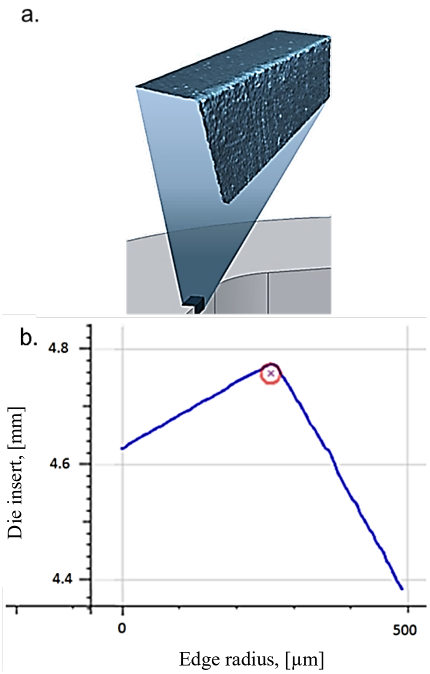

Fig. 2. (a) Measurement on edge radius of forging die inserts used to determine wear; (b) graph showing the measurement of the edge radius of the die insert

3. RESULTS

3.1 Laboratory results

The Rockwell C Hardness of all materials is presented in Figure 3. As noted, H13 and E40K steels had a hardness of HRC 53.2 and HRC 52.4, respectively. Nitriding treatment increased the hardness of both steels to ~HRC 65.

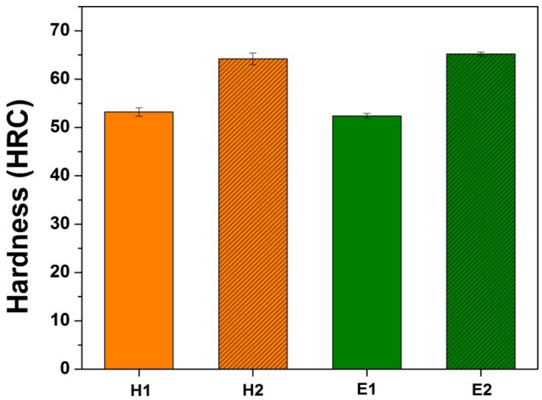

Fig. 3. Hardness of selected steels with and without nitriding treatment

Figure 4 shows the comparison of H13 and E40K tool steels and the effect of the nitriding thermochemical treatment. It can be noted that for all materials, the anti-wear properties were higher with the application of the nitriding treatment. For example, for H13 tool steel, nitriding reduced wear by ~40%. Similarly, nitriding reduced wear of E40K by ~43%. The overall results show that in laboratory conditions the material with the best performance was the E40K with nitriding treatment with 64% less wear than un-treated H13 steel.

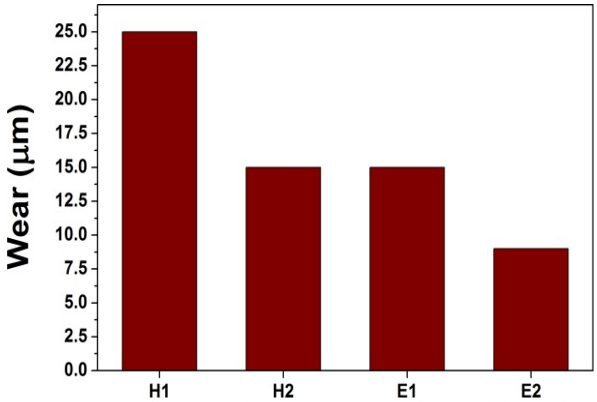

Fig. 4. Wear loss of selected materials obtained from the displacement in microns of the tribosystem

3.2 Forging of brass products

Following the laboratory tests die inserts were fabricated of hot-work tool steels H13 and E40K with and without the nitriding treatment. Three die inserts were tested for each combination and employed for producing brass forgings. The results obtained in the forging tests were: manufactured products or pieces, rejected products, and equipment downtime. The number of manufactured products results is presented in Figure 5. Regarding material selection, it can be noticed that the best result was obtained by the E40K material, which represents a 67% of increase in manufactured parts in comparison with H13 tool steel. This result is consistent with the those obtained for wear resistance in laboratory tests (Figure 4).

According to Higuera et al. [16] the chemical composition is strongly related to the behavior of a material. Chromium is added to tool steels to refine the grain size, which increases the material strength; whereas nickel is added to increase the toughness. Steels that contain nickel and chromium suffer from embrittlement during the tempering heat treatment, therefore molybdenum is added in order to prevent the formation of the embrittlement carbides [14]. As can be noted, the chemical composition of both materials is very similar (Table 1), however E40K steel has lower chromium and nickel content, and a higher molybdenum content, thus its stability after tempering is higher explaining the better performance compared to H13 tool steel.

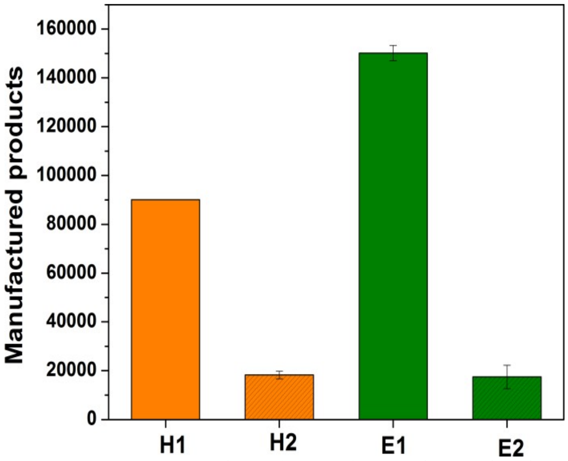

Fig. 5. Average number of manufactured parts by the forging process with the selected materials

As shown in Figure 6, the die inserts of H13 and E40K with nitriding thermochemical treatment (Figure 6(b) and (d), respectively) demonstrated a poor performance, whereas the inserts without nitriding had very little wear and fractures (Figure 6(a) and (c)). It was found during the forging tests that the nitrided inserts presented fractures on the edges, which caused the manufactured parts to be rejected due to being defective according to quality standards. The poor behaviour of the nitrided die inserts can be attributed to their higher surface hardness compared to the base material, that when subjected to constant impacts due to the forging process suffered shedding of the material. It should be noted that for the laboratory results of Figure 4, the samples were only subjected to wear, and not to impacts. As explained by Castro et al. [13] nitriding time affects the performance of forging dies, thus the length of the nitriding treatment of this study created a hard layer that was too thick and with poor toughness causing the surface of die inserts to be susceptible to fractures by any minimal variation in the forging process. Therefore, future studies should focus on the optimization of the nitride layer thickness in order to take full advantage of this surface engineering technique in industrial applications.

The measurements of edge radii of the die inserts are shown in Figure 7. These results are consistent with those of the manufactured parts (Figure 5), where the nitrided die inserts presented a higher amount of wear due to the fractured edges of their forging surfaces causing unsatisfactory production. The E40K material showed the least amount of wear representing a decrease of 48.91% in comparison with the H13 material's results. Also, the lower standard deviation shows a better consistency of the results of the dies used for forging of brass products.

A similar trend in the amount of manufactured pieces was obtained for the parts that were rejected due to worn or fractured insert dies, as shown in Figure 8. In the case of H13, the smallest quantity of rejected products was obtained with nitrided H13 die inserts; however, this result is because the amount of manufactured parts by this material was also the lowest.

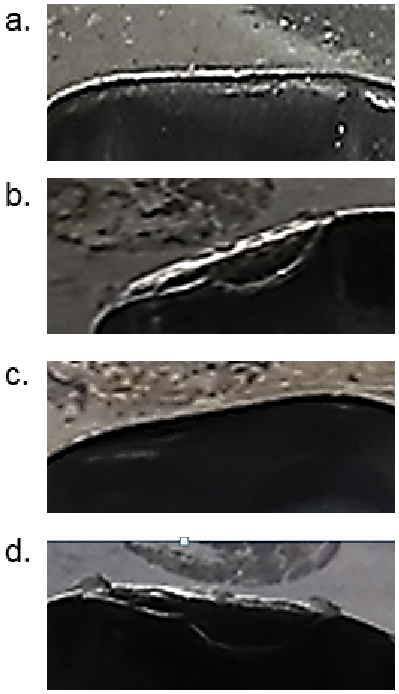

Fig. 6. Images of the edges of forging die inserts after manufacturing brass products: (a) H13, (b) H13 with nitriding, (c) E40K, (d) E40K with nitriding

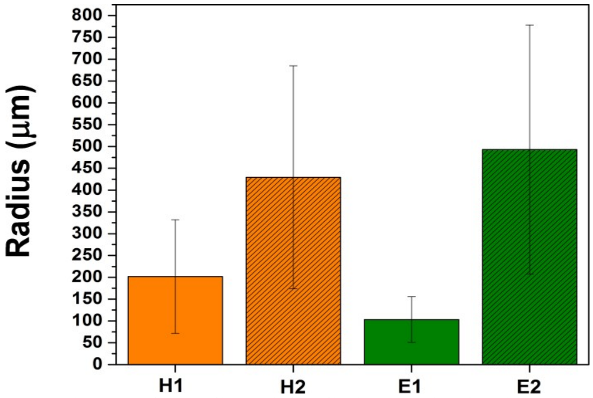

Fig. 7. Edge radius of the die inserts for forging manufactured of different materials

The results of the rejected parts of the E40K material with the nitriding treatment were also lower; therefore, the best result was obtained by the untreated E40K material with a 73% reduction in rejected pieces compared to H13 die inserts (figure 8). It should be kept in mind that a reduction in rejected pieces reduces costs and increases productivity of the forging process.

Figure 9 presents the results of equipment downtime during the forging tests, showing that the E40K inserts also had the best performance with a decrease of 51% in comparison with the H13 die inserts. The lower downtime by the nitride inserts, as previously explained, is due to the lower amount of manufactured parts and overall lower tool life.

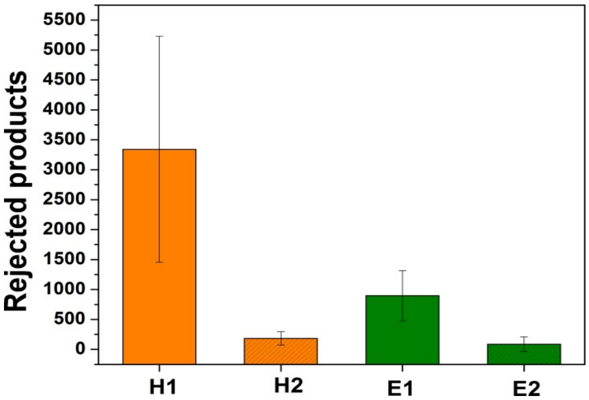

Fig. 8. Average number of rejected products for each material combination

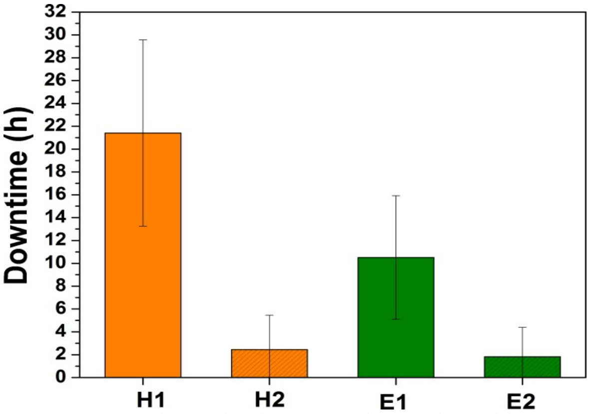

Fig. 9. Results of the downtime during the field test

The industry is constantly looking for reducing unnecessary downtime [18]. Equipment downtime, as explained by Holmberg and Erdemir [6] is part of the costs related to wear of tooling, in this case, the die inserts. Therefore, after the forging tests under industrial conditions, the results of this study show that hot-work tool steel E40K is a good candidate for fabricating die inserts with enhanced tool life, improving the overall efficiency of the process by reducing waste, reducing equipment downtime and maintenance, and increasing the amount of manufactured pieces.

4. CONCLUSIONS

Laboratory tests performed in a block-on-ring tribostester showed that Thermodur E40K had higher wear resistance than H13, and thus could be a good alternative for forging die inserts. Also, nitriding thermochemical treatment demonstrated the best tribological performance in laboratory tests. However, in forging tests of brass products under industrial conditions, it was found that the application of the nitriding thermochemical treatment on both materials was detrimental to the forging die inserts´ performance. This was due to the increase on the surface hardness and due to high thickness of the nitrided layer resulting in fractures of forging die dies.

Thermodur E40K steel presented the best results in the industrial forging tests, achieving an increase of 67% in the manufactured parts, a 73% reduction in the amount of rejected parts and a 51% reduction in equipment downtime, compared to H13 die inserts that are commonly employed in the industry for forging processes.

5. ACKNOWLEDGEMENT

The authors acknowledge the support of Plomaq and Institute of Materials Engineering, Faculty of Mechanical Engineering, Cracow University of Technology for this project.

6. REFERENCES

1. Kchaou, M., Elleuch, R., Desplanques, Y., Boidin, X., Degallaix, G., (2010). *Failure mechanisms of H13 die on relation to the forging process - A case study of brass gas valves*, Eng. Fail. Anal., **17**(2), 403-415
2. Schwingenschlögl, P., Niederhofer, P., Merklein, M., (2019). *Investigation on basic friction and wear mechanisms within hot stamping considering the influence of tool steel and hardness*, Wear, **426-427** (Part A), 378-389.
3. Bayramoglu, M., Polat, H., Geren, N., (2008). *Cost and performance evaluation of different surface treated dies for hot forging process*, J. Mater. Process. Technol., **205**(1–3), 394–403.
4. Hawryluk, M., (2016). *Review of selected methods of increasing the life of forging tools in hot die forging processes*, Arch. Civ. Mech. Eng., **16**(4), 845–866.
5. Phakatkar, H. H., Ghorpade, R. R., (2009). *Tribology*, 2nd ed. Nirali Prakashan (Maharashtra).
6. Holmberg, K., Erdemir, A., (2017). *Influence of tribology on global energy consumption, costs and emissions*, Friction, **5**(3), 263–284.
7. Fradinho, J., Nedelcu D., Gabriel-Santos, A., Gonçalves-Coelho, A., Mourão, A., (2015). *Some trends and proposals for the inclusion of sustainability in the design of manufacturing process* IOP Conf. Series: Materials Science and Engineering, **95**, 1-6. 012142
8. Mindru, T.D., Filip, I., Nedelcu, D., (2010). *CAE system importance in cutting tools,* ModTech-New Face of TMCR, 395-399

9. Gronostajski, Z., Hawryluk, M., Widomski, P., Kaszuba, M., Nowak, B., Polak, S., Rychlik, M., Ziemba, J., Zwierzchowski, M. et al., (2019). *Selected effective methods of increasing the durability of forging tools in hot forging processes*, Procedia Manuf., **27**, 124–129.

10. Kalpakjian, S., Schmid, S., (2016). *Manufacturing Processes for Engineering Materials,* (N.Y., USA: Pearson Education).

11. Pérez, M., Belzunce, F. J., (2016). *A comparative study of salt-bath nitrocarburizing and gas nitriding followed by post-oxidation used as surface treatments of h13 hot forging dies,* Surf. Coat.Tech. **305**, 146-157.

12. Klocke, F., Arntz, K., Teli, M., Winands, K., Wegener, M., Oliari, S., (2017). *State-of-the-art laser additive manufacturing for hot-work tool Steels,* Procedia CIRP, **63**, 58–63.

13. Castro, G., Fernández-Vicente, A., Cid J., (2007). *Influence of the nitriding time in the wear behaviour of an AISI H13 steel during a crankshaft forging process,* Wear, **263**, 1375-1385.

14. Arai, T., (1992), *Tool materials and surface treatments*, Journal of Materials Processing Technology, **35**(3–4), 515-528.

15. Suchánek, J., Kuklík, V., (2009). *Influence of heat and thermochemical treatment on abrasion resistance of structural and tool steels,* Wear, **267**(11), 2100-2108.

16. Higuera, O., Tristancho, J., Florez, L., (2007). *Fundamentos Teóricos De Los Aceros Auteníticos Al Manganeso (Aceros Hadfield),* Sci. Tech., **34**, 231–236.

17. ASTM G77-17, *Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test*, ASTM International, West Conshohocken, PA, 2017, www.astm.org accessed on: 26 January 2020

18. Loria, K., (2013). *Reducing downtime in process systems*, World Pumps, **2013**(1), 19-20.

Received: March 14, 2020 / Accepted: June 15, 2020 / Paper available online: June 20, 2020 © International Journal of Modern Manufacturing Technologies