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A comparison of the performance of cold work tool steels used in die-making

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Abstract

Steel is one of the most common metals. In the die business, cold work tool steels (CWTS) are widely preferred. In addition to regular CWTS, next-generation CWTS have recently been used. This study investigates the use of classic and two new-generation CWTS as punch materials in pressing electric motor rotors. It has been discovered that new-generation CWTS have a longer lifespan than traditional ones. SEM and X-ray spectroscopy (EDS) were used to examine the microstructures, and the carbide structures they could produce were analyzed using FactSage® 8.2 thermodynamic software. The formation of fine and uniformly dispersed carbide structures and numerous carbide structures has been observed in the latest generation CWTS. These were thought to be the causes behind the CWTS's lengthy service life.

Key words: CWTS, material, punch rotor, carbide, FactSage

1. Introduction

Iron is the most important of all metals. It is the base metal used for producing a wide variety of steels, which are the most popular engineering materials of our time [1]. Although iron is important, it is mostly used in daily life in the form of its alloys, namely steel, in various compositions [2]. To make optimum use of steel materials in the automotive industry in Europe, they have announced targets for developing new products, improving production processes, and designing [3]. The latest trend in the automotive industry is to increase the use of advanced high-strength steel (AHSS) to increase fuel efficiency by reducing the weight of vehicles. To process these steels, it is necessary simultaneously for the steels, which are the main material of dieing, to be more durable than the processed steels for processes such as press forming, punching, and cutting. Tool steels are alloys used in forming and/or cutting and slitting both steels and non-ferrous metals and plastics [4]. With general acceptance, many international standards for many years, for example, AISI/ASTM A681: D2, TS BS EN ISO 4957: 1.2379/X153CrMo12, JIS G4404: SKD11 were used as suitable cold work tool steels (CWTS) and are still widely used. More successful results can be obtained with the new generation CWTS, which is developed as an alternative and referred to with special definitions given by the manufacturer. Some traditional and new-generation CWTS are given in Table 1 and Table 2.

If the die is continued to be used after its life has expired, burrs may occur in the parts produced. According to the ASTM standard, the definition of burr is defined as surface damage in the form of roughness and protrusion, which appears on the original surface between two touching solids, which can be distinguished macroscopically, whose location and characteristics are generally known, including material transport, and whose distinctive feature is defined by plastic deformation [5].

Considering tribological issues, tool-workpiece interaction is an important feature that affects product quality, process performance, and tool life. The contact and adhesion between two solid surfaces and the abrasiveness of a particle can be explained by the uncharged contact of the surfaces, the applied load causing plastic flow and cold welding, the sliding action

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Table 1. Conventional Cold Work Tool Steels (CWTS)

AISI A681	EN 4957	%C	%Si	%Mn	%Cr	%Mo	%V	%W
D6	1.2436	2.00–2.30	0.10–0.40	0.30–0.60	11.00–13.00	–	–	0.60–0.80
D3	1.2080	1.90–2.20	0.10–0.60	0.20–0.60	11.00–13.00	–	–	–
D2	1.2379	1.45–1.60	0.10–0.60	0.20–0.60	11.00–13.00	0.70–1.00	0.70–1.00	–
O2	1.2842	0.85–0.95	0.10–0.40	1.80–2.20	0.20–0.50	–	0.05–0.20	–
S1	1.2550	0.55–0.65	0.70–1.00	0.15–0.45	0.90–1.20	–	0.10–0.20	1.70–2.20

Table 2. New generation Cold Work Tool Steels (CWTS)

CODE	%C	%Si	%Mn	%Cr	%Mo	%V	Others %
S2	0.90	0.90	0.50	7.80	2.50	0.50	–
V2	0.50	0.90	0.45	7.20	1.40	1.20	Ni 0.30
C2	1.00	1.30	0.45	8.00	2.50	0.30	Ni 0.20
K2	1.10	1.00	0.50	8.00	2.10	0.50	Ni 0.20, Al 0.50, Nb 0.15

and the applied load producing strain hardening, and the displacement of the particles at the boiling point [6]. For example, the accumulation of worn materials in sheet metal forming processes can cause adhesion wear of sheet materials on the tool contact surface. This tribological problem, called "burr", often causes a loss of tolerance and affects product quality. It is known that the adhesion wear tendency is directly dependent on the quality of the steel, i.e., the chemical and phase structure of the tool steel. The carbide phase prevents adhesion to the matrix between each other due to critical metal-to-metal contact. However, it is difficult to separate the contribution of each phase to the wear mechanism in macro-scale tests. The size and distribution of carbides, carbonitrides, and nitrides are important parameters that affect tribological behavior, contributing to the adhesion and friction properties of the matrix and the final performance [7]. In Fig. 1, the factors affecting the mechanical and performance properties of steel are shown schematically [8].

In a study by Picas on traditional and new generation steels, based on the fatigue and fracture results and fractographic observations, the role of each microstructural component of tool steels and their effects on crack initiation was defined, in which the mechanisms of crack formation under static loads differ from those under static loads in material fatigue resulting in fracture. At static loads, cracks begin when the applied force is higher than the fracture strength of the carbide; tool steels with smaller and more homogeneously dispersed carbides show higher strength. Damage to the metallic matrix was observed under repeated loads. Stress fractures around carbides can be triggered and lead to fatigue-inducing cracks, for both conventional and new-generation tool steels, metallic matrix and different carbide properties and morphologies are responsible for fatigue [9].

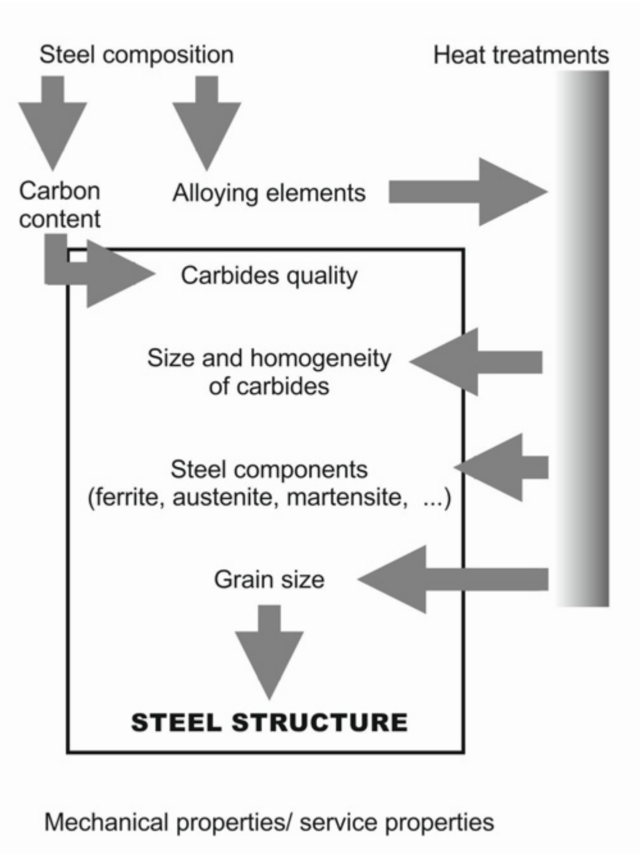

Fig. 1. Factors affecting the mechanical and performance properties of steel [8].

Material and material selection plays an important role in the engineering design process. The selection of suitable materials for a particular product is one of the important tasks for designers. To meet the final

Table 3. Chemical analysis of alloy elements of cold work tool steels used in the study

	%C	%Mn	%Si	%Ni	%Mo	%Cr	%V	%Al	%Nb
D2 (1.2379)	1.42	0.29	0.23	0.26	0.66	11.40	0.92	0.03	0.02
	1.41	0.44	0.23	0.39	0.62	10.86	0.63	0.02	0.03
	1.33	0.24	0.24	0.19	0.67	11.13	0.68	0.01	0.02
C2	0.79	0.25	0.93	0.17	1.86	7.30	0.21	0.02	0.01
	0.89	0.25	0.92	0.16	2.08	7.75	0.24	0.02	0.02
	0.95	0.26	0.95	0.15	2.31	7.97	0.27	0.02	0.02
K2	0.96	0.38	0.77	0.30	1.85	7.88	0.41	0.83	0.11
	1.08	0.41	0.86	0.18	2.07	8.28	0.46	0.30	0.11
	1.02	0.48	0.98	0.19	2.08	8.02	0.49	0.85	0.16

requirements of the product, designers need to analyze the performance of various materials and identify suitable materials with precise functions [10]. Electrical-Electronics, white goods, automotive etc. “Punches” are used for cutting/drilling processes during the manufacture of identical parts, and they are widely used in industries with various profiles. In this study, the performances of using traditional (AISI A681; D2) and new generation CWTS (C2 and K2) as die punches in the production of “rotor” and “stator” lamination used in electric motor production were compared.

2. Materials and methods

In this study, Tool Steels of dies used to produce “rotor” and “stator” lamination packages in electric motors from silica sheet material by Sheet Metal Forming were examined (EN 10341). The material used for producing sheets utilized in “stator” and “rotor” parts is called non-oriented electrical steel, which has a chemical composition in wt.%: Fe = 97.2 %, Si = 2.38 %, Mn = 0.12 %, P = 0.030 %, Al = 0.018 %, S = 0.018 %, N = 0.0053 %, Sn = 0.0531 %, O = 0.0068 %, C = 0.00 1 %, and other elements ~ 0.16 %. A representative initial microstructure of the non-oriented electrical steel is given in Fig. 2 based on the literature [11]. The Vickers microhardness of the non-oriented electrical steel was about 223 HV, similar to the Ref. [12]. The properties of the traditional D2 (1.2379) and the new generation CWTS were compared due to its multi-purpose and widespread use as a punch die material. Punch die materials were supplied by Mebsan Die & Wire Erosion company. Performance tests were carried out on press machines of Mebsan Kalip & Wire Erosion company. The chemical analysis values of three materials from each steel used in the study are given in Table 3.

Although the manganese (Mn) and nickel (Ni) ratios are similar in all steels, the carbon (C), chromium (Cr), and vanadium (V) ratios are lower, and the silicon (Si) and molybdenum (Mo) ratios are lower in the new generation CWTS. In the new generation K2 CWTS, aluminum (Al) and niobium (Nb) are added.

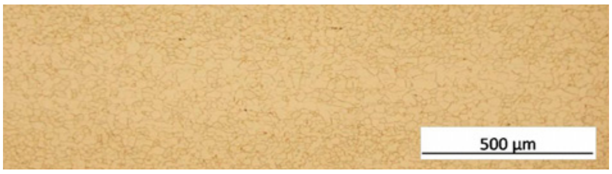

Fig. 2. Microstructure of non-oriented electrical steel [11].

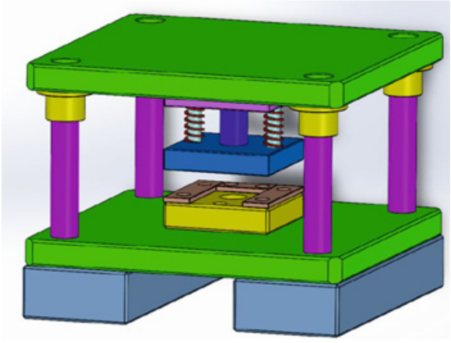

Fig. 3. Basic parts of sheet metal cutting die.

In Fig. 3, the basic parts of the sheet metal cutting die are shown schematically. The real parts of the die, punch, and sample of the produced “rotor” and “stator” parts are given in Fig. 4. The maximum number of parts that can be produced without causing burr formation was used to determine the life of 3 different CWTS used as punch material. In addition, Rockwell (HRC) hardness measurements were taken from the said punch materials and compared. Values are the average of 3 measurements. In addition, the microstructures of the punch materials were also examined with the help of a scanning electron microscope (SEM)/energy dispersive X-ray spectroscopy (EDS) (Zeiss Sigma 300 Gemini FEG SEM) by going through standard metallographic sample preparation

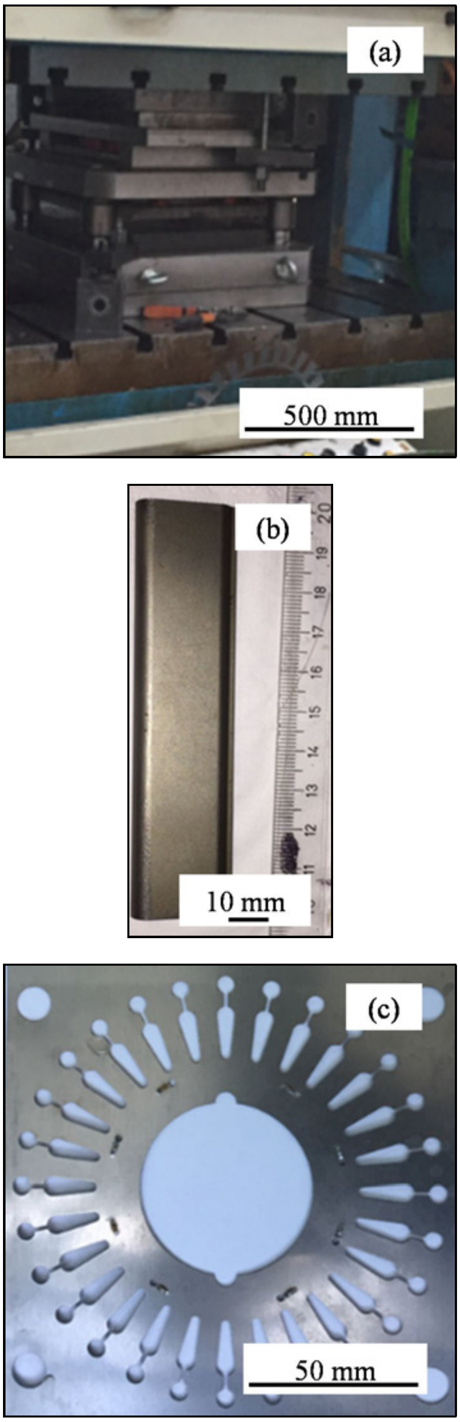

Fig. 4. (a) sheet metal cutting die used in the study, (b) the punch used, and (c) the sample piece printed.

procedures. The carbide structures that may occur in the CWTS were investigated with the FactSage® 8.2 thermodynamic analysis program.

3. Results and discussion

D2, C2, and K2 tool steels were used to print the same rotor parts used in electric motors and made of silicon steel. The most important finding that determines the life of the punch is the deterioration that occurs in the punch after a certain number of printing and the burrs in the parts produced as a result. According to the punch materials used, the number of parts that can be printed without any burr problems is given in Table 4. The traditional tool steel with the shortest lifetime is D2. However, the one that offers the longest service life is the new generation K2 tool steel.

Table 4. Number of products that can be printed by punch material

Punch material	Number of products that can be printed
D2 (1.2379)	112 500
C2	203 000
K2	224 000

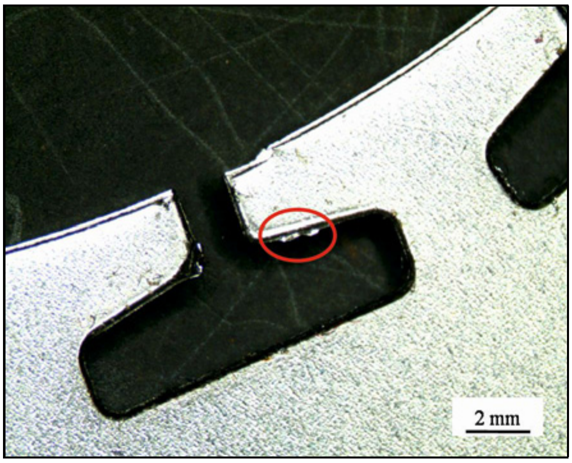

Fig. 5. Macro view of the part printed with end-of-life punches (burr formation is circled in red).

Table 5. Hardness values measured according to the punch material

Punch material	Hardness (HRC)
D2 (1.2379)	60.4
C2	61.2
K2	61.7

In Fig. 5, the macro image of the piece obtained with the punches that continue to be used after reaching the maximum number of prints is given. When the punches are used after this point, burr formation starts in the product, and the product quality deteriorates. This situation is also called friction adhesion or adhesion wear [13].

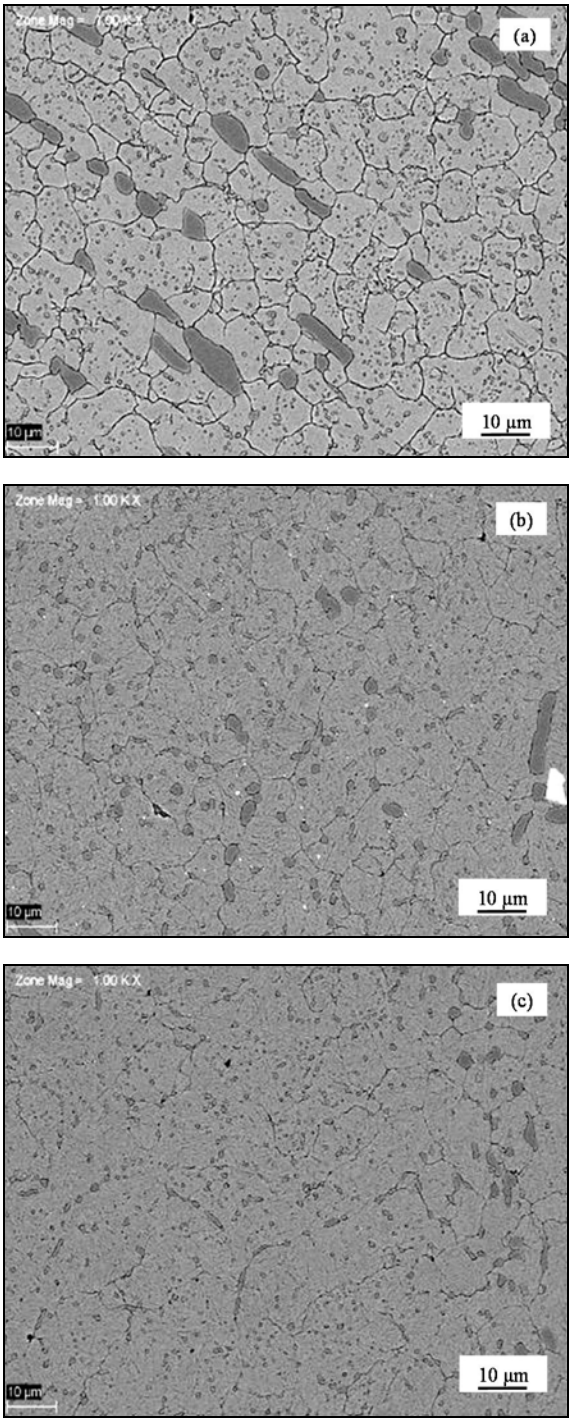

Fig. 6. CWTS scanning electron microscope microstructure images (a) D2, (b) C2, and (c) K2.

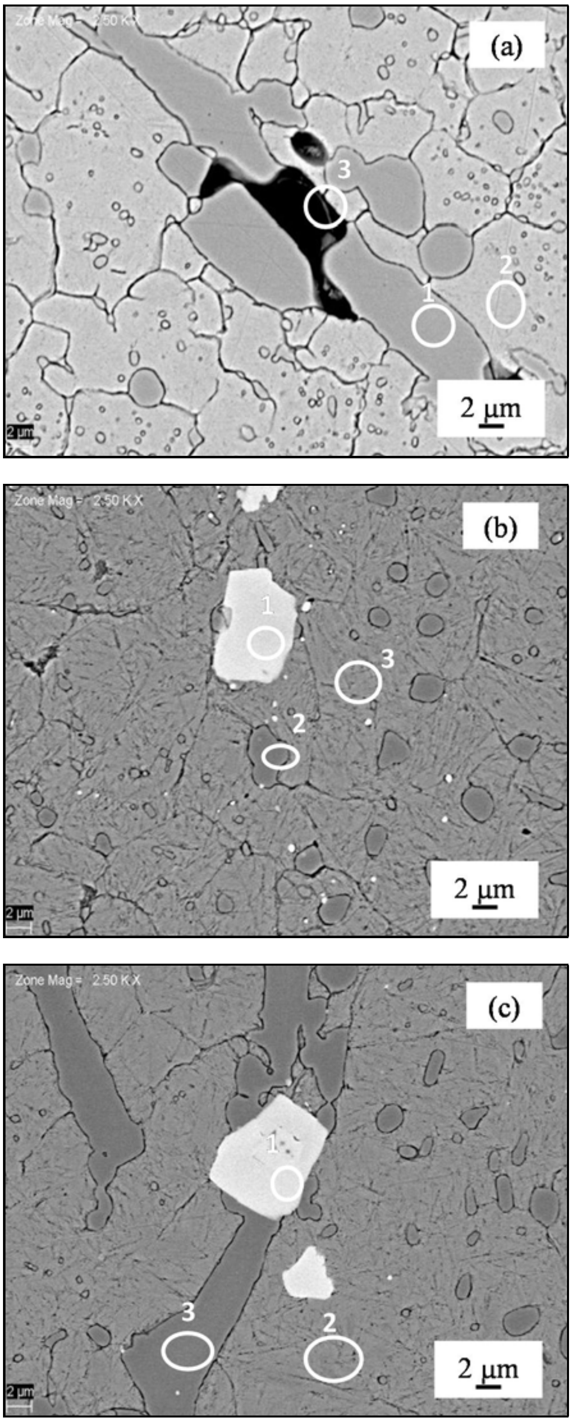

Fig. 7. Microstructure images for SBA scanning electron microscope elemental analysis (EDS).

Average hardness values of punch materials are given in Table 5.

SEM microstructure images of CWTS are given in Fig. 6. While it is observed that the main carbide structures of D2 conventional steel are coarse-grained and less homogeneous, it is observed that the carbide structures of the new generation CWTS, C2, and K2, are finer and homogeneously distributed. Different studies have determined that the finer and homogeneous distribution of carbide structures has a positive effect on wear resistance and mechanical properties [14, 15]. Thin and evenly dispersed carbide structures also increase the toughness [16]. Fukaura et al. reported a significant improvement in fatigue fracture

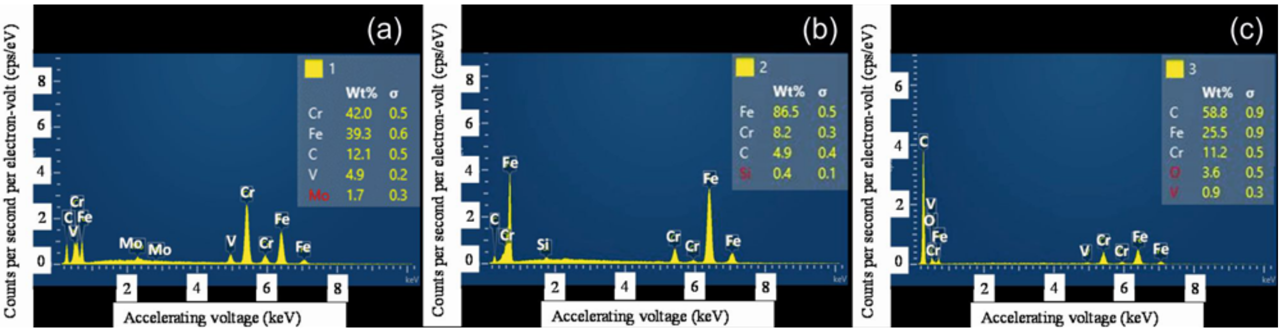

Fig. 8. EDS analysis results of areas 1, 2, and 3 taken from the SEM microstructures of the CWTS given in Fig. 7: (a) D2, (b) C2, and (c) K2.

toughness and Charpy C-notch toughness of a modified CWTS compared with a conventional one, attributed to the refinement and volume reduction of primary carbides in modified CWTS where the fracture initiation occurs at larger stress [17]. The beneficial effect of the small globular carbides with a higher population density on the resistance to brittle fracture for Cr-V ledeburitic steel was also illustrated [18]. Considering this context, the longer service life of C2 and K2 steels compared to D2 can be associated with a finer and homogeneous distribution of carbides. In addition, as given in Table 5, it is seen that the hardness values of the new generation CWTS are 1.32 and 2.15 % higher than the traditional D2.

In addition, the microstructure and analysis results of the SEM-EDS elemental analyses performed on the microstructures of D2, C2, and K2 steels in this study are given in Fig. 7 and Fig. 8, respectively.

In Fig. 7, the selected regions for EDS elemental analysis are shown in white circles. In conventional D2 steel, the main carbide structures consist of the M7C3 system. These can be chromium-weighted, vanadium-supported carbide structures [19]. Figure 8a shows the results of elemental analysis 1 also support this situation. Unlike the traditional CWTS D2, C2, and K2, which are the new generation CWTS, show that the bright-grained coarse-grained carbides shown with the number 1 in Fig. 7b,c are shown in Fig. 8b,c. It can be seen that there are niobium-doped carbide structures, and hard carbide structures contribute positively to mechanical properties such as wear resistance [16]. However, when the main carbide structures are examined (Fig. 6a number 1, Fig. 7b number 2, and Fig. 7c number 3), it is seen from the elemental analyses given in Figure 8 that the new generation CWTS carbides are enriched in molybdenum.

The phases of D2, C2, and K2 CWTS, which were studied with the FactSage® 8.2 software program, one of the world's largest fully integrated database information processing systems in the field of chemical thermodynamics, are given below. Accordingly, the active phase at temper temperatures is M7C3 in conventional D2 steel and M23C6 in new generation C2 and K2 steels. The effect of molybdenum on active carbide phases is seen in the new generation SIT (Table 6). Liu et al. [21] systematically investigated the mechanical properties and electron and bond structures of M23C6-type multicomponent carbides and analyzed the results by comparing them with the available theoretical and experimental data. Accordingly, M23C6 (M = Fe, Cr, Mn) multicomponent carbides are thermodynamically stable. In general, it has been stated that M23C6-type carbides in steels are generally structured using various other metallic elements as mixed precipitates, and M23C6 compounds have high melting point and hardness due to combinations of metallic and covalent bonds. Considering that hardness is an important parameter to characterize the wear resistance of the material, it can be concluded that Fe21Mo2C6 from this group is harder and more brittle than other carbides, and therefore, it is an ideal wear-resistant material, and as a result, it contains molybdenum (Mo) or iron (Fe). It reveals that the mechanical properties of M23C6 compounds are superior to the pure phases of Cr23C6, Mn23C6, and Fe23C6 [21]. Considering this context, the higher performance obtained in the new generation CWTS in this study can be associated with M23C6 (M = Fe, Cr, Mn) multicomponent carbides.

Table 6. According to FactSage analysis – carbides that may occur in CWTS

D2		C2		K2	
Carbide	%	Carbide	%	Carbide	%
Cr_7C_3	77.1	$Cr_{20}Mo_3C_6$	39.6	$Cr_{20}Mo_3C_6$	43.9
Fe_7C_3	18.6	$Fe_{20}Mo_3C_6$	34.7	$Fe_{20}Mo_3C_6$	37.5
V_7C_3	2.9	$Cr_{20}Fe_3C_6$	6.5	$Cr_{20}Fe_3C_6$	4.4
Mn_7C_3	1.4	$Fe_{23}C_6$	5.8	$Fe_{23}C_6$	3.8
		$Cr_{23}C_6$	6.5	$Cr_{23}C_6$	4.7
		$Fe_{20}Cr_3C_6$	5.7	$Fe_{20}Cr_3C_6$	4.0
		Other (V, Mn, Ni)	1.2	$Cr_{20}Mn_3C_6$	0.9
				$Fe_{20}Mn_3C_6$	0.8

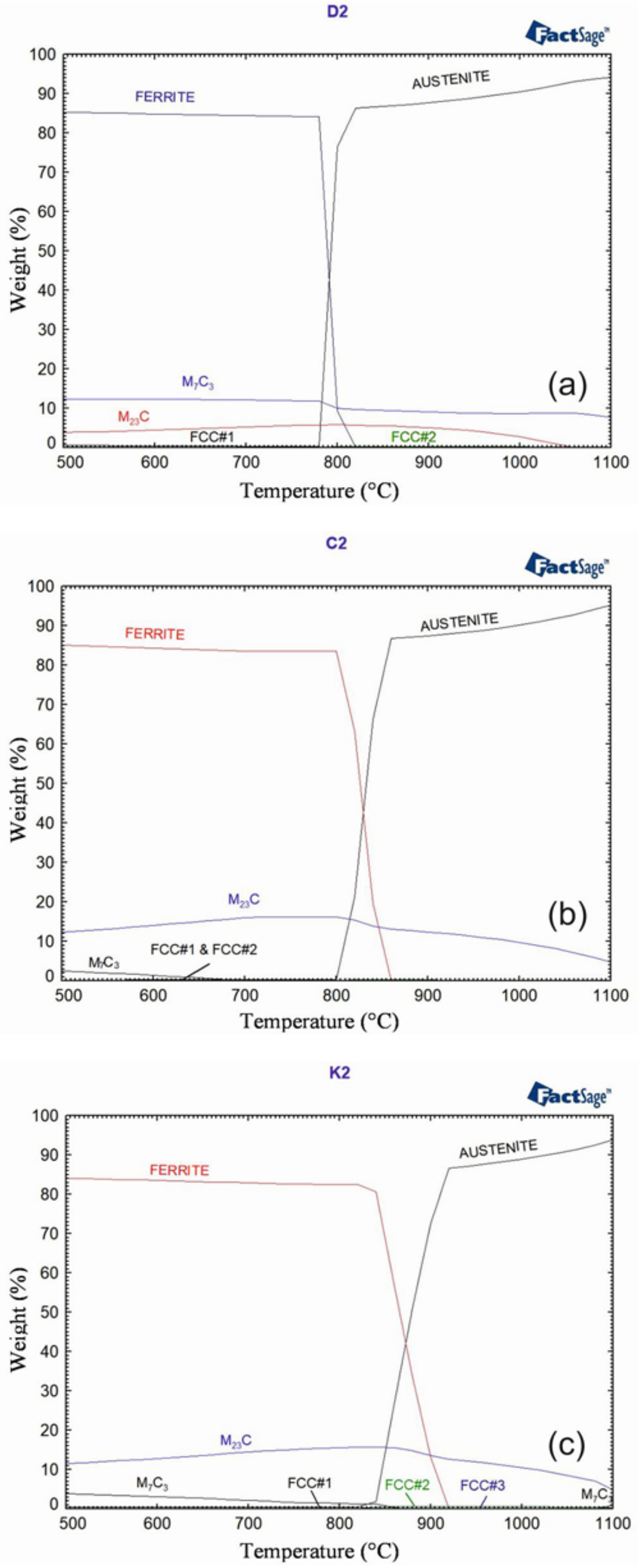

Fig. 9. FactSage phase diagrams of temperature-weight percentage of CWTS (a) D2, (b) C2, and (c) K2.

As a result, it is thought that the multi-carbide structures and fine and homogeneously dispersed carbides formed in the new generation CWTS affect prolonging the life of the punch material.

4. Conclusions

In this study, the use of traditional and new generation CWTS as punch material in the production of rotor parts used in electric motors is compared. It has been observed that the new generation CWTS reaches higher print numbers and offers a longer service life than the traditional one. The microstructures of the punch materials were investigated with the help of SEM/EDS, and it was observed that the main carbides were finer and homogeneously dispersed in the new generation CWTS than in the traditional ones. In addition, carbide structures enriched in niobium (Nb) and molybdenum (Mo) were observed in new-generation steels. It is evaluated that these differences in carbide structures allow the new generation CWTS to offer a longer life.

References

[1] K. H. Prabhudev, Handbook of Heat Treatment of Steels. McGraw-Hill, New Delhi, 1988. ISBN 0074518313

[2] R. C. G. H. N. Gupta, A. Mittal, Manufacturing Processes, second ed., New Age International, New Delhi, 2009. ISBN (13) 978-81-224-2844-5

[3] M. Jeanneau, P. Pichant, The trends of steel products in the European automotive industry, Metall. Res. Technol. 97 (2002) 1399–1408. https://doi.org/10.1051/metal:2000118

[4] G. A. Roberts, R. Kennedy, G. Krauss, Tool Steels, fifth ed., ASM International, 1998. ISBN 1615032010

[5] ASTM G40-22a, Standard Terminology Relating to Wear and Erosion, ASTM International, 2022.

[6] J. A. Collins, Failure of Materials in Mechanical Design Analysis, Prediction, Prevention, second ed., John Wiley, New York, 1993. ISBN 0471558915

[7] A. Norrby, Nanotribological characterization of advanced tool steels, M.Sc. Thesis, Karlstad University, Sweden, 2010.

[8] J. B. D. Viale, F. Chenou, G. Baron, Optimizing microstructure for high toughness cold-work tool steels, 6th International Tooling Conference, Karlstad, Sweden, (2002), pp. 299–318. ISBN 978-918-94228-2-7

[9] I. Picas, Mechanical Behaviour of Tools, Microstructure on Fatigue, Fracture and Damage, Ph.D. Thesis, Universitat Politècnica de Catalunya, Spain, 2012.

[10] M. F. Ashby, Materials Selection in Mechanical Design, fifth ed., Elsevier Science, 2016.

[11] I. Petryshynets, F. Kováč, B. Petrov, L. Falat, V. Puchý, Improving the magnetic properties of non-oriented electrical steels by secondary recrystallization using dynamic heating conditions, Materials 12 (2019) 1914. https://doi.org/10.3390/ma12121914

[12] H. Wang, Y. Zhang, S. Li, Laser welding of laminated electrical steels, J. Mater. Process. Technol. 230 (2016)

99–108.
https://doi.org/10.1016/j.jmatprotec.2015.11.018

[13] L. Kirkhorn, V. Bushlya, M. Andersson, J. E. Ståhl, The influence of tool steel microstructure on friction in sheet metal forming, Wear 302 (2013) 1268–1278. https://doi.org/10.1016/j.wear.2013.01.050

[14] D. A. Porter, K. E. Easterling, Phase Transformations in Metals and Alloys. Third ed. (Revised Reprint), Taylor & Francis, Cheltenham, 1992. ISBN 0748757414

[15] K. Miao, Y. He, N. Zhu, J. Wang, X. Lu, L. Li, Coarsening of carbides during different heat treatment conditions, J. Alloys Compd. 622 (2015) 513–523. https://doi.org/10.1016/j.jallcom.2014.10.115

[16] S. Farahany, M. Ziaie, N. A. Nordin, Effect of triple tempering temperature on microstructure, mechanical, and wear properties of K340 cold work tool steel, J. of Mater. Eng. and Perform. 32 (2023) 9000–9010. https://doi.org/10.1007/s11665-022-07791-4

[17] K. Fukaura, Y. Yokoyama, D. Yokoi, N. Tsujii, K. Ono, Fatigue of cold-work tool steels: Effect of heat treatment and carbide morphology on fatigue crack formation, life, and fracture surface observations, Metall. Mater. Trans. A. 35 (2004) 1289–1300. https://doi.org/10.1007/s11661-004-0303-5

[18] P. Jurči, J. Ďurica, I. Dlouhý, J. Hornik, R. Planieta, D. Kralovič, Application of −140 °C sub-zero treatment for Cr-V ledeburitic steel service performance improvement, Metall. Mater. Trans. A 50 (2019) 2413–2434. https://doi.org/10.1007/s11661-019-05180-6

[19] D. Casellas, J. Caro, S. Molas, J. M. Prado, I. Valls, Fracture toughness of carbides in tool steels evaluated by nanoindentation, Acta Mater. 55 (2007) 4277–4286. https://doi.org/10.1016/j.actamat.2007.03.028

[20] G. Z. S. Wilmes, Effect of niobium and vanadium as alloying element in tool steels with high chromium content. 6th International Tooling Conference, Karlstad, Sweden (2002), pp. 269–287. ISBN 978-918-94228-2-7

[21] Y. Liu, Y. Jiang, J. Xing, R. Zhou, J. Feng, Mechanical properties and electronic structures of M23C6 (M = Fe, Cr, Mn)-type multicomponent carbides, J. Alloys Compd. 648 (2015) 874–880.
https://doi.org/10.1016/j.jallcom.2015.07.048