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SYNERGY BY MOLYBDENUM AND NIOBIUM ON PERFORMANCE OF COLD WORK TOOL STEELS

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ABSTRACT

For the die industry, where future products have a decisive role in material selection, the subject of steel is an area of interest with high innovation potential. With new production and processing technologies that prioritize knowledge, the quality of materials has improved significantly, and these developments continue. Material selection in die design is a crucial aspect of engineering aimed at developing sustainable and effective solutions to technical challenges. Die manufacturing is open to innovation as the main input is steel. Cold work tool steels (CWTS) are frequently preferred in the die industry. Recently, in addition to traditional CWTS, next-generation CWTS systems have been introduced into use. This article examines the application of one conventional and two next-generation CWTS units as punch tools in sheet metal pressing and thread rolling die for screw manufacturing It has been observed that the new-generation CWTS offers a longer lifespan compared to the traditional one. The microstructures were investigated, and the fine and evenly distributed multiple carbide structures that they can form were evaluated using FactSage® thermodynamic software. The carbides in new-generation CWTS were also rich in molybdenum and niobium. With the use of next-generation materials, modern heat treatments, and advanced coating technologies, it is possible to design specialized products tailored to each specific application. For the innovation approach of modern tool steels in the context of cold-forming dies, traditional and new-generation Cold Work Tool Steels (CWTS) were compared in terms of chemical composition and the use of refractory metals as alloying elements, and their performances were evaluated and interpreted.

Keywords: refractory metals, tool steels, carbides

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1. INTRODUCTION

The word refractory comes from the Latin root "refractorius" and means resistant to high temperatures. Among the many elements that can alter the properties of alloy steels—whose production dates back over a century—*refractory metals* (RM) have particularly significant effects. There are various scientific and commercial studies concerning which metals should be classified as refractory metals (RM), with the number of considered elements ranging from 5 to 14. The melting points of RM are higher than their oxides. They have a body-centered cubic (BCC) structure. According to Calister, niobium, molybdenum, tungsten, and tantalum are classified as refractory metals [1]. ASM Handbook and Habashi also include hafnium, vanadium, chromium, zirconium, and titanium [2, 3]. The International Journal of Refractory Metals and Hard Materials defines RM as metals with melting points above 1850°C [4].

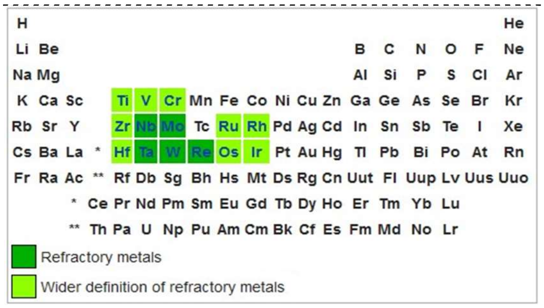


Figure 1. Refractory metals, all [5]

In steels containing both molybdenum and niobium, morphological benefits are particularly evident during thermomechanical processes applied after solidification, such as hot rolling or forging. In low-carbon steels, more successful results are obtained with the addition of boron. The total synergistic effect of niobium and molybdenum is more than the sum of the impacts of each one individually [6]. In another new study completed in 2022, where the words molybdenum, niobium, and synergy are frequently used together; by the addition of these two metals and boron as an alloying element, the gains were examined thermodynamically and phase transformations kinetically. Refined texture provided by the grain reduction effect of the Mo-Nb duo on the microstructure, the contribution of the increases in hardness and toughness properties to ultra-durable steel production was determined. The series of benefits that begin in the controlled hot rolling stage continues in heat treatments such as annealing, quenching, and tempering [7].

Mo and Nb are common elements that improve the microstructure even when used in small amounts, both alone and together. They contribute to mechanical properties with grain reduction and precipitation, providing benefits. With the carbides or carbonitrides they form, hardenability increases starting from the thermomechanical process stage [8].

When it comes to tool steel, the first thing that comes to mind is "carbide". In all tool steels, the main priority of the alloying elements is to create wear-resistant carbide structures formed by alloying elements within the main matrix of iron. The carbides are the actors that provide different properties to tool steel compared to other types of steel. Carbides work as strength agents, but they can also act as crack initiation sites [9].

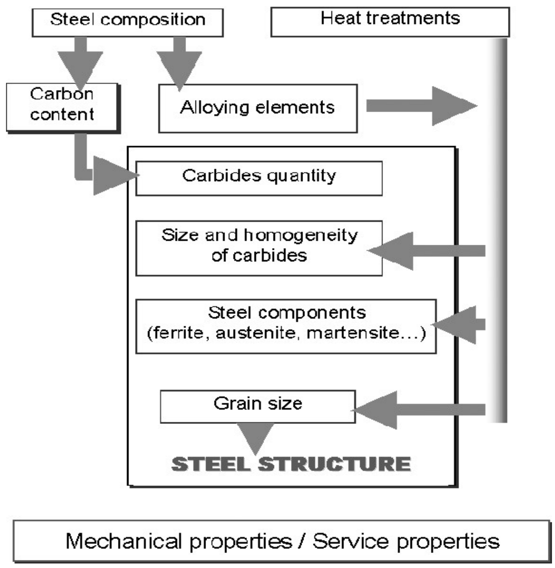


Figure 2. Carbide-structure-property relation [10]

The physical and chemical structures of carbides and how they are distributed in the matrix directly affect the mechanical properties of steel. Depending on the heat treatment and carbon content, seven types of carbides can form, generally represented by the elemental metal symbol 'M'; MC, M_2C, M_3C_2, M_5C_2, M_7C_3, M_6C, and $M_{23}C_6$. M_2C is rich in molybdenum, M_7C_3 is rich in chromium, M_6C is rich in iron and molybdenum and is found close to the outer surfaces. However, other types of carbides are found everywhere [11].

The following transformations occur during the tempering of different M_xC_y carbides;

$$M_3C \rightarrow M_2C \rightarrow M_{23}C_6, \text{ and/or} \quad (1)$$
$$M_3C \rightarrow M_7C_3 \rightarrow M_{23}C_6 \quad (2)$$

This leads to an additional increase in wear resistance [12]. $M_{23}C_6$ is the most thermodynamically stable among Cr-containing carbides. Therefore, it is understood that $M_{23}C_6$ phases will be more durable in wear behavior [13]. To bring together the wear behavior and fracture resistance at the most appropriate point, a microstructure that provides the optimum between the hardness and fracture toughness behaviors of the different primary carbides in the steel should be provided by selecting the most suitable carbide type [14].

2. MATERIALS AND METHOD

Conventional AISI D2 series tool steels have excellent wear resistance and non-deformability, making them very useful as cold work die steels. They are widely used in cold-forming dies. Among these, D2 Steel is by far the most popular grade [15].

New Generation CWTS is offered to users with the names given by the manufacturing companies. Since not only chemical composition but also factors such as heat treatment, mechanical processing, and surface treatments affect product satisfaction, these products, which are patented and not included in the standards, are used instead of company and product names as codes C2 and K2 to avoid a positive or negative perception.

Chemical compositions of 9 products, 3 from each of three different steel types, traditional AISI D2 (1.2379) and new generation C2 and K2 steels were determined and 32 elements were measured with 0.0001% precision by ARL 8860 Optical Emission Spectrometer at R&D Center of MATIL Material Testing and Innovation Laboratories Inc. at Istanbul Technical University (ITU) according to ASTM E415, is shown at Table 1:

Table 1. Analysis of traditional D2 (1.2379) and new generation C2 and K2 steels

D2															
C	Mn	Si	S	P	Cu	Ni	Mo	Cr	V	Co	B	N	Al	Ti	W
1,4194	0,2916	0,234	0,004	0,023	0,133	0,255	0,658	11,396	0,918	0,017	0,00021	0,0177	0,026	0,002	0,028
As	Sn	Pb	Sb	Ta	Zr	Bi	Ca	Mg	Te	Zn	Ce	La	Nb	O	Fe%
0,0068	0,0065	0,002	0,007	1E-04	0,004	0,002	0,015	0,0101	0,002	0,0044	0,0001	0,0002	0,023	0,005	84,5

C2															
C	Mn	Si	S	P	Cu	Ni	Mo	Cr	V	Co	B	N	Al	Ti	W
0,7912	0,2468	0,927	0,002	0,008	0,146	0,166	1,862	7,2964	0,211	0,0167	0,00032	0,0102	0,019	0,002	0,01
As	Sn	Pb	Sb	Ta	Zr	Bi	Ca	Mg	Te	Zn	Ce	La	Nb	O	Fe%
0,0081	0,0085	0,002	0,007	1E-04	0,003	0,003	0,054	0,0096	0,001	0,0026	0,0041	0,0001	0,015	0,001	88,18

K2															
C	Mn	Si	S	P	Cu	Ni	Mo	Cr	V	Co	B	N	Al	Ti	W
0,9641	0,3802	0,775	6E-04	0,01	0,079	0,3	1,853	7,8788	0,409	0,0449	0,00045	0,0141	0,834	0,002	0,07
As	Sn	Pb	Sb	Ta	Zr	Bi	Ca	Mg	Te	Zn	Ce	La	Nb	O	Fe%
0,004	0,0059	0,002	0,009	1E-04	0,004	0,003	0,019	0,0112	0,002	0,0028	0,0043	0,0001	0,111	0,006	86,22

An analysis of all chemical compositions reveals differences between conventional and new-generation CWTS, as well as among the various types of new-generation CWTS themselves. When examined all together;

- It is seen that the manganese (Mn) and nickel (Ni) ratios are similar and close in all.
- New-generation CWTS C2 contains lower amounts of carbon, chromium, and vanadium.
- New-generation CWTS C2 contains higher amounts of silicon and molybdenum.
- New-generation CWTS K2 steel contains aluminum (Al) and niobium (Nb) additions.

By obtaining very high-quality steels with codes D2, C2, and K2;

- three different punches for the manufacture of electric motors lamination rotor sheets from 0.50 mm non-oriented electrical steel (EN 10341), having Vickers microhardness of about 223 HV were manufactured (Figure 3), and

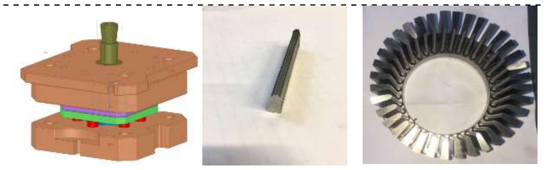


Figure 3. Die press, a single punch, and a set of 36 punches

- three different thread rolling die sets (fixed die; mm 25.2x52x105 and movable die; mm 25.2x52x90) for the manufacture of Ø4x50 mm screws were manufactured (Figures 4 and 5).

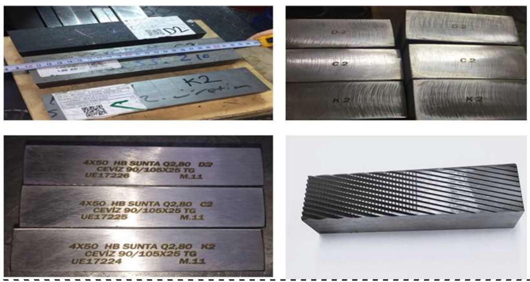


Figure 4. Raw and machined sets of thread-rolling dies

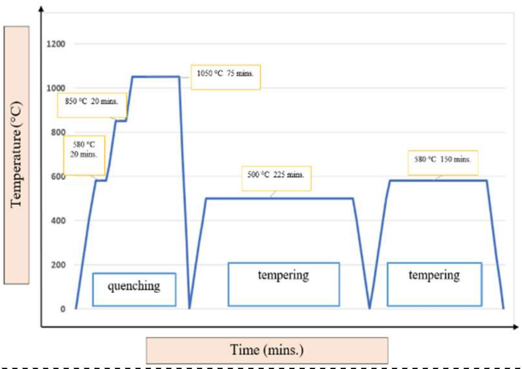


Figure 5. The heat treatment procedures applied

3. RESULTS

Upon performance, tests were carried out the number of reached products during each manufacture is shown in Table 2.

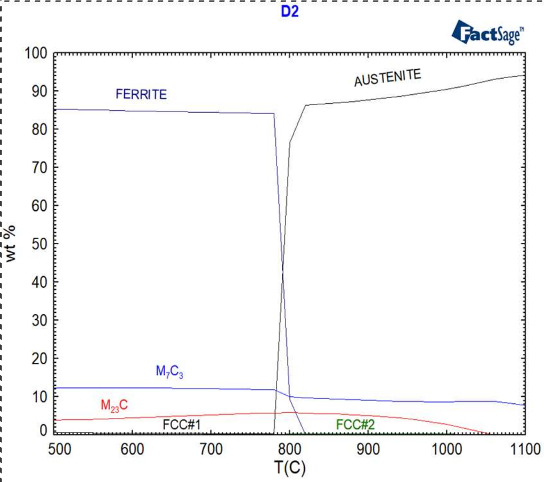
Table 2. Results of pieces manufactured by D2, C2 and K2 CWTS

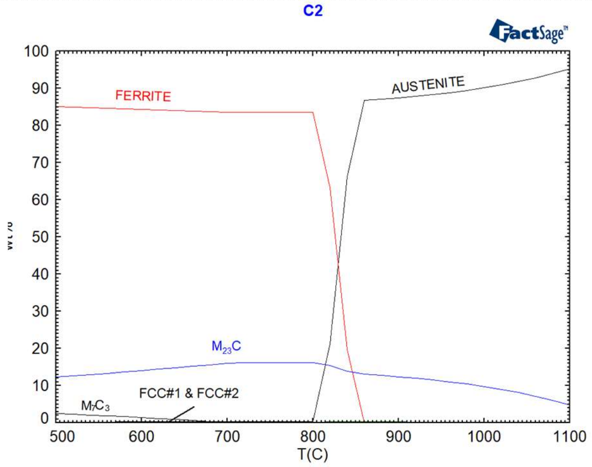
	As punch material	As thread rolling die
D2 (1.2379)	112.500	983.800
C2	203.000	1.406.000
K2	224.000	1.861.100

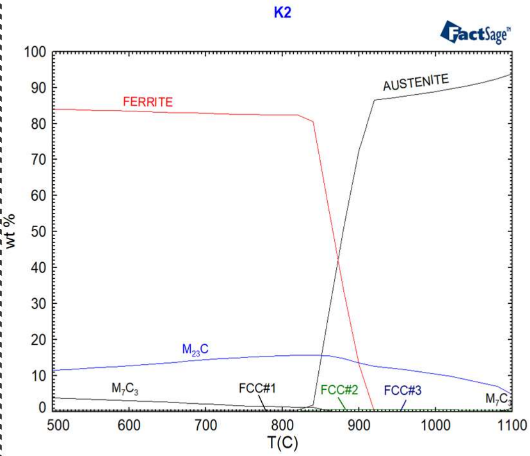
FactSage® is a fully integrated thermochemical optimization and modeling information processing system that encompasses Iron-Steel databases with processing modules in materials science, corrosion, glass technology, ceramics, and other fields, particularly metals. It enables a detailed examination of phase formations as they relate to temperature (Figure 6).

A phase diagram was drawn and the phases formed were determined. The amounts of carbides at the tempering temperatures of the D2, C2, and K2 were calculated. Generally, various carbide combinations determine mechanical properties. Mainly M_7C_3 and $M_{23}C_6$ type carbides were taken as the basis.

The effective phase at tempering temperatures is M_7C_3 with 71% in traditional D2 steel, and $M_{23}C_6$ with 90.9% and 75.2% in new generation C2 and K2 steels, respectively. The ratio of chromium carbide (Cr_7C_3) in D2 steel is 54.8%, which is higher than the total of all other carbide formations. Fe_7C_3 is also formed in this steel, with a ratio of 18.6% in its group and 13.2% in the whole steel (Figure 7). Here, the weight and effect are formed by Chromium Carbide (77%), Iron Carbide (11%), and Vanadium Carbide (3%), respectively. Although the weight is in this group, 3 out of every 4 carbides formed in D2 steel (24.1%) are $M_{23}C_6$. The effect of molybdenum is seen here: They are triple carbide clusters formed by molybdenum with chromium (41%) and iron (35%), with a total ratio of 76%.







D2		C2		K2	
Carbide	%	Carbide	%	Carbide	%
Cr7C3	77.1	$Cr_{20}Mo_3C_6$	39.6	Cr20Mo3C6	43.9
Fe7C3	18.6	$Fe_{20}Mo_3C_6$	34.7	Fe20Mo3C6	37.5
V7C3	2.9	$Cr_{20}Fe_3C_6$	6.5	Cr20Fe3C6	4.4
Mn7C3	1.4	$Fe_{23}C_6$	5.8	Fe23C6	3.8
		$Cr_{23}C_6$	6.5	Cr23C6	4.7
		$Fe_{20}Cr_3C_6$	5.7	Fe20Cr3C6	4.0
		Other (V,Mn, Ni)	1.2	Cr20Mn3C6	0.9
				Fe20Mn3C6	0.8
Total	100.0		100.0		100.0

Figure 6. FactSage® thermodynamic software carbide phases and ratios of tested samples

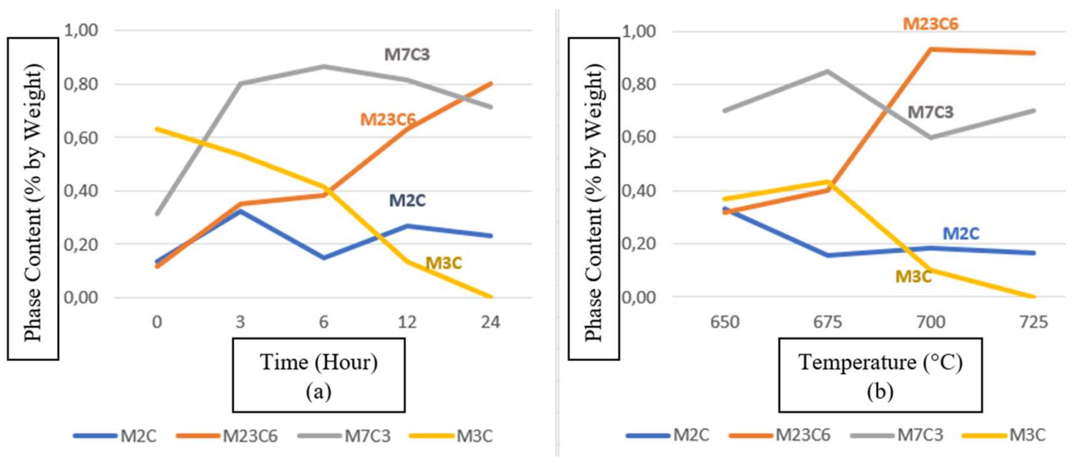


Figure 7. Changes in carbide ratios during tempering for (a) time and (b) temperature

In the New Generation CWTS, the active phases are phases formed by iron and chromium with molybdenum, 67.6% in C2 and 61.2% in K2. Here, the effect of molybdenum is seen clearly. The triple carbide clusters formed by molybdenum with chromium and iron are more than all other total carbides.

In all tool steels, a large number of carbides are formed, which make the steel unique with its microstructure, the amount of metallic elements it contains, and its morphology are different from each other. The most common carbide types encountered in the melting and casting stages in CWTS are M_2C, M_3C, M_7C_3, and $M_{23}C_6$ carbides. During heat treatments, these carbides depending on the heating rate, reached temperature, cooling rate, and time of holding at that temperature dissolved and transformed into their final form in the matrix, taking their place in the texture. During tempering, M_2C and M_3C decrease first, while M_7C_3 and $M_{23}C_6$ ratios increase. These transformations in carbides provide improvements in mechanical properties. Microcarbide islands improve performance [16].

4. CONCLUSIONS

The background of successful performance in steels is generally additional elements. Refractory metals which the world has been working on for a century, should not be overlooked. It is thought that the choice of using molybdenum, niobium, and aluminum in the new generation CWTS is not a coincidence.

Molybdenum, together with niobium, is an element that establishes microstructural control not only in tool steels but also in all alloy steels where superior performance is expected. These steels will become increasingly important in the production of lighter and more durable parts that will provide heavy-duty service conditions in vehicles, machines, and power plants.

The most critical stage is tempering, as it plays a key role in inducing microstructural changes in the carbides, which are essential to the manufacturing process. Successful results can be obtained to the extent that the coarsening of fine carbides can be prevented. The functionality of the ratios of the elements forming the chemical composition depends only on the quantity and quality of the carbide types to be formed, and this directly depends on the temperature and duration of tempering. Here, every few degrees and minutes that can change downward or upward are potential gains or untimely damage, i.e. a source of loss.

In all three steels studied, D2, C2, and K2, the primary elements are chromium, molybdenum, and vanadium, along with carbon, while manganese and silicon serve as supporting elements. In our K2 example, niobium should also be added to these. The knowledge that carbides can transform into each other provides us with valuable data. Since a 'knife-edge' decision that is of critical importance for the development of steel with factors affecting one may hurt another, a performance threshold that combines all positive features and optimizes them by knowing the relevant parameters better can be achieved in order not to 'break one side while doing another'.

Molybdenum and niobium will be the more important alloying elements for future steels. It is inevitable that other elements, especially Boron (B), will be added to them.

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Conflicts of Interest

The authors declare no conflict of interest.

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