

The Effect of Cooling Rate on the Microstructure and Mechanical Properties of the Plastic Injection Molds

Z. S. Seyedraoufi^{1,*}, M. Samiee¹, F. Abdi²

¹Advanced Materials Engineering Research Center, Karaj Branch, Islamic Azad University, Karaj, Iran.

²Institute of Materials and Energy, Karaj, Iran.

Received: 30 January 2021 - Accepted: 15 April 2021

Abstract

In this research, the effect of cooling rate on the microstructure, hardness and impact energy of a plastic injection mold made of X210Cr12 steel was investigated. The microstructural studies showed that with increasing cooling rate, the amount of residual austenite (Ar) decreases until it is completely removed. Statistical analysis showed that the size and volume fraction of chromium stabilized with block carbides decreases with increasing cooling rate. As the cooling rate increased, bainites were observed in the microstructure. The hardness decreased via increasing the cooling rate and austenitization time due to the reduced interaction of carbides with dislocations. Martensitic structure prevented a significant reduction in hardness. These factors increased the toughness of the X210Cr12 and led to the ductile failure. Cryogenic treatment modified the structure via distribution of fine carbides into the stable lath martensite. With optimizing the hardness and toughness to withstand the impact of the die, toughness increased to 125 j and hardness decreased to 624 H.V.

Keywords: X210Cr12 Steel, Cryogenic, Toughness, Microstructure, Hardness.

1. Introduction

Competition in the materials market is still growing, whether it is the widespread use of plastics, ceramics, composites or other materials. However, despite these alternatives, steel has a unique place among raw materials due to its special properties. One of the most common reasons for failure of the mechanical parts is due to severe wear. Wear causes significant damages on the component surfaces, leading to poor performance, high maintenance time, and increases the repair costs. The general measure of wear is usually related to the hardness of the material. However, this rule only applies to materials of the same group. The existing literature on the field of tool steels shows that with the increase of volume fraction of martensite and hardness, a reduction in material wear is expected. In the case of using a material in severe wear conditions, in addition to the type of microstructure and hardness, other factors such as grain size, chemical composition, matrix saturation, size and morphology of secondary particles, pressure and particle size of abrasive particles should also be considered [1, 2]. Parts made of tool steels are often exposed to additional loads that include stress cycle oscillations, chemical environments, or friction processes. For this reason, fatigue and excessive wear may start at the beginning, which eventually leads to a premature fracture [3, 4]. The mentioned mechanisms are the main reason for the fracture of plastic injection molds.

However, in plastic injection molds, in order to apply the periodic impacts, the impact energy must also be high. Therefore, increasing the hardness and decreasing the elongation should not overshadow this issue. However, the focus for making these molds has always been on their wear resistance and fatigue [3, 4]. Cold working tool steels are classified into three types: low-alloy steels and hardened steels in oil, high-chromium and high-carbon cold-rolled steels, and medium-hard alloy steels. These steels cannot maintain their hardness at high temperatures. Also they have high hardness depth and low distortion during heat treatment. It is more economical to use this type of steel for cutting at low temperatures. X210Cr12 or special K steel is one of the cold working tool steels which is named using standard numbers 1.2080 and X210Cr12. This steel is used to make cutting blades, hummer, welding, etc. X210Cr12 steel is known as high hardness steel and has high wear resistance due to high chromium (Cr) [5]. Quenching and tempering of these steels, especially X210Cr12, is called *vergütet (+QT)*.

In steels, with increasing the percentage of carbon and alloying elements, the start and end temperature of martensitic transformation decreases. Even with increasing the percentage of carbon, the start and end temperature of martensite (M_s and M_f) transformation decreases significantly. In fact, carbon present in solid solution increases the shear strength of austenite. Therefore, with increasing carbon, more driving force is needed to start sliding to form martensite [6]. Residual austenite is soft phase and unstable at low temperatures; in such a

*Corresponding author

Email address: z.seydraoufi@kiaou.ac.ir

way that it turns into brittle martensite at low temperature and during work. The conversion of austenite to martensite produces approximately 4% volumetric expansion, leading to Parts distortion. Therefore, cryogenic treatment or multiple annealing at relatively high temperatures or for a long time is used to minimize the amount of residual austenite in steels [7-9]. Cryogenic treatment is a suitable treatment to reduce the percentage of γ_{re} . Cryogenic treatments include heating the steel to austenitic temperature, cooling in quench medium, immediately placing at sub-zero degrees Celsius and then tempering treatment. Increasing wear resistance, reducing internal stresses, dimensional stability and deposition of fine carbides in the matrix can be considered as the most important advantages of using cryogenic treatment. The lower the ambient temperature, the faster the properties improve [10, 11]. Gural et al. [12] investigated the effect of grain size on the sliding wear behavior. Fine martensite demonstrates higher hardness and lower surface friction, resulting in reduced wear. In another study, Ebner et al. [13] reported that tool fracture and its evolution depends on many parameters. But heat treatment or mechanical operation of tool steel and related microstructure are playing a major role. Carbides in tool steels mainly prevent the movement of dislocation as well as phase changes, especially when exposed to high temperatures. In the present study, the effect of cryogenic treatment on the microstructure, hardness and toughness of X210Cr12 plastic injection molds was investigated.

This operation was done to ensure environmental friendliness. If these molds have the best performance, It saves energy and time and reduces environmental pollution.

2. Materials and Methods

SPK steel or X210Cr12 is used in this research, which is considered as a cold steel tool.

The chemical composition of this steel is determined by Atomic Emission Spectroscopy (AES) and is given in Table. 1.

Table. 1. Chemical composition (wt.%) of X210Cr12 steel.

wt.%	El.
Bal	Fe
2.900	Cr
0.860	C
0.500	Mn
0.890	Si
0.004	P

First, samples were cut to dimensions of 10mm×10mm×55mm from the desired mold. Then, samples were placed inside the furnace under argon

gas and heated to 950 °C for 1 and 2 hours until completely austenitized and then cooled and quenched in different environments to convert the structure of sample to martensite. Some samples were cooled in liquid nitrogen at -170 °C. The heat treatment stages have been presented in Table. 2.

Table. 2. The nomination of samples and stages of heat treatment.

sample code	Temperature/ Time/ Cooling environment
MF0	---
MF1	950°C / 1h / FC
MF2	950°C / 1h / PC
MF3	950°C / 1h / WQ
MF4	950°C / 1h / NQ
MF5	950°C / 1h / DC
MF6	950°C / 2h / AC
MF7	950°C / 2h / WQ
MF8	950°C / 2h / NQ
MF9	950°C / 2h / DC

AC = cooling in air
WQ = quenching in water
PC = quenching in polymer
NQ = quenching in liquid nitrogen
DC = keeping in liquid nitrogen for 24 hours
FC = cooling in the furnace

After heat treatment, the samples were polished to achieve a smooth surface. Then, the microstructures were studied by using an optical microscope (Olympus model) equipped with an image analysis. The hardness of the samples was measured using a microhardness tester made by Copa MH3 model, with a force of 500 g and a holding time of 20 s. Fracture toughness of heat treated samples was measured by charpy impact test at ambient temperature. Test results were reported on average after five tests.

3. Results and Discussion

Fig. 1. shows the OM image of MF0 sample. In this image, the presence of tempered martensite as a matrix and chromium carbide particles with η structure can be clearly seen.

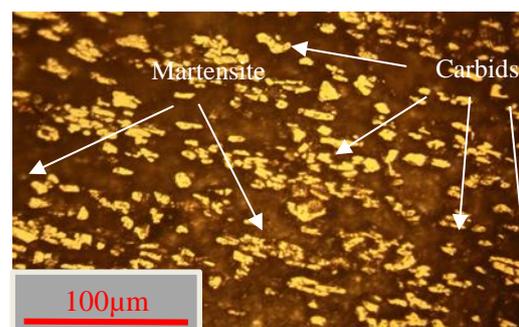


Fig. 1. OM image of MF0 sample.

The presence of η carbides with different sizes indicates that the standard *vergütet* cycle has been performed on the samples. Large carbides have existed from the beginning and their block morphology has been modified during heat treatment and fine carbides are secondary carbides that have either formed or had limited growth during heat treatment. Fig. 2. shows the OM images of heat treated and quenched samples. As can be seen, the change in cooling rate has affected the microstructure of the samples. In the sample cooled in the furnace, the large conjuncted carbides are observed that these carbides have been grown through diffusion mechanisms in order to establish suitable temperature conditions in sufficient time. In the sample structure of MF1, next to the coarse martensite around the carbides, a perlite structure is observed, which indicates the equilibrium cooling. However, by decreasing the cooling rate in the quenched sample in the polymer, along with reducing the size of carbides, the structure has become completely martensitic, where the dark colored points of the residual austenite are observed. In MF3 sample which has been quenched in water, along with reducing the dimensions and amount of carbides, the amount of the residual austenite has also decreased.

In several researches, the end temperature of the martensitic shear transformation of this steel has been reported about -70 to -80°C , which has caused small amounts of austenite to remain in the structure [14]. In this sample, along with matrix martensite, due to incomplete transformation, some amounts of bainite are also observed in the structure. At MF4 and MF5 samples, the structure is completely hollow martensite and the amount and size of carbides are reduced; The difference is that keeping the sample at a temperature below zero has led to the formation of small carbides or stopped growth. Research also confirms this. By doubling the austenite time, the increase in time also shows its effect on the microstructure in the form of metallographic images. As can be seen in MF6 sample, the Triple structure is a mixture of hollow martensite, residual austenite and perlite. As the cooling rate increases in the samples austenitized for 2 hours, there is still some austenite remaining in the structure, but along with this phase, fine-grained martensite and bainite are observed. As in the previous examples, by lowering the temperature below zero and ultra-fast quenching, the size of carbides is decreased and the structure becomes completely martensitic.

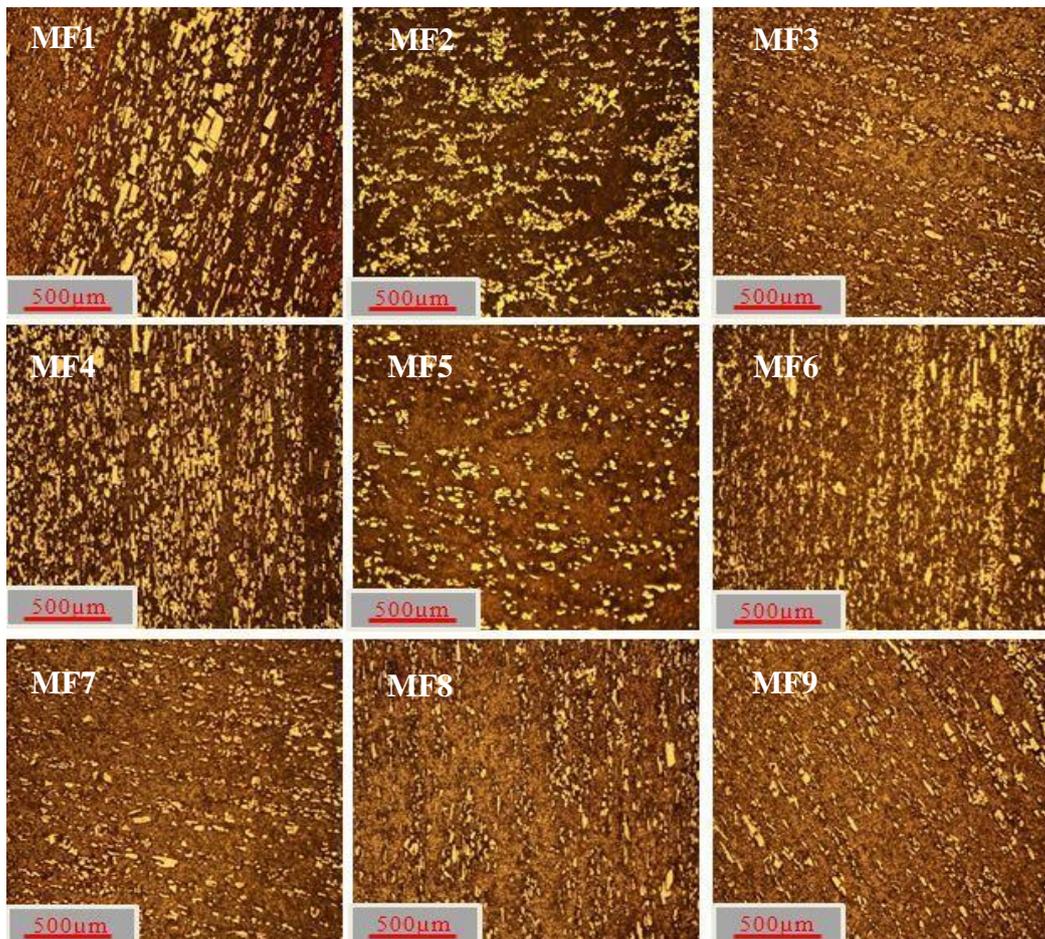


Fig. 2. OM images of heat treated and quenched samples.

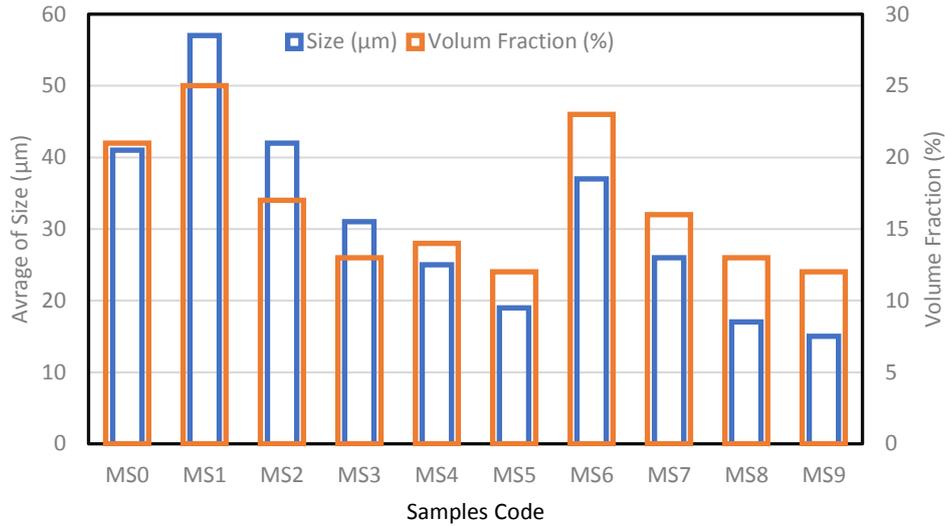


Fig. 3. Diagram of the size and volume fraction of carbides.

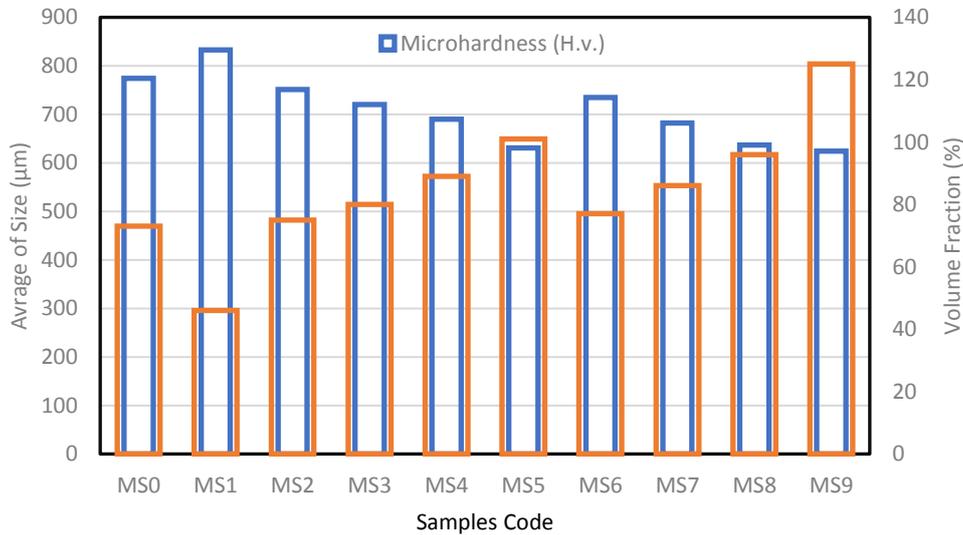


Fig. 4. Diagram of changes in hardness and impact energy after heat treatment.

Fig. 3. shows the diagrams of average carbide sizes and their volume fraction. For this measurement, the criterion was the large diameter of these block carbides. It can be seen that with increasing the cooling rate, the size of carbides decreases due to the reduction of cooling time and limited growth [15]. As the austenite time increases, the chromium carbides are pushed back into the iron matrix and the martensite becomes more stable, so with increasing time, the size of carbides decreases. This reduction trend enriches the surrounding carbides with chromium that these carbides will be the nucleation site for secondary carbides in the tempering process and therefore, the size and volume fraction of carbides will decrease and increase, respectively. Keep in liquid nitrogen or performing cryogenic treatment along with completing the martensitic shear transformation has reduced the atomic distances and makes difficult the

diffusion process and growth of carbide. This acts as an auxiliary arm in the temper stage and improves the structural characteristics of the carbides and on the other hand, tempered martensite is stable against impact and periodic tensile loading [15]. With increasing the austenitizing time and cooling rate, in most cases, the volume fraction of carbides has decreased. This decrease occurred based on two mechanisms: a) Lack of diffusion conditions for the growth of existing carbides and b) Lack of diffusion conditions for nucleation and growth of new carbides during cooling. This reduction in volume fraction of carbides and the correction of morphological characteristics can reduce the strength of the part in shear and impact loads by creating a softer substrate and the absence of high destructive energy in the carbide interface [16, 17]. Fig. 4. shows the effect of these changes on the hardness and impact energy after heat treatment.

It can be seen that as the size of carbides decreases, the impact energy increases and the amount of hardness decreases. Coarseness and increase in the amount of carbides causes more interaction of dislocations with carbides. On the other hand, the presence of martensite in the matrix does not significantly reduce the hardness. In fact, carbide properties have some effect on hardness and the rest is affected by the matrix. On the other hand, martensite created during heat treatment is a new barrier against the movement of dislocations [18, 19].

The impact energy, regardless of the underlying microstructure, is strongly influenced by the characteristics of the second phase. As can be seen, the amount of energy absorption decreases due to the difference in isotropic energy and the nonconforming factor with the coarsening and increasing the amount of carbides in the matrix. The interface of this type of carbide is itself a very suitable place for nucleation and crack growth. Now, if these carbides are evenly distributed in the structure with a small size, they can deflect the crack path and increase the impact energy [18, 19]. As can be seen in MF9 sample, carbides have the best structural characteristics due to the sufficient time of austenitizing and high cooling rate and keep in liquid nitrogen. It showed the highest energy absorption during the impact test. Uniform distribution of fine carbides has led to increased energy absorption and fracture tends to soften. The reason for this is to divert the growth path of cracks due to the distribution of carbides, because the matrix itself is a relatively brittle but strong.

4. Conclusion

1. By applying cryogenic treatment and increasing the cooling rate and austenitizing time, the microstructure and mechanical properties of steel can be improved.
2. The volume fraction and size of carbides can be reduced by increasing the austenitizing time and cooling rate and applying cryogenic treatment.
3. As the cooling rate increases, the amount of residual austenite decreases and this value is zeroed by applying cryogenic treatment.
4. By reducing the size and volume fraction of carbides, the hardness decreases and the impact energy increases due to crack deflection and reducing the interaction between the dislocation and the barriers.

References

[1] S. G. Sapate, A. D. Chopde, P. M. Nimbalkar and D. M. Chandarkar, *Mater. Des.*, 28(2007), 1923.
 [2] I. Sevim and I. B. Eryurek, *Kov. Mater.*, 43(2005), 158.

[3] H. Jirková, K. Rubešová, P. Konopík and K. Opatová, *Metals.*, 8(2018), 713.
 [4] D. Tobola, W. Brostow, K. Czechowski and P. Rusek, *Wear.*, 382(2017) 29.
 [5] R. Karimdadashi and M. A. Mohtadi-bonab, *Int. j. Res. Appl. Sci. Eng. Technol.*, 4(2016), 2321.
 [6] A. Bensely, A. Prabhakaran, D. Mohan Lal and G. Nagarajan, *Cryogenics.*, 45(2005), 747.
 [7] Y. Dong, X. Lin and H.S. Xiao, *Heat Treat. Met.*, 25(1998), 55.
 [8] J.D. Darwin, D. Mohan Lal and G. Nagarajan, *J. Mater. Process. Technol.*, 195(2008), 241. [9] M. Sitko and B. Skoczzeń, *Int. J. Solids. Struct.*, 49(2012), 613.
 [10] W. Han, Y. Liu, F. Wan, P. Liu, X. Yi, Q. Zhan, D. Morrall and S. Ohnuki, *J. Nucl. Mater.*, 504(2018), 29.
 [11] V. G. Gavriljuk, W. Theisen, V. V. Sirosha, E. V. Polshin, A. Kortmann, G. S. Mogilny, Y. N. Petrov and Y. V. Tarusin, *Acta Mater.*, 61 (2013) 1705.
 [12] A. Gural, *Kov. Mater.*, 48(2010), 25.
 [13] R. Ebner, H. Leitner, F. Jeglitch and D. Caliskanoglu, *Proc. of the 5th Int. Conference on Tooling, Leoben, (1999)*, 3.
 [14] D. Tobola, W. Brostow, K. Czechowski and P. Rusek, *Wear.*, 382(2017) 29.
 [15] R. Hood, F. M. Aguirre, L. S. Gonzalez, D. Novovic and S. L. Soo, *Manuf. Technol.*, 68(2019) 329.
 [16] M. Novelli, P. Bocher and T. Grosdidier, *Mater. Charact.*, 139(2018), 197.
 [17] V. Vinay, M. R. Ramesh and D. Chakradhar, *J. Manuf. Proc.*, 37(2019), 242.
 [18] W. Kaikai, K. Gu, J. Miao, Z. Weng, J. Wang, Z. Tan and B. Bai, *Mater. Sci. Eng. A.*, 743(2019), 259.
 [19] P. Germán, J. E. P. Ipiña and W. R. Tuckart, *Mater. Sci. Eng. A.*, 605(2014), 236.