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Development of Molybdenum Nickel Steel to Improve Mechanical Properties at High Temperature

*Saeed Ghali

Department of Steel Technology, Central Metallurgical Research and Development Institute, Cairo, Egypt

*Corresponding author: E-mail: a3708052@gmail.com

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Abstract

This article concerns developing molybdenum nickel steel through increasing chromium content from 0.6 to 7.81 %. Three steel grades were produced in an induction furnace with a capacity of 30 kg. The chemical composition of the produced steel grades was determined. It was found that carbon content ranged from 0.044 to 0.056%, silicon content was less than 0.08%, manganese percentage was not more than 0.15%, molybdenum content ranged from 1.35 to 1.54 %, and nickel content ranged from 0.73 to 1.1%. The normalizing process was carried out for the produced steels, followed by the free forging process. The start forging temperature was 1100 ºC and the finishing forging temperature was 950 ºC. The forged steels were solution-treated to dissolve precipitates. Mechanical properties at room and high temperatures (300, 500, and 700 ºC) were measured. Increasing chromium content improved the mechanical properties at room and high temperatures (up to 500 ºC). It was found that the yield and ultimate tensile strength increase from 370 & 520.1 MPa to 959.18 & 1163.8 MPa respectively at room temperature, and from 270.5 & 584.5 MPa to 844.81 & 1081 MPa at 500 ºC. The developed steel (with 7.81 % chromium content) was nominated to be used at high temperatures at different parts for nuclear reactors and in a boiler of steam power plants up to 500 ºC.

Keywords: Boiler steel; Nuclear steel; Chromium steel; Cr-Mo steel; Mechanical properties; Elevated temperature.

1. Introduction

Chromium is an essential element in heat resisting steel because it enhances resistance to oxidation and corrosion at elevated temperatures. Chromium also has an important effect on the toughness and strength of elevated temperatures [1-4]. Chromium is a powerful alloying element in steel. It strongly increases the hardenability of steel, and markedly improves the corrosion resistance of alloys in oxidizing media. Its presence in some steels could cause excessive hardness and cracking in and adjacent to welds. Stainless steels may contain more than 12% chromium [5]. Chromium is one of the most active alloy elements in steel matrix and chromium content determines the properties of the composite. Chromium can form a continuous solid solution with iron and reduce the austenite region of the iron-carbon phase diagram. Chromium can also form a variety of carbides in the presence of carbon. What is more, chromium can significantly improve the hardenability of steel and can precipitate $(Cr, Fe)_{23}C_6$ in the process of tempering resulting in the secondary hardening effect. When chromium content is lower (< 5 wt%), chromium plays an important role in improving the hardenability of the steel matrix [6-10]. Chromium-Molybdenum steels have several applications in different fields such as heat exchangers, high temperature ducting, oilfield tools, flanges, pipe clamps, valves, power plants, and pressure vessels especially at high temperatures [11]. A study [12] reported that Z-phase is responsible for the sudden breakdown of creep strength of 12% Cr steels after 8000 h at 650 ºC. Another study [14] concluded that to avoid Z-phase formation, the content of Cr could be reduced. For Cr contents below 11%, the Z-phase formation can be retarded considerably.

In the present work, new steel alloys containing 1.5 Mo1Ni were developed through the addition of chromium.

The novelty of this work is increasing the chromium content to increase the fine precipitates (different chromium carbides). These precipitates are stable and have a positive influence on preventing grain growth and hence on the mechanical properties at high temperatures. The mechanical properties of the investigated alloys were studied at different temperatures.

2. Experimental work

Modified grades Cr-Mo steels were melted using a 30 kg pilot plant medium frequency induction furnace. The induction furnace melting unit was lined with a basic lining. The started raw materials are ferroalloys (ferrochromium, ferromolybdenum), Armco iron, and nickel-metal. All melts were cast in the sand mold of inner diameter 70 mm. The cast steels were reheated up to 1200 ºC, hold for 2 hours. The forging process was started at 1100 ºC and finished at 950 ºC. The produced ingots were hot forged to steel bars with cross-sections 30 × 30 mm^2. Samples from the forged steels were initially solution-treated at 1050 ˚C for 30 min followed by water quenching. The chemical compositions of the obtained steel alloys were analyzed using the spectroscopic analyzer. The tensile specimens were machined with a diameter of 4 mm and a gauge length of 35 mm. The microstructure was performed for all the melted steel grades using an optical microscope. The influence of chromium addition on mechanical properties was investigated at 25, 300, 500, and 700 ºC using a 50 kN MTS 810 testing machine. Thermo-Calc software version 3.1 was used to predict the formed precipitates at different temperatures for the steel grades.

3. Results and discussion

The chemical composition of three grades of developed Mo-Ni steels is listed in Table (1). The three steel grades nearly have the same chemical composition with different chromium contents and a little bit difference in carbon content wher, chromium content ranging from 0.6 – 7.81, 0.043 and carbon content is ranging from 0.044 to 0.056%. The mechanical properties at room and high temperatures are listed in Table (2).

Fig. 1. represents the relation between yield strength test temperature for the three steel grades. From the figure, it is clear that increasing test temperature from room temperature up to 500 ºC leads to a gradual decrease of the yield strength for steel number 1. It can be seen that the rate of decreasing yield strength increases for steel number 2 at the same range of temperature. This can be attributed to the higher chromium content in steel 2 than in steel 1.

Table 1. Chemical composition of developed steels.

Heat No.	Chemical composition, wt.%									
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Fe
1	0.044	0.014	0.062	0.013	0.011	0.60	1.54	1.12	0.005	Bal.
2	0.046	0.024	0.074	0.012	0.009	1.37	1.44	0.85	0.007	Bal.
3	0.056	0.079	0.14	0.013	0.009	7.81	1.35	0.73	0.033	Bal.

Table 2. Mechanical properties of developed steels at room and high temperatures (23 ºC, 300 ºC, 500 ºC, and 700 ºC).

Heat No.	Temp., °C	$Rp_{0.2\%}$ [MPa]	Rm [MPa]
1	23	370.0	520.1
	300	270.5	614.7
	500	255.6	584.5
	700	153.9	155.9
2	23	275.6	464.1
	300	271.4	524.2
	500	270.4	596.4
	700	121.5	134.3
3	23	959.18	1163.8
	300	957.26	1236.5
	500	844.81	1081
	700	134.53	159.28

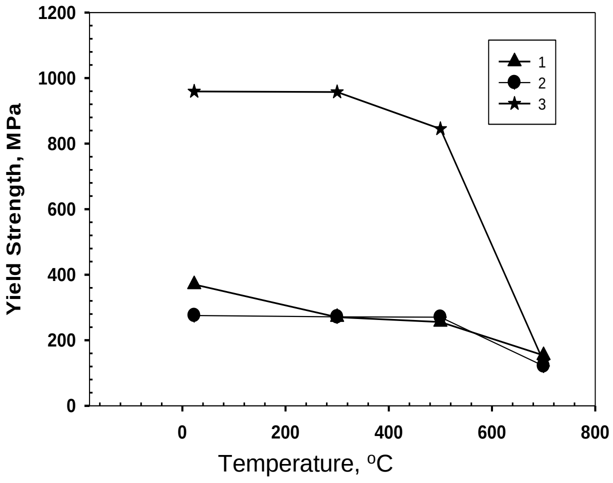


Fig. 1 Change of Yield strength of developed steels with temperature.

However, for steel 3, the yield strength is higher than that of steel grades 1 & 2 at the whole temperature range. This is attributed to the higher chromium and carbon contents in steel number 3 than steel grades 1 & 2 which leads to the formation of more stable chromium carbides in steel number 3. The yield strength of developed steel grades decreases dramatically at temperature 700 $^{\circ}$C. This may be attributed to the fact that the chromium carbides dissolve at this temperature. Nearly the same behavior of ultimate tensile strength for developed steels is given in Fig. 2. It was noticed that the ultimate tensile strength increases gradually by increasing test temperature up to 500 $^{\circ}$C for steels number 1 & 2. This behavior may be related to the start of martensitic temperature which can be calculated according to Equation (1):

$$Ms = 550\ ^{\circ}C - 450[C\%] - 33[Mn\%] - 20[Cr\%] - 17[Ni\%] - 10[W\%] - 20[V\%] - 10[Cu\%] - 11[Nb\%] - 11[Si\%] + 15[Co\%]. \tag{1}$$

Resulting in a start martensitic temperature of steels 1, 2 & 3 being 497, 485, and 350 $^{\circ}$C respectively.

The microstructures of different steel grades are illustrated in Figure 3. The microstructure of steel grades 1 & 2 mainly consists of ferrite – pearlite while the microstructure of steel 3 is tempered martensite. This microstructure demonstrates the similarity in behavior of both steel grades 1 & 2. Also, it illustrates the difference in behavior (yield & ultimate) between steel 3 compared with either steel 1 or steel 2.

Thermo-Calc. was used as a tool to illustrate the phases which may be formed at different temperatures of various carbon content for the three steel grades.

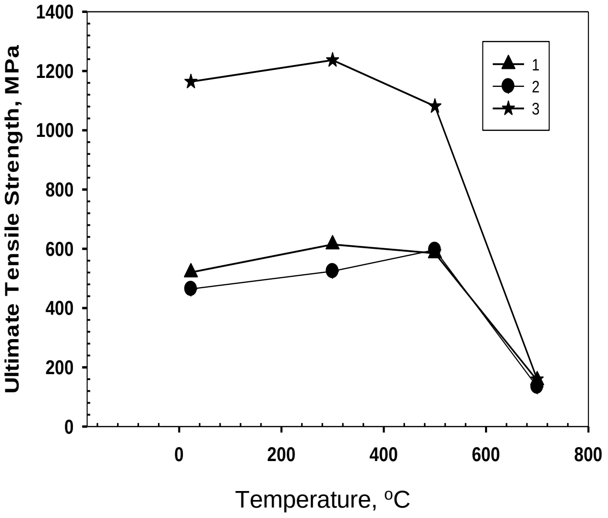


Fig. 2 Change of ultimate tensile strength of developed steels with temperature.

Thermo-Calc results of different steel grades showed the formed phases at different temperatures as is clear in Figures 4-6 for steels 1, 2, and 3 respectively.

It was noticed that $M_{23}C_6$ and M_6C phases can be formed in the three steel grades. The amount of this carbide phase is dependent on carbon content and temperature. These carbides are responsible for the strength. The dissolving of these phases leads to a dramatic decrease in yield and ultimate tensile strength.

The change of yield and ultimate tensile strength varies depending on the phases. Where the M_6C phase is present in the three steel grades. The $M_{23}C_6$ is not present in steel 1 but is present in steel 2 & 3 by ratios 0.002 and 0.008% respectively. The relationships of yield and ultimate tensile strength with temperature up to 500 $^{\circ}$C are illustrated in Figures 7 - 8 respectively.

The linear equations (2-4) represent the yield strength as a function of temperature (within temperature range 23 – 500 $^{\circ}$C) of the three steel grades 1, 2, and 3 respectively.

$$\text{Yield strength} = 366.5 - 0.2472*T \tag{2}$$
$$\text{Yield strength} = 275.5 - 0.0112*T \tag{3}$$
$$\text{Yield strength} = 982 - 0.2253*T \tag{4}$$

Where T is the test temperature in Celsius.

It was noticed that the rate of decreasing yield strength with temperature in steel is greater than that in steel grades 2 & 3. This may be attributed to the that there are two opposite effects. By increasing temperature, there are carbides formed and other carbides dissolved accompanied with grain size changed. These two effects have a significant effect on yield and ultimate tensile strength.

The relationship between ultimate tensile strength with temperature (up to 500 $^{\circ}$C) can be represented in equations (5-7) for steels 1-3 respectively.

$$\text{Ultimate tensile strength} = 532.6 + 0.1478*T \tag{5}$$
$$\text{Ultimate tensile strength} = 453.17 + 0.2736*T \tag{6}$$
$$\text{Ultimate tensile strength} = 1201 - 0.1466*T \tag{7}$$

It was noticed that the ultimate tensile strength of steel grades 1 & 2 increases by increasing the test temperature. While the ultimate tensile strength of steel 3 decreases with increasing test temperature. Also, it can be noticed that the rate of increasing the ultimate tensile strength of steel 2 is greater than that of steel 1.

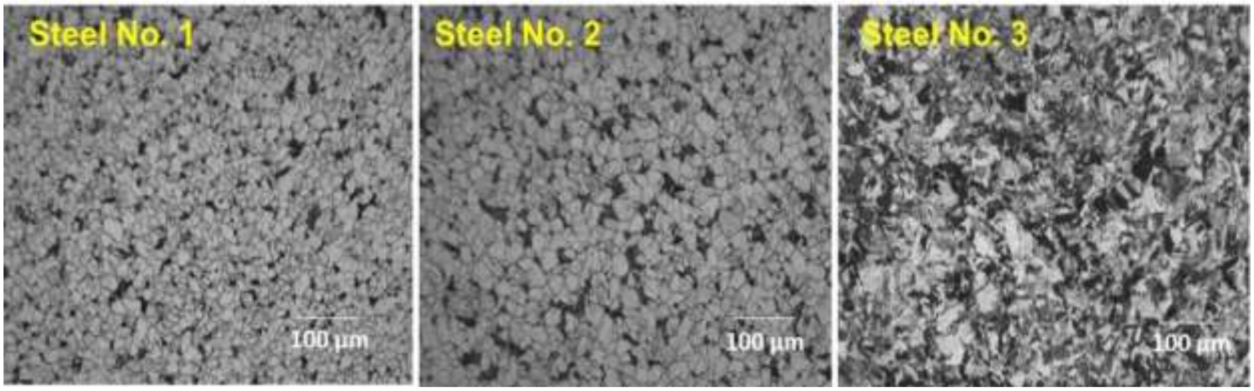


Fig. 3 Microstructure of steels.

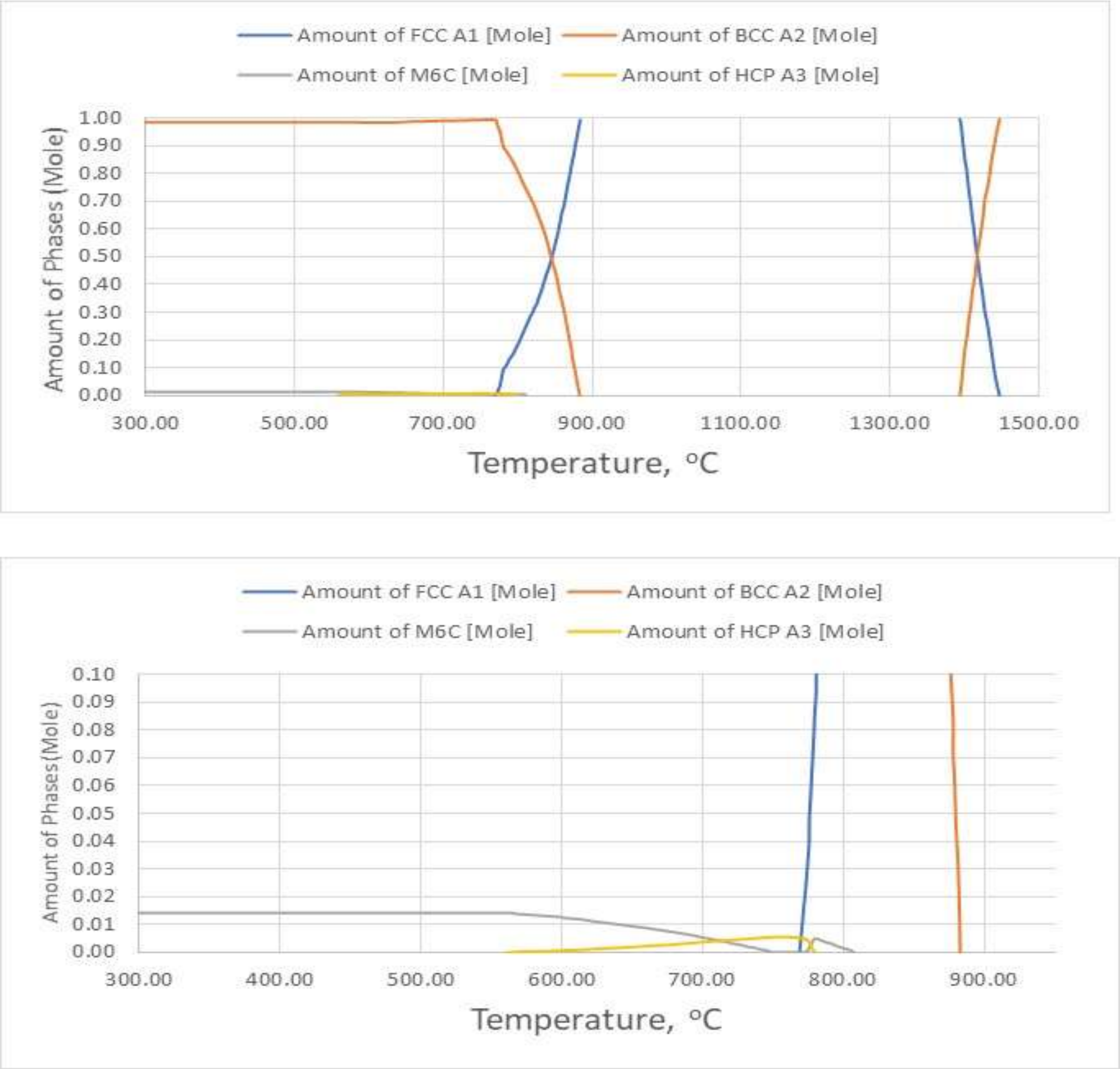


Fig. 4 Variation of phases for steel number 1 at different temperatures.

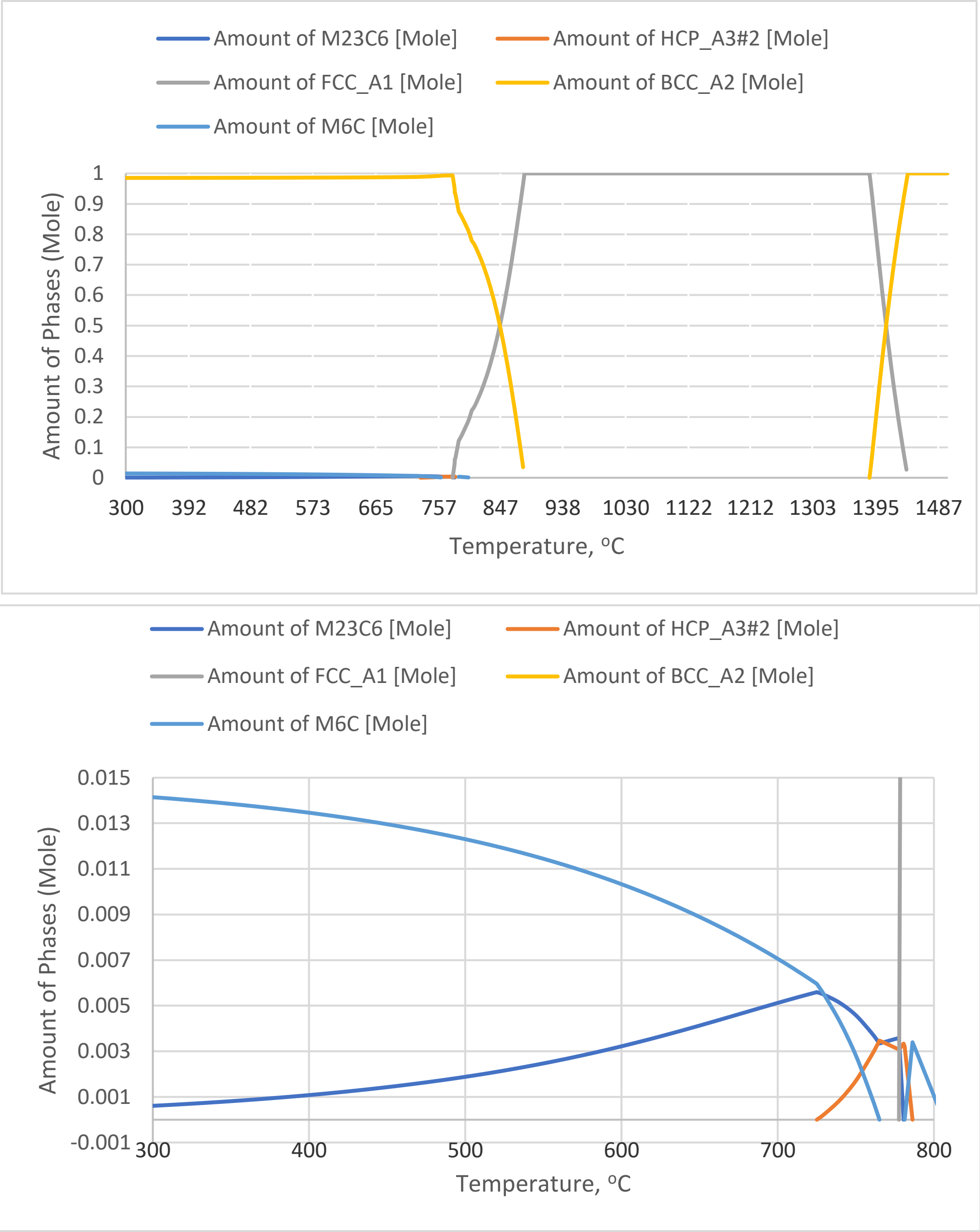
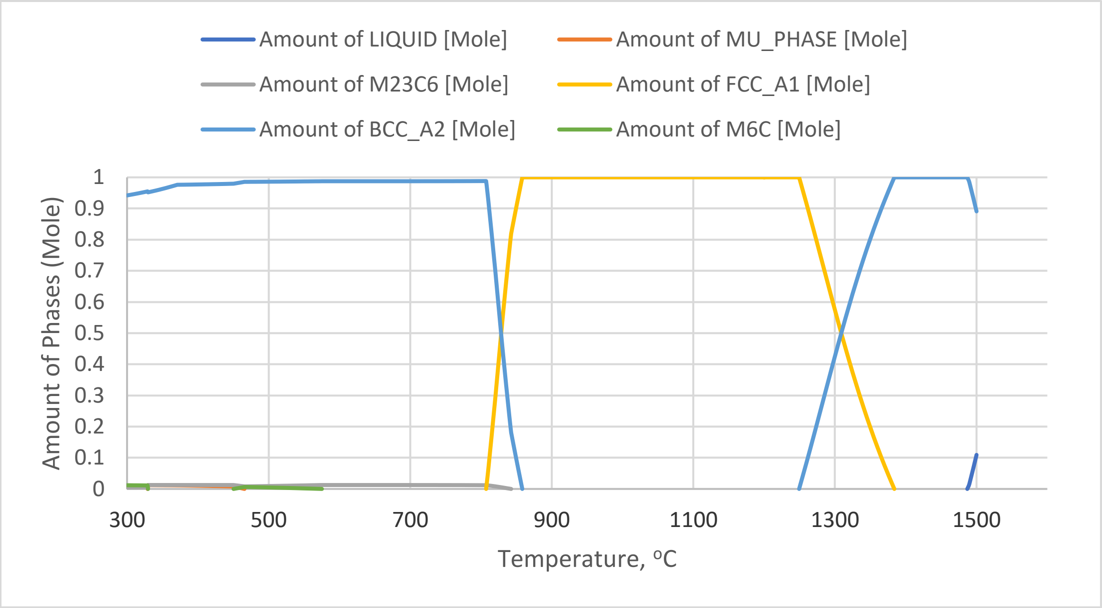


Fig. 5 Variation of phases for steel number 2 at different temperatures.



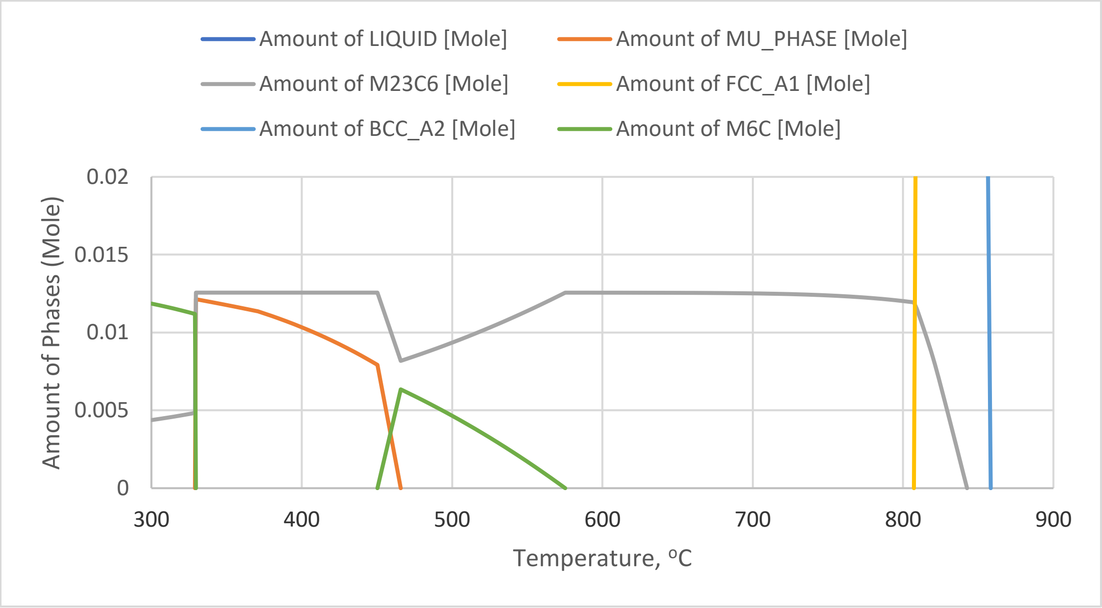


Fig. 6 Variation of phases for steel number 3 at different temperatures.

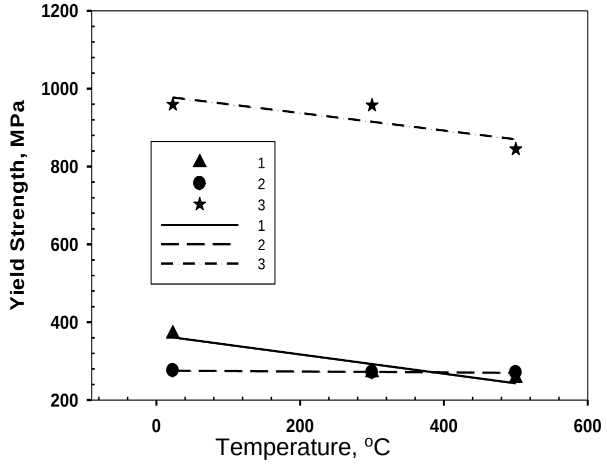


Fig. 7 Yield strength of developed steels at the temperature range 23 – 500 °C.

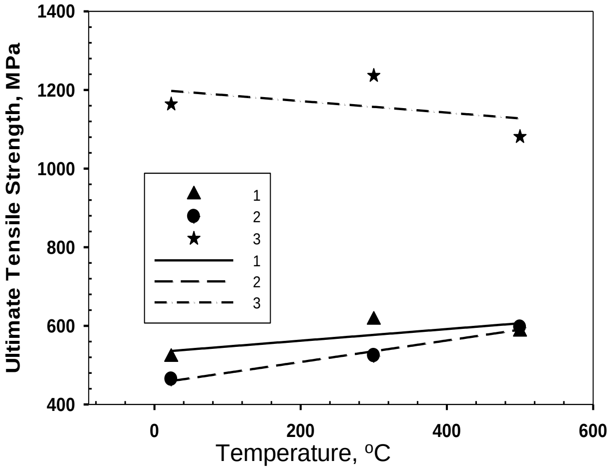


Fig. 8 Ultimate tensile strength of developed steels at the temperature range 23 – 500 °C.

4. Conclusions

The chromium addition to steel containing 1.5% Mo and about 1% Ni has a positive significant effect on the mechanical properties. Increasing chromium content leads to more retardation in decreasing yield and ultimate tensile strength. The yield and ultimate tensile strength increase dramatically when the chromium content increases from 1.37 up to 7.81%. Where the yield and ultimate tensile strength increase from 370 & 520.1 MPa to 959.18 & 1163.8 MPa respectively at room temperature and from 270.5 & 584.5 MPa to 844.81 & 1081 MPa at 500 °C. The developed steel containing 7.81% chromium is nominated to be used at temperatures up to 500 °C. The subsequent work will be carrying out TEM to demonstrate the size and type of the formed carbide.

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