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Effect of Tempering Temperature on the Mechanical Properties and Microstructure of low alloy Steel DIN 41Cr4

Abaidi Ismail*, Zenasni R., Khiat Sidi Mohammed Amine, Sadok Ahmed

Department of Mechanical Engineering, Faculty of Science and technology, UMAB of MostaganemAlgeria

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Abstract

This research is focused on the effect of tempering temperature on the microstructure and mechanical properties of low alloy steelDIN 41Cr4 used for the manufacture of bolts, threaded, screws and shafts by manufacturing company in Algeria. We use an experimental approach by applying heat treatment of quenching and tempering temperature. Mechanical testing of tensile, impact fracture toughness, hardness tests and microstructures were conducted on all the heat-treated samples. All samples were austenitized at 850°C for 30 min followed by oil quenching, and then tempered at temperatures between 200 and 600 °C for 1h and air cooledin order to investigate the influence of microstructure. The results of tensile testing indicated that yield strength (YS), ultimate tensile strength (UTS) and the hardness decrease with increasing tempered temperature, but the elongation, impact energy and grain size increase with increasing the tempering temperature.

Keywords: tempering temperature; mechanical property; microstructure; low alloy steel;

1. Introduction

The use of low alloy steel DIN 41Cr4 has been increased in many industries in particularly the automotive industry [1 -7]. This class of steel has been used for quenching and tempering to improve the mechanical properties and increase longer service life [8 - 10]. While industrial requirement of higher mechanical properties and longer service life of these steel requires some compositional modifications and various heat treatment techniques by addition of Cr, Ni and Mn elements to improve its mechanical properties [11-16].

Many researchers [17 - 20] have done a lot of works to study the effect of heat treatment of quenching and tempering temperature (Q & T) on the mechanical properties and microstructure.S.Z. Qamar has explored the effect of heat treatment on mechanical properties of H11 tool steel, and it was found that with increasing temper temperatures hardness first increases to a maximum and then gradually decreases and yield strength first decreases, then increases, and then increases again, R.Zapala, B.Kalandyk[11] have studied the effect of tempering temperature on the mechanical properties of Cast L35HM steel, the results showed that the values of elongation (EL) and retained austenite(RA) did not show any significant differences. Attention was drawn to large differences in strength and hardness observed between the metals tempered at 600 and 650 °C.

In the present work the mechanical properties and microstructure of quenched and tempered steel DIN 41Cr4vary by tempering at 200, 600 °C for all samples at different temperatures were studied.

2. EXPERIMENTAL

The chemical composition of the test material DIN 41 Cr4 (AFNOR 42C4) was determined by emission spectrometry in industrial company BCR, Relizane (Algeria)Figure1.The chemical composition of investigated steel is shown in Table1.In the present work, all the samples of tensile testing and impact test were austenitized at 850°C for 30 min, followed by oil quenching, and then tempered at different temperatures that range from 200 to 600°C (Figure 2), for each step the tempering duration is 1hour and cooled in air, schematic of heat treatment cycle used in this study is shown in Figure 2.

After heat treatment, the specimens were tested by tensile test, impact toughness test (Kv) and completed with Rockwell hardness measurements, for the tensile testing and impact toughness the specimens with the dimensions are shown in Figure3 and Figure 4.For the tensile testing, we used the KARL FRANK GMBH, WEINHEIM-BIRKENAU, type 83431 Werk–Nr 10650 machine Metallographic examinations of samples were observed by a light microscope, they were mechanically polished and etched with 3% nital solution, test specimen polishing shown in Figure 5. The average value of three specimens were considered and the deviation of HRC is 0.02. (2%).

* Corresponding author e-mail: abaidigm@gmail.com.

Figure 1. Emission spectrometry

Table 1. Chemical compositions of DIN 41Cr4 steel (mass fraction, %)

C	Mn	Si	Al	Cr	Mo	Cu	P	S	Ni
0,43	0,74	0,25	0,03	1,05	0,04	0,12	0,013	0,012	0,17

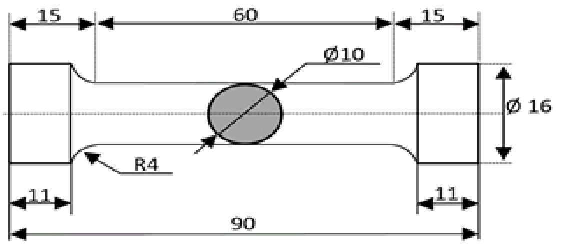

Figure 3. Schematic diagram of tensile testing sample

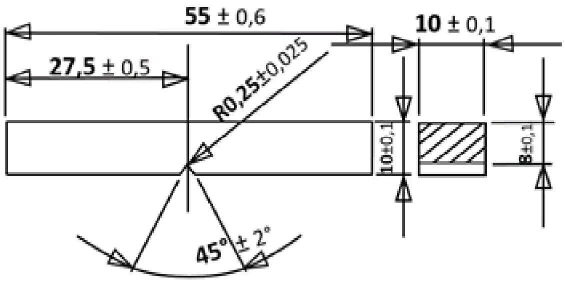

Figure4. Schematic diagram of impact test sample

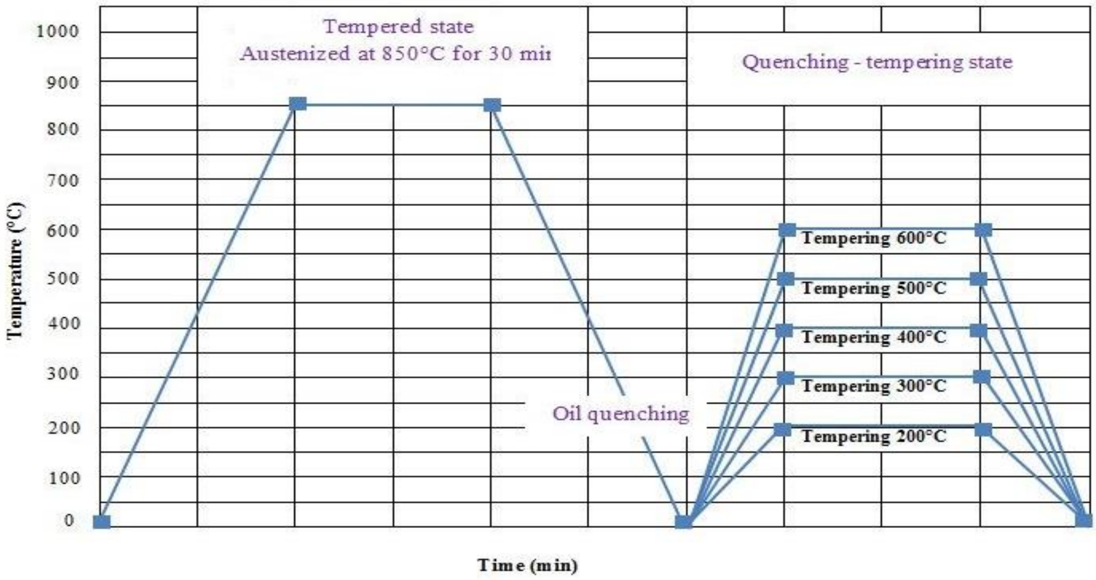

Figure 2. Schematic illustration of heat treatment cycle used in this study

Figure 5. Test specimen polishing on disc abrasive

3. RESULTS AND DISCUSSIONS

Fracture toughness, $K_{IC}/MPam^{1/2}$ can be estimated from the mechanical properties obtained by tensile test. The Rolfe-Novak correlation can be successfully used for that purpose [15]. In table 2, we present a short summary of the results of mechanical tests carried out on the DIN41Cr4 steel.

$K_{IC} = \sqrt{6.4\, R_e(100\text{KV} - R_e)}$ (1)

Where:

K_{IC} : Fracture toughness

R_e: Yield strength

KV: Impact energy

3.1. Hardness

Figure6 exhibits the influence of tempering temperature at various tempering temperatures for 1hour on the average value of Rockwell hardness. It can be seen that the hardness of 41Cr4 steel gradually decreases from 48 HRC to 24 HRC with increasing the tempering temperatures in the range of 200 - 600°C; it is found that the rate of decrease of Rockwell hardness in lower tempering temperature range of 200-400 °C is higher than that in temperatures ranges of 400-500 °C and 500- 600°C. It was observed that different heat treatment processes gave different hardness. The hardness gradually decreases in ranges of 200 -400 °C and 500- 600°C but from 400 to 500°C the hardness decrease sharply about 10 HRC. It can be explained on the phase transformation of steel during the quenching process, the tempered martensite formation, the reduction in dislocation density and coarsening of transition carbides [4, 7, 16, 20].

Many researches [16-18] have done the effect of retained austenite and the reduction in dislocation density and coarsening of transition carbides for decreasing of hardness, this material has a martensitic structure combined of bainite, and it was brittle after the quenching state [19,20]. The carbon rejected for these two phases is the major factor controlling all the microstructural transformation of the steel studied, the addition elements such as Cr and Mn are also known to promote steel during continuous cooling by bainite formation, with the increase of Mn and Cr content, the bainitic ferrite plate thickness decreased and the volume fraction of retained austenite increased. The bainite can also be produced as a result of decomposition of austenite γ during quenching, a small change in hardness at low tempering temperatures between 200 - 300°C is observed [21,22]. It can be explained that the decrease in hardness could be attributed to softening effect of the hard martensite and recrystallization of more ferrite on tempering [12].

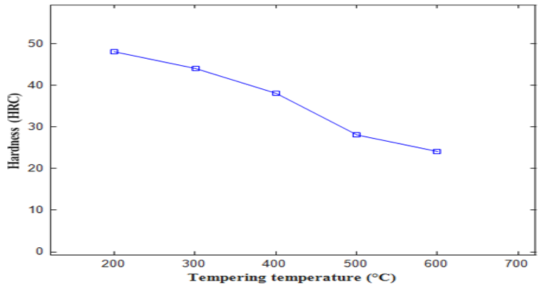

Figure 6. Variation of hardness with tempering temperature

3.2. Tensile properties

The values of tensile properties of DIN 41Cr4 steel are shown in Figure 7. There are three stages of yield strength (YS) and the ultimate tensile strength (UTS) as a function of the tempering temperature.

1. With the tempering temperature increasing up to 400°C, the YS and UTS slightly decreases about 100 MPa.
2. From 400 to 500°C, the YS and UTS decrease sharply from 1377 to 970.6MPa for YS and 1509 to 1061MPa for UTS.
3. From 500 to 600°C the YS and UTS decrease gradually about 200 MPa.

Many research studies [23-25] explained that with an increase in the tempering temperature, the carbon concentration of the matrix in the tempered martensite decreases due to the diffusion of carbon atoms into cementite. Therefore, the strength of the tempered martensite decreases, and its ductility increases. As a result, the higher the tempering temperature, the lower the dislocation density, and the lower the rate of work hardening [26-28].

It can be seen also from Figure7 that there is no significant effect of phenomenon of tempered martensite embrittlement (TME) on the tensile properties [29, 30].

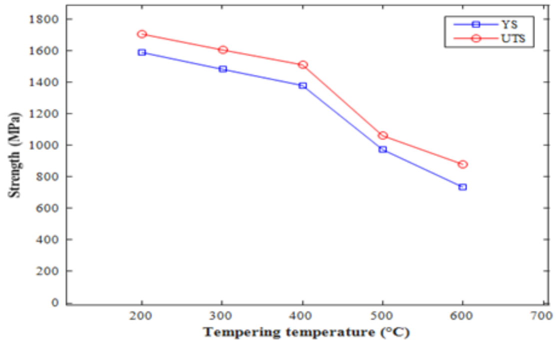

Figure 7. Variations of tensile properties with tempering temperature

Table 2: Mechanical test results for heat treatment

Treatment	YS [MPa]	UTS [MPa]	EL [%]	Kv [J]	K_{IC} [$MPa\sqrt{m}$]	HRC
quenching 850°C.tempering 200°C	1586.11	1703.08	2.35	9.51	5.52	48.07
quenching 850°C.tempering 300°C	1480.10	1603.13	3.67	10.33	6.07	44.12
quenching 850°C.tempering 400°C	1377.02	1509.10	4.04	17.02	10.39	38.17
quenching 850°C.tempering 500°C	970.16	1061.03	8.05	99.33	63.24	28.03
quenching 850°C.tempering 600°C	773.18	880.05	9.66	118.66	75.69	24.15

3.3. Impact energy

The impact energy is shown in Figure 8, the variation of impact energy KV depending on the tempering temperature. The variation of impact energy with temperature consist a several stages. A Charpy hammer with an energy of 150J according to ASTM D6110 [38].

1. With the tempering temperature increasing up to 300°C, the impact energy increases slowly;
2. From 300 to 400°C, the impact of energy increases slightly about 7 J;
3. From 400 to 500°C, the impact of energy increases very sharply from 17 to 99.33 J;
4. From 500 to 600°C, the impact of energy increases sharply about 20J.

At state of tempering temperature 200- 400°C the impact energy is low (9,5J - 17) , it causes a slight increase in this energy at the tempering temperature 400°C, above the temperature 400°C, impact toughness of DIN 41Cr4 is increased when the tempering temperature is increased. Same researches [4, 31] explained that retained austenite has soft structure and increment of impact toughness directly related to retained austenite. Developments of tempering processes and coarsening of the structure are responsible for this increase of impact toughness; this behavior reflects a growing plasticity of steel studied as the tempering temperature increases. It can be observed phenomenon of ductile-brittle transition temperature according the impact energy [32].

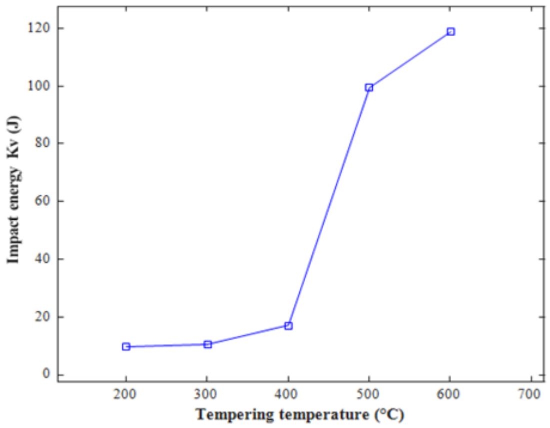

Figure 8. Variations of impact energy with tempering temperature

3.4. Elongation

The variation of elongation (EL) as function as tempering temperature is shown in Figure9.It can be seen the increase of elongation with the tempering temperature increasing up to 600°C, the gradual increasing of percent elongation due to the effect of retained austenite and the decrease of dislocation density and lower work hardening rate at high tempering temperature [8, 33].

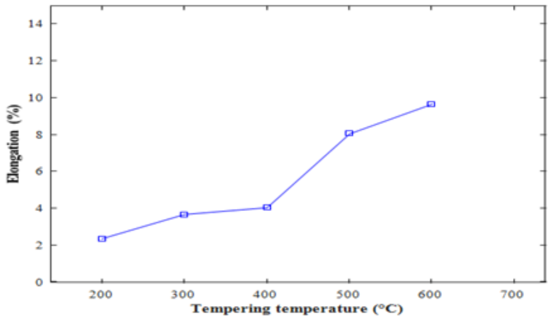

Figure 9. Variations of elongation with tempering temperature

3.5. Grain size

The Figure 10 shows the evolution of grain size according to the tempering temperature, at range of tempering temperatures of 200-500°C the grain size is gradually increase, above tempering temperature 500°C the grain size will be increased sharply until the value of 14 µm which corresponds to the tempering temperature of 600°C.

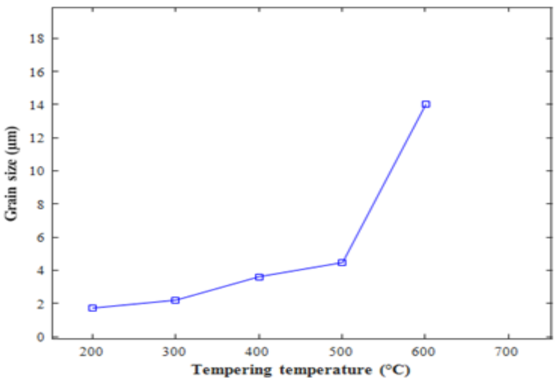

Figure 10. Variations of grain size with tempering temperature

3.6. Morphology and microstructure

The microstructural analysis of samples is shown in Figure 11, in (Figure 11 (a)) the microstructure consists of tempered martensite (M) and characterized by cementite plates in the ferrite matrix at the tempered microstructure state [7, 34]. The microstructure of the sample tempered at 200°C (Figure 11 (b)) consists of the lath martensite, which differs slightly from the quenched sample [33-38], the carbide precipitation takes place of the lath martensite with increasing of tempering temperature. When the tempering temperature increases to 400 °C (Figure 11 (c)),the microstructure of the tempered sample mainly consist the lath martensite and ferrite , some research [4,7] explained that the austenite decomposes and further increase of temperature ranges (300 - 450°C) leads to the formation of cementite (Fe_3C) platelet phase (Figure 11(c)).The microstructure of the tempered sample correspond to the tempering temperature 600 °C (Figure 11 (d)), consists of ferrite and carbides.

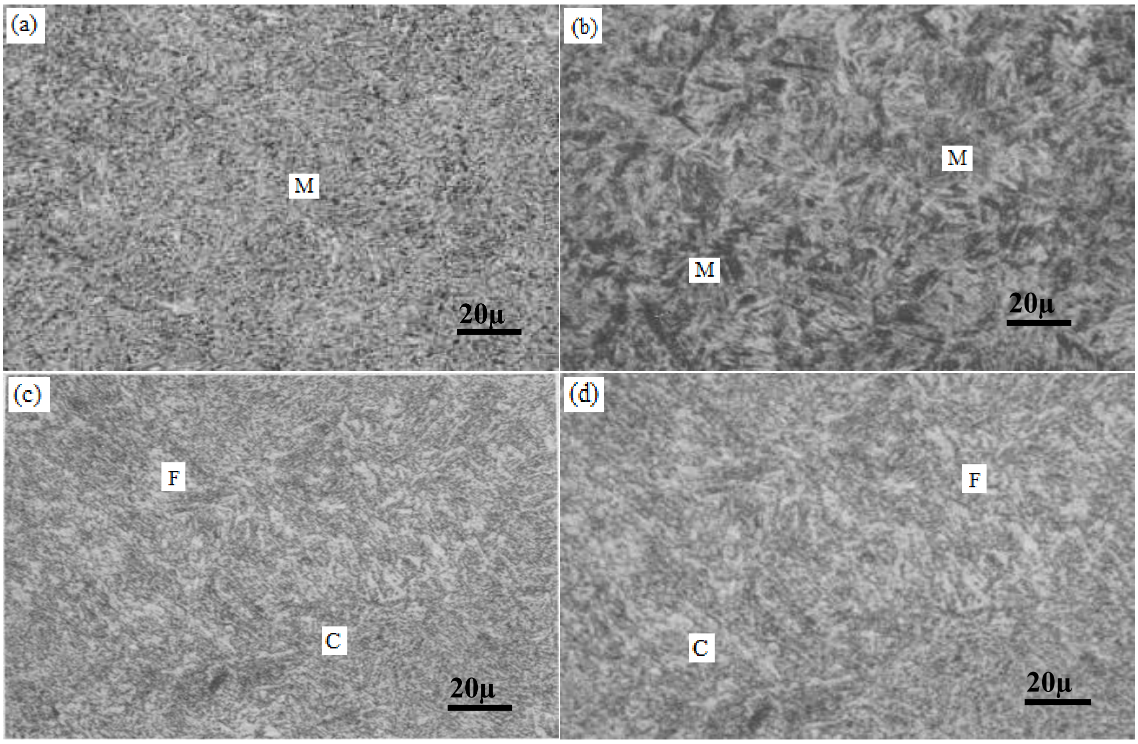

Figure 11. Optical micrographs of investigated DIN 41Cr4 steel as function of heat treatment

(a) As-quenched sample; (b) Tempering at 200 °C; (b) Tempering at 400 °C, (d) Tempering at 600 °C

4. CONCLUSION

Studies have demonstrated the effect of tempering temperature on the mechanical properties of DIN 41Cr4 steel, testing of all samples (tensile testing and impact test) with heat treatment of tempering temperature are revealed.

The main conclusions are summarized as follow:

- Hardness gradually decreases till tempering temperature reaches 400°C, and then decreases rather sharply;
- Yield strength and ultimate tensile strength gradually decrease till tempering temperature reaches 400°C, and then sharply decreases;
- Impact toughness steadily increases till tempering temperature becomes 400°C, and then it rises sharply;
- Percent elongation gradually increases till tempering temperature reaches 400°C, and then it increases rather sharply;
- At tempering temperature of 200°C the microstructure of DIN 41Cr4 steel consists of lath martensite, with increasing of tempering temperature the carbide precipitation takes place of the lath martensite, till tempering temperature of 600°C the microstructure consists of ferrite and carbides.

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