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The effect of heat treatment on mechanical properties of 42CrMo4 steel

A. Çalık [a], O. Dokuzlar [a], N. Uçar [b,*]
[a] Department of Machine and Manufacturing, Isparta University of Applied Sciences, Turkey
[b] Department of Physics, Suleyman Demirel University, 32260, Isparta, Turkey
* Corresponding e-mail address: nazimucar@yahoo.com

ABSTRACT

Purpose: In this study, the effect of heat treatment on the microstructure and mechanical properties of 42CrMo4 steel were investigated.

Design/methodology/approach: The samples were annealed at 860°C for 120 min. followed by oil quenching and then tempered at temperatures between 480 and 570°C for 120 min. The microstructure of untreated 42CrMo4 steel mainly consists of pearlite and ferrite whereas the microstructure was found to be as a martensitic structure with a quenching process.

Findings: The results showed that there is an increase in yield stress, ultimate tensile stress, hardness and impact energy, while elongation decreases at the end of the quenching process. Conversely, yield stress, ultimate tensile stress and hardness decrease slightly with the increasing of tempering temperature, while elongation and impact energy increase.

Research limitations/implications: Other types of steels can be heat treated in a wider temperature range and the results can be compared.

Practical implications: It is a highly effective method for improving the mechanical properties of heat treatment materials.

Originality/value: A relationship between the mechanical properties and the microstructure of materials can be developed. The heat treatment is an effective method for this process.

Keywords: 42CrMo4 steel, Quenching and tempering, Martensitic structure, Mechanical properties

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PROPERTIES

1. Introduction

AISI 4140 or 42CrMo4 is a low-alloy steel widely used in various applications such as automotive driving elements, bolted assemblies, forged parts, armour materials, etc. due to high strength and toughness behaviour [1-4]. In the literature [5-8], it has been indicated that this steel is frequently used after heat treatment when a combination of good strength and toughness is required. Quenching and tempering are heat treatments that is strengthen and harden materials like steel and other iron-based alloys. Tempering is normally applied to decrease brittleness, increase ductility and toughness, as well as to relief tensile residual stresses generated during the cooling phase [9]. Corresponding to this, Chaouch et al. showed that tempering treatment on 42CrMo4 steels introduces a decrease of in both hardness levels, yield and failure strengths by 42%, increase of both in ductility and reduction in area by 16% and 163%, respectively [10]. On the other hand, a mathematical model based on finite volume method for prediction of mechanical properties of quenched and tempered 42CrMo4 steels was developed by Smoljan et al. [11]. According to this model, hardness of quenched and tempered steel was expressed as a function of maximal hardness of actual steel according to the time and temperature of tempering. Although mechanical properties of 42CrMo4 steel are well documented as theoretical and applied [12-15], there is still an interest in studying the mechanical properties of this steel. The aim of the present study is to examine the effect of tempering on the microstructure and mechanical properties of 42CrMo4 steel.

2. Experimental procedure

38 mm in diameter and 220 mm in length cylindrical samples from 42CrMo4 medium alloyed carbon steels were used in this study. The chemical composition of the alloy is shown in Table 1. The heat treatment of samples consisted of annealing, quenching and tempering. Firstly, the 42CrMo4 steels were inserted into a heated furnace at 870°C for 120 min, quenched in oil, and then tempered at different temperatures 480-570°C for 120 minutes, respectively, followed by air cooling (Fig. 1). Before and after heat treatment, microstructure of polished and etched specimens was studied using an optical microscope (Zeiss). In addition, tensile and hardness tests were performed for the specimens in order to determine the mechanical properties after the tempering. To determine the hardness and mechanical properties of 42CrMo4 steel grades alloyed carbon steels, a Vickers microhardness tester with a load of 300 g and an Instron type machine, fully automatic and having with a 60 ton capacity were used, respectively. The Charpy impact tests were performed using an instrumented Charpy impact testing machine with an energy capacity of 300 J at 20°C.

Table 1.
Composition of 42CrMo steel, %

Steel	C	Si	Mn	P	S	Cr	Mo
42CrMo4	0.44	0.22	0.86	0.009	0.017	1.07	0.25

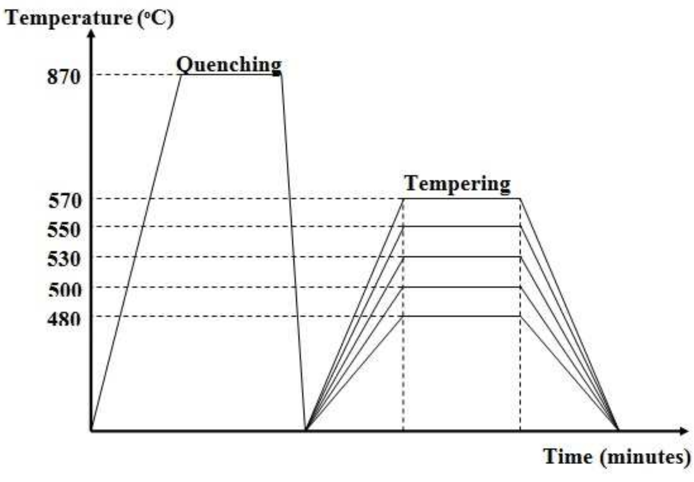

Fig. 1. Temperature-time graph involving quenching and tempering

3. Results and discussion

The initial microstructure of the 42CrMo4 before heat treatment was the 70% perlite and 30% ferrite (pearlite having dark contrast and ferrite having light contrast) (Fig. 2a). After annealing (at 860°C for 120 min.) the microstructure of steels was obtained as austenite and dissolved perlite and ferrite (Fig. 2b). On the other hand, the microstructures after quenching process are observed as martensite (lath martensite) and small amount of austenite (<8%) (Fig. 3a).

Finally, Figure 3b shows the optical micrographs of the tempered specimens. The structure of tempered 42CrMo4 steels is made of tempered martensite (and 3% bainite) with much finer carbides. Similar results were obtained from Liu's study on 718H pre-hardened mould steel [16]. Liu et al. [16] showed that the tempered martensitic produces a large amount of carbides which depends on tempering time as well as the tempering temperature.

From tensile tests, ultimate tensile stress (maximum stress on the stress–strain curve, σ_{UTS},), yield stress (stress at 0.2% offset strain, σy), elongation, hardness and impact energies were determined. Their obtained values for 42CrMo4 steels of quenched at 900°C and tempered at temperature in the range 480-570°C together with untreated steels are given in Table 2 and Figure 4. These values represent the average of five measurements.

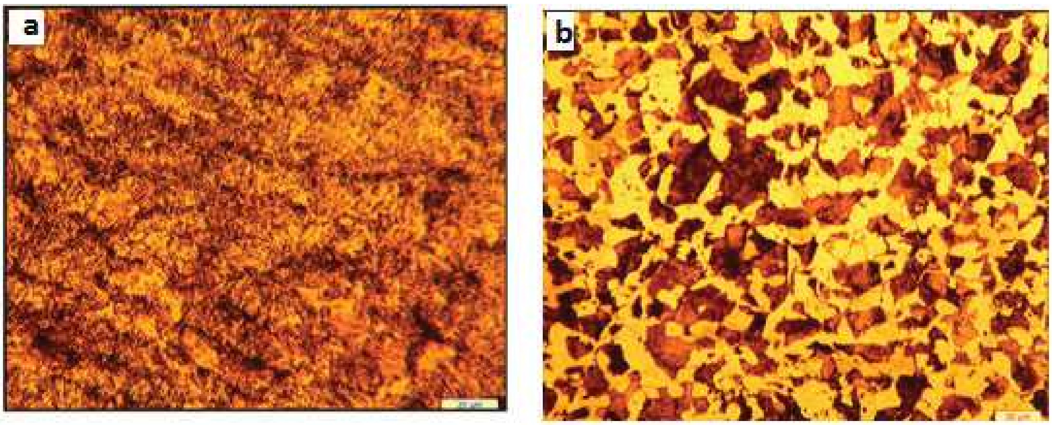

Fig. 2 Optical micrographs of 42CrMo4 steel before heat treatment (a), and after annealed at 870°C for 120 min. (b)

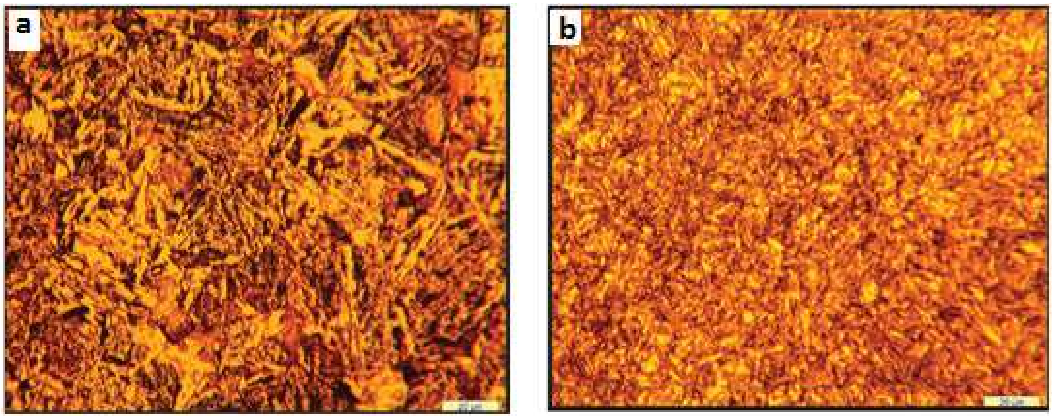

Fig. 3. Optical micrographs of 42CrMo4 steel after quenching in oil (a), and after tempering at 550°C (b)

Table 2.
Mechanical properties of 42CrMo steel versus tempering temperatures

	Yield Stress (σy), MPa	Tensile Stress (σ_{UTS}), MPa	Elongation, %	Vickers Hardnes	Impact Energy, J
Untreated	834	940	11.4	235	22
After quenching	1080	1194	8.1	401	37
Temp. 480°C	1066	1157	13	373	40
Temp. 500°C	1063	1147	14	364	42
Temp. 530°C	1044	1116	14.3	362	45
Temp. 550°C	1006	1115	15.2	357	50
Temp. 570°C	1003	1113	16	354	54

As can be seen from Table 2 and Figure 4, the tempering and quenching effect on the mechanical properties is clearly seen. The σ_{UTS} and σy variations have almost the same pattern as hardness variation. The σ_{UTS}, σy and hardness decrease with the increasing of tempering temperature, while elongation and impact energy increase.

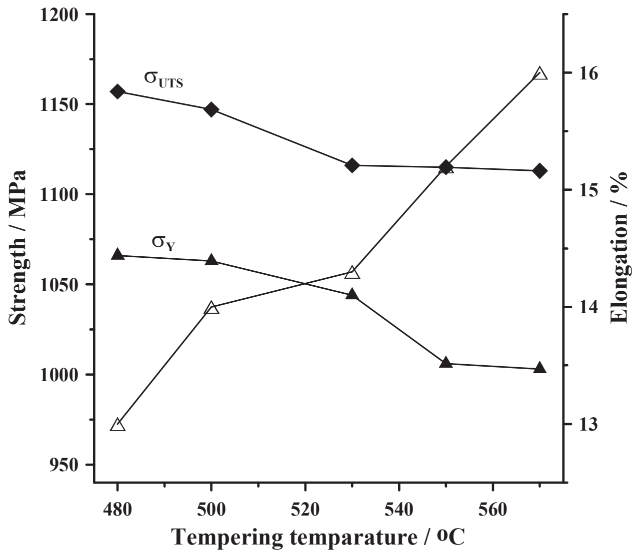

Fig. 4. Variations of tensile properties with tempering temperature

Firstly, we look at the quenching effect on the mechanical properties. From Table 2 and Figure 4, compared to untreated samples, quenching has a serious effect on mechanical properties. In this study, the structure of samples is martensitic phase after the quenching process. It is well known that this phase is accompanied by a large amount of internal stress due to especially extreme point defects and dislocations and also other defects with quenching, which rapidly increases the σy, σ_{UTS} and hardness of samples. However, the internal stress generated during martensite formation causes a significant reduction of the elongation. Thus, we think that the change of the mechanical properties after the quenching process is strength caused by microstructure or martensite as well as internal stress.

Now let us consider the relation between tempering temperature and mechanical properties of samples. When σ_{UTS}, σy and hardness reach their maximum values, when quenching process due to martensite formation, they rapidly decrease after tempered at 480°C and continue to steadily decrease with increasing tempering temperature. This effect can be explained as a result of the reduction of dislocation locking and concentration of the tempered martensite with increasing tempering temperature. Corresponding to this, Li et al. [17] reported that with increasing the tempering temperature, the concentration of the tempered martensite decreases mainly due to the movement of dislocations by thermal assistance. Therefore, the σ_{UTS}, σy decrease and the elongation increases.

Similarly, it is well known that the quenching creates a supersaturated solid solution and increase vacancies in quenched specimens. Thus, high hardness such as tensile properties correlates with high resistance to slip and dislocation. On the other hand, we noticed that the hardness decreases with increasing tempering temperature (Fig. 5). This is a consequence of diffusion of carbon atoms from martensite to form a carbide precipitate as indicated by studies [18-21].

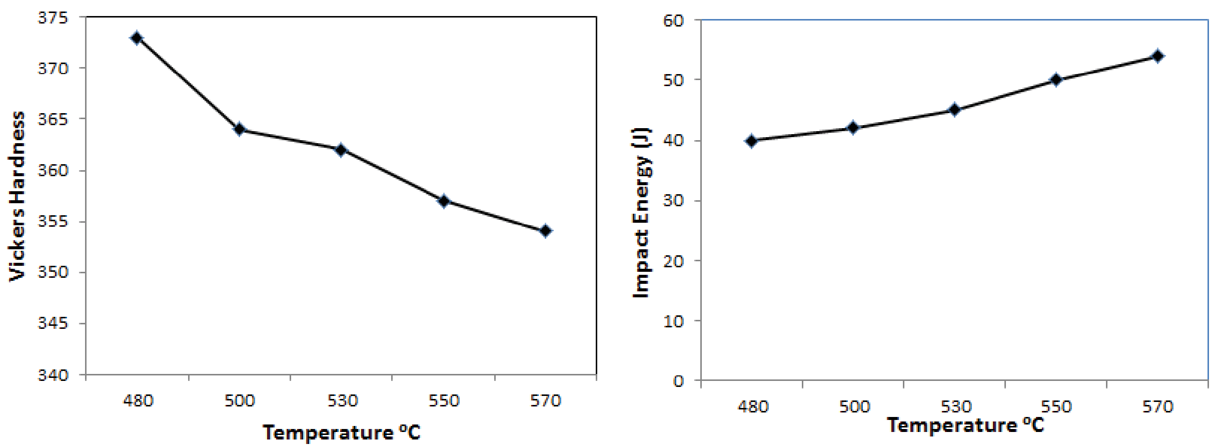

Fig. 5. Effect of tempering temperature on hardness and impact energy

Moreover, the impact energy increases with increasing the tempering temperature due to increasing the elongation and toughness, which are essential for enhancing impact energy absorption (Fig. 5).

In conclusion, the heat treatment process leads to a change in phase microstructural and also dislocation behaviour in 42CrMo4 steels. Tempering at 480-570°C for 120 minutes results in a good combination of tensile strength, percent elongation, impact energy and hardness. Thus, this steel can be used at different purposes and applications as per the requirement.

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