

Influence of Si and Cu Content on Tempering and Properties of 54SiCr6 Steel

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The 54SiCr6 steel belongs to spring steels which excel high strength and at the same time reaches high values of reduction of area and sufficient value of elongation. Nowadays, new methods are searched and examined how to get better properties from materials, higher strength and toughness, longer fatigue resistance or better corrosion properties. In the case of silicon-chromium spring steels, innovative heat treatments are investigated such as quenching and partitioning which enables to achieve higher ductility of steel due to higher content of retained austenite. The way of modification of the chemical composition of the 54SiCr6 steel was chosen in combination with conventional heat treatment composed of quenching and tempering to get better properties. The materials with increased content of copper to 1.5 wt. % and silicon to 2.5 wt. % were prepared. The influence of alloying elements on microstructure and mechanical properties was followed up to the tempering temperature of 400 °C.

Keywords: High-strength steel, spring steel, 54SiCr6, copper precipitation, heat treatment

1 Introduction

The 54SiCr6 steel is a low-alloyed medium carbon steel exceeding with high yield and tensile strength, ductility and fatigue resistance. It is used as automobile and rail vehicle springs, flexible elements and other vibration dampers. The desired mechanical properties are usually achieved by conventional heat treatment including quenching and tempering. Other cooling regimes as quenching and partitioning are explored to gain steel with high strength and at the high elongation as well [1-3].

The influence of the initial microstructure before hardening is described in work [4]. The states of microstructure after hot rolling (HR), soft annealing (SA) and accelerated carbide spheroidisation and refinement (ASR) were chosen for the investigation and the quenching temperatures in the range of 810 – 890 °C were also examined. The ASR material showed higher tensile strength than the SA material and at the same time, it reaches higher values elongation and reduction of the area than specimen after hot rolling. The microstructures after HR and ASR enable to use lower quenching temperature than after SA [4].

Several transformations occur in as-quenched steel during the heating process, which can be divided into several temperature stages. At the lowest temperatures under 80-100 °C, segregation of carbon atoms to lattice defects and formation of clusters occur. In the second stage of tempering approximately from 100 °C to 200 °C, the transition ϵ -carbide precipitates. The temperature range from 200 °C to 300 °C involves the decomposition of retained austenite into ferrite and

cementite. In the fourth stage of tempering (250 – 500 °C), the transition ϵ -carbides are transformed into more stable cementite [5, 6]. Firstly, cementite precipitates at interfaces as fine plates and the tetragonality of martensite fully diminishes [7].

The non-carbide alloying elements like silicon and copper affect the tempering process too. Silicon delays the tempering transformations generally. It retards the formation of the ϵ -carbide, extends the temperature range of stability of ϵ -carbide and shifts the cementite formation to higher temperatures. Silicon affects the evolution of the lattice mismatch, dislocation density, amount of retained austenite as well and it contributes to solid solution strengthening of steels significantly [8-10]. Alloying by copper in an amount higher than 0.5 wt. % enables to achieve precipitation strengthening during tempering. The copper-precipitates observation and increase of strength was reported after aging at the temperatures between 400 and 600 °C in [11, 12]. The process of strengthening is associated with the formation of copper precipitates in the following sequence: copper rich clusters, bcc copper, 9R (orthorhombic lattice), 3R and finally stable fcc copper precipitates [12-14]. The possibility of copper strengthening was researched in low carbon steel [11], medium carbon steel [12, 15] and interstitial free steel [16].

In the present study, the effect of alloying by silicon and copper on properties of the 54SiCr6 steel is investigated. The conventional heat treatment was applied. The microstructure, mechanical properties by the hardness, impact energy and tensile test were characterized.

2 Experimental

The chemical compositions of the studied materials are given in Tab. 1 (measured with Q4 TASMAN optical emission spectrometer). Their chemical compositions differ substantial in Si and Cu content. The steels were melted in vacuum induction furnace and casted into 45 kg ingots. The ingots were heated up at the temperature of 1050 °C and the blocks were hot rolled to the thickness of 14 mm followed by air cooling. The samples were normalised by annealing at 850 °C for 40 minutes. The manufactured cylinders (length of 120 mm, diameter of 13 mm) were austenitised at 900 °C for 20 minutes and quenched into room temperature oil and then tempered at the temperatures of 200 °C, 300 °C and 400 °C for 120 minutes.

Tab. 2 Chemical compositions of steel in wt. %

| Steel | C | Si | Mn | Cr | Cu | Fe |
|-------|------|------|------|------|------|------|
| A | 0.57 | 1.51 | 0.68 | 0.75 | 0.12 | Bal. |
| B | 0.56 | 1.54 | 0.70 | 0.77 | 1.48 | Bal. |
| C | 0.57 | 2.49 | 0.75 | 0.78 | 1.47 | Bal. |

Metallographic samples were prepared on the cut parallel to the longitudinal direction of the cylinders by mechanical grinding and polishing. The microstructure of samples was revealed by in 2% Nital reagent. The microstructural observation was performed with a light microscope (LM) NIKON ECLIPSE MA200 and scanning electron microscope (SEM) JEOL IT 500 HR. Mechanical properties were examined by tensile test, hardness measurements and Charpy impact test at room temperature. Two tensile test samples were machined from each sample. The tensile specimens had the diameter of 8 mm and a length of 50 mm. Quasistatic tensile tests were performed according to the EN ISO 6892-1 standard with a deformation rate of 0.75 mm/min, using a Zwick Z250 testing machine with a 250 kN capacity. The values of the ultimate tensile strength (UTS), yield strength (YS), total plastic elongation (elongation A5) and contraction (Z) were determined for samples tempered at 400 °C. Hardness according to Vickers with a load of 10 kg was measured at 10 points for each sample and Charpy impact testing was conducted with two specimens for each condition.

3 Results and discussion

3.1 Microstructure

The microstructure of the investigated steels is found almost the similar. The microstructure of the steel B after normalisation annealing is shown in Fig. 1. There are several ferritic grains in the pearlitic matrix. The TiN and MnS inclusion particles are visible

as well. The microstructures of all quenched samples consist of lath martensite mainly. The microstructure of steel A represents martensitic structures of samples after quenching. Moreover, primary austenite grain (PAG) boundaries can be seen in microstructure of steel A in Fig. 2.

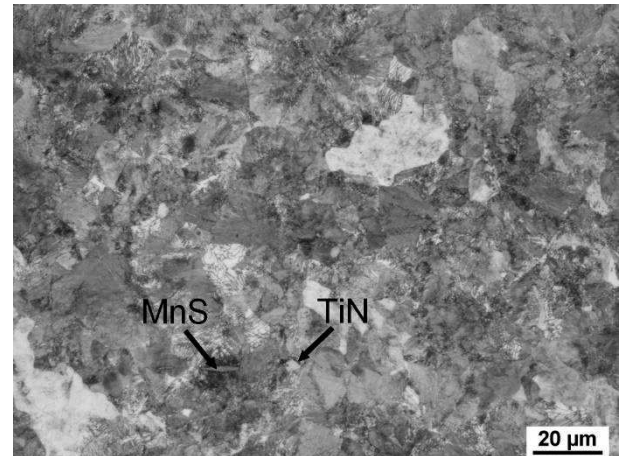


Fig. 1 Microstructure of the steel B after normalisation (LM).

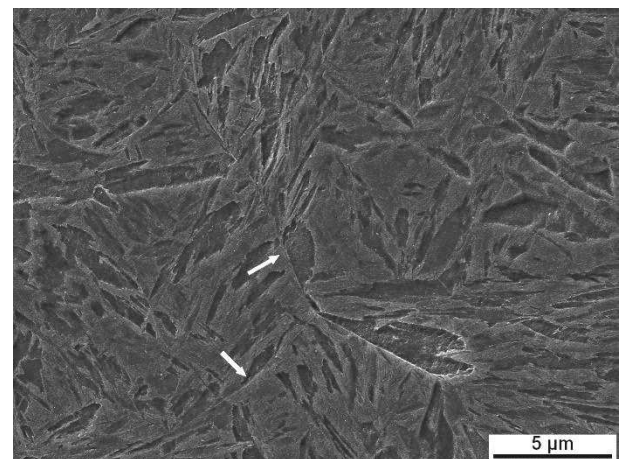


Fig. 2 Martensitic microstructure of steel A after quenching. White narrow lines show PAG boundaries.

The redistribution of carbon and formation of the ϵ -carbides occurs during tempering at 200 °C. The rod-like ϵ -carbides are present in all steels in the interior of the martensitic crystal during tempering between temperatures of 200 – 400 °C as it is possible to observe it in Fig. 3 and Fig. 4. The visibility of ϵ -carbides depends on the orientation of the martensitic crystal and the grade of etching. The retained austenite (RA) is also well visible in the microstructure of the steel B after tempering at 200 °C and 300 °C. The microstructures of studied steels do not undergo a significant transformation during tempering up to the temperature of 400 °C by observation at lower magnification. The microstructure corresponds to tempered martensite and the ϵ -carbides are stable in microstructure still and only its density is a little bit lower in comparison to lower tempering temperatures of 200

°C and 300 °C. Similar results were received by the study [17] focused on steel with chemical composition closed to our steels. There was concluded, that the martensite tempered at 400 °C and below contains a larger amount of ϵ -carbides compared to martensite

tempered at 425 °C. The small difference in the crucial tempering temperature can be caused by the use of shorter tempering time in [17]. The retained austenite was observed by SEM after tempering at 200 °C and 300 °C (Fig. 3a,b).

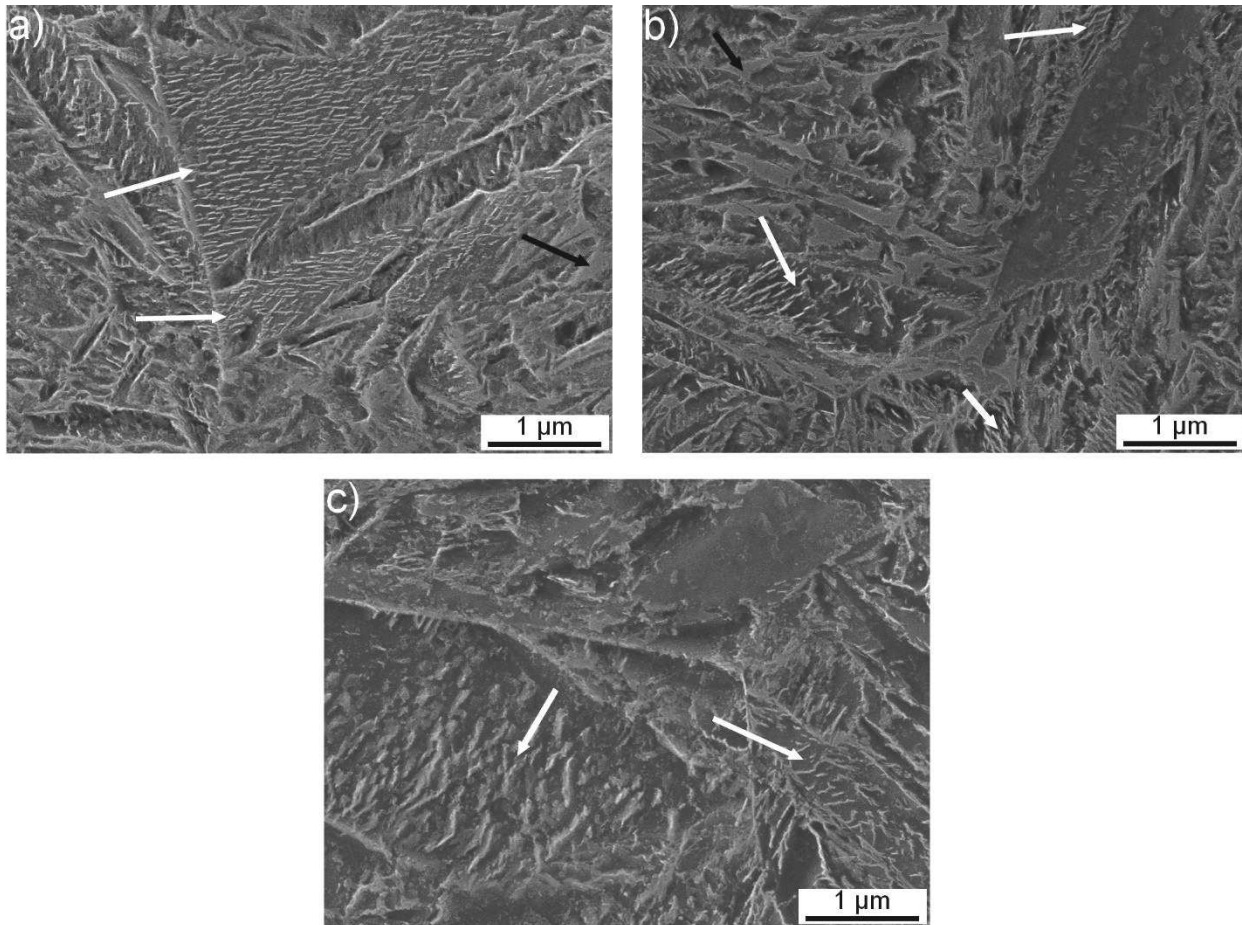


Fig. 3 Microstructures of steel A after tempering a) at 200 °C, b) at 300 °C, c) 400 °C. White narrows label ϵ -carbides rich area and black narrow shows RA.

The fine globular particles start to nucleate in the interior of the martensite of steel alloyed by Cu, see in Fig. 4. In [12], the temperature range for the initiation of Cu precipitation is stated between 400 – 500 °C. Another paper [15] describes the beginning of precipitation already below the temperature of 400 °C. To

decide if the nucleus belongs to precipitation of the Cu particles in the steels B and C it is necessary to perform further a transmission electron microscopy observation. The difference between microstructure of these steels modified by silicon was not visible by the SEM observation.

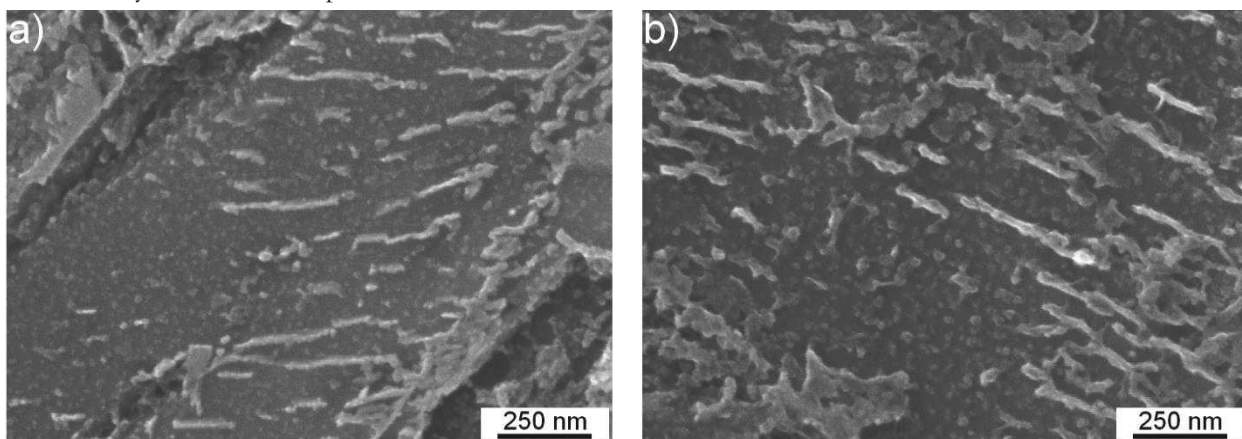


Fig. 4 ϵ -carbide and fine globular particles formed during tempering at 400 °C in steels alloyed by Cu - a) steel B, b) steel C.

3.2 Mechanical properties

The changes in mechanical properties will be evaluated separately for the effect of copper and silicon. Fig. 5 shows the evolution of hardness after quenching and during tempering. Hardness of the steel B modified by copper is lower in all states of tempering compared to steel A. It means that any strengthening mechanism (solid solution strengthening and precipitation strengthening does not succeed significantly in the applied tempering temperature range. The fine globular particles observed in the microstructure of steel B after tempering (Fig. 4) do not strengthen significantly the steel as well. The results of the tensile test after tempering at 400 °C confirm the values of hardness measurement. The steel A reached the following results: UTS = 1897 MPa; YS = 1705 MPa; A5 = 10.3 % and Z = 43.9 %. All parameters are lower for steel B: UTS = 1890 MPa; YS = 1626 MPa; A5 = 9.0 % and Z = 30.4 %. These results are in contradiction to some studies, e.g. in the study [11], copper caused the clear increase in mechanical properties during tempering at 400 °C of low carbon steel; in the work [15] the beginning of the hardness increase for investigating medium carbon steel was detected at the same tempering temperature. The presence of chromium and main silicon can shift the strengthening effect to higher tempering temperatures [9]. Alloying by copper decreases the impact toughness of material (Fig. 6). The highest worsening of impact toughness was determined after tempering at 400 °C. In this state, the impact energy of steel B was close to the half value of the impact energy of the steel A.

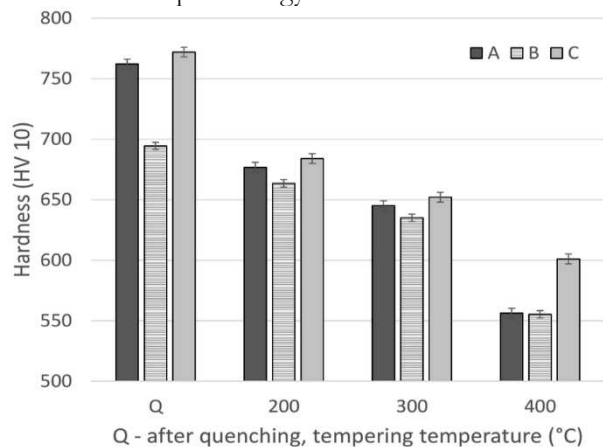


Fig. 5 Hardness of samples after quenching and tempering

In case of the steel C alloyed by the highest amount of silicon, the highest values of hardness were measured in quenched and tempered states, see in Fig. 5. The values of UTS and YS were the highest or very close to steel A as well with exception of the quenched state. The biggest increase in hardness and UTS compared to the steels A and B were determined after tempering at 400 °C (UTS = 2078 MPa; YS = 1753 MPa; A5 = 4.5 % and Z = 8.0 %). The reason for it consists

in solid solution strengthening by silicon (this phenomenon takes place in all states) and the influence of silicon on the tempering process like stabilisation of the ϵ -carbides and retardation of cementite growth occur during tempering at 400 °C. However, the increase in strength is accompanied by a considerable decrease in the reduction of area and elongation. The lowest value of impact energy of the steel A is located after tempering at 300 °C whereas this minimum of impact energy for steel C is shifted to the tempering temperature of 400 °C (Fig. 6). The loss of impact toughness with increasing tempering temperature is due to tempered martensite embrittlement (TME) and the same development of impact toughness was observed previously [9]. The coarsening or lateral thickening of cementite at martensitic lath boundaries seem to be responsible for the onset of TME according to [9]. Based on the previous study [9] it is possible to expect a further decrease in impact toughness of the steel C by increasing the tempering temperature up to 550 – 600 °C.

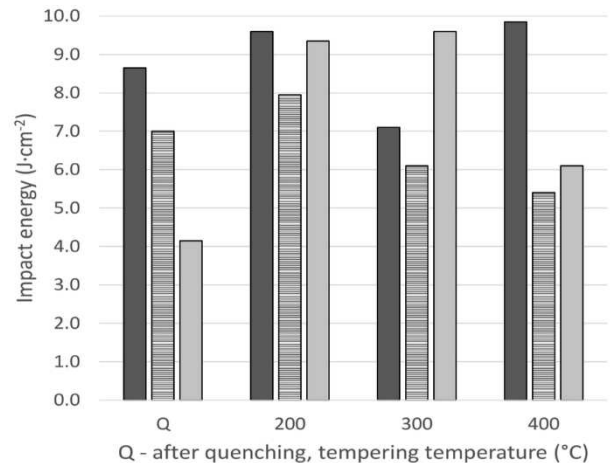


Fig. 6 Charpy toughness after quenching and tempering

4 Conclusions

The conventional heat treatment consisting of quenching and tempering of the medium carbon 54SiCr6 steel with different copper and silicon contents was performed. The effect of both alloying elements did not prove to be on the microstructure after tempering at the temperature of 200 °C, which was created by tempered martensite with the rod-like particles of ϵ -carbides. These ϵ -carbides were present in the microstructure after tempering at 400 °C as well and new globular particles appeared in steels modified by copper. The positive influence of copper addition into the 54SiCr6 steel on mechanical properties was not found by tempering up to the temperature of 400 °C. On the contrary, the values of reduction of area, elongation and impact toughness were worsened. In the material with the high silicon content, the values of hardness are increased by solid solution strengthening. The development of tempered martensite embrittlement is delayed and shifted to higher tempering

temperatures in the steel with 2.5 wt. % compared to steel with 1.5 wt. % of silicon.

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