

COPPER-ALLOYED STEEL WITH BAINITIC STRUCTURE

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Abstract

This article is devoted to the influence of copper on the bainitic transformation. Copper addition hinders proeutectoid ferrite formation and thus is favourable for bainitization. Copper is also one of the alloying elements used for the precipitation in ferrite matrix. The precipitation is usually induced by the formation of supersaturated copper solution in ferrite and subsequent heating. Normal way to achieve this treatment is quenching and tempering.

However, copper precipitation can be also induced during continuous cooling, if the austenite decomposition temperature is sufficiently high. Isothermal quenching into salt bath is a possibility to obtain both transformation strengthening and precipitation strengthening in one-step process.

Steel with 0.2 % of carbon and different Mn and Cu content was examined. Samples were austenitised and cooled in salt bath of different temperatures; from 320 to 420 °C. Mechanical properties were measured by tensile test and hardness measurement. Metallography analysis was performed to compare structure of the samples.

Keywords: Steel, bainite, copper precipitation, precipitation hardening

1. INTRODUCTION

Copper alloying is one of the possible means for ferrite strengthening. Temperature dependence of copper solubility in austenite and ferrite allows perform precipitation hardening. Copper is solved in solid solution at higher temperatures, steel is cooled down and precipitation treatment is then performed. Quenching and tempering is an obvious choice from classical heat treatment repertoire to induce copper precipitation in steel [1,2,3]. However, copper needs typically high temperatures and long tempering times to precipitate. Typically 1 hour at 500 °C. It is a high tempering temperature for low alloyed steels where high tensile strength is required. High tempered martensite loses most of its initial strength before onset of copper precipitation strengthening. This phenomenon is inevitable due to the difference between mobility of interstitial carbon and substitutional copper in ferrite crystal lattice.

This article is devoted to the experiment with copper precipitation strengthening during formation of ferrite in steel at higher temperatures [4]. Bainitic transformation gives an opportunity to this approach. Bainite gains its strength from small size ferrite sheaves and from precipitation of carbide particles. Retained austenite can be also present in the structure, however composition of used experimental steel did not promise its presence in significant amount. Copper precipitation within bainitic sheaves is another mechanism for bainite strengthening.

The experiment compares three experimental materials with and without copper and with different manganese content. Bainitization was performed by steel austenitization and cooling in salt bath with temperatures from 320 to 420 °C. Salt bath dwell time was chosen 15 minutes to ensure that bainitic transformation will be complete. It was not longer to avoid copper precipitation from supersaturated solid solution during temperature

hold. Salt bath temperatures were set too low for significant copper precipitation during 15 minutes hold. Any possible copper precipitation occurred during the bainitic transformation or very shortly after it.

2. EXPERIMENT

Experimental melts were produced in vacuum induction furnace under the argon atmosphere. Three melts with raw mass 500 kg were casted. Chemical composition of the melts is in the **Table 1**. Alloying was chosen to show influence of addition of copper and its synergy with manganese since Mn is element increasing hardenability and potentially increasing amount of retained austenite. Boron was added to suppress proeutectoid ferrite and pearlite formation. Titanium was added primarily as nitrogen binding agent. Nitrogen can impair boron effect by bonding with it. When titanium is present, nitrogen prefers bonding with Ti, forming titanium nitride. Secondary, Ti can form fine carbides and carbonitrides, which persist in microstructure during austenitization and hinder austenite grain growth, as used in micro-alloyed steels [5]. Ti was added in concentration four times higher than expected concentration of the nitrogen.

Ingots with round cross section were produced. They were forged by the hydraulic press between flat swages into billets with cross section 300x80 mm. These billets were machined to remove scales and hot-rolled in duo rolling mill into sheets with thickness 4.5 mm. These sheets were descaled by sand-blasting and cold-rolled to the final thickness of 3.2 mm. Sheets were cut into the experimental samples 250 x 75 mm. Samples were cut in the rolling direction of the sheets. These samples were used for the heat treatment.

Table 1 Chemical composition of the experimental materials (in wt. %)

Material	C	Mn	Cu	Si	B	Ti	N	P	S
V0	0.22	0.98	0.12	0.073	0.0014	0.022	0.0056	0.008	0.003
V1	0.19	0.98	1.08	0.081	0.0013	0.025	0.0063	0.009	0.002
V2	0.21	1.91	0.98	0.095	0.0013	0.021	0.0053	0.008	0.002

Heat treatment consisted of heating samples and cooling in the salt bat. Samples were heated to the 870 °C in electric atmospheric furnace with holding time 30 minutes. Then they were put into salt bath with temperature 420, 380, 350 and 320 °C. Samples were left in the bath for 15 minutes.

Tensile test specimens were machined by milling from the samples. Flat specimens had gauge length 60 mm and width 8 mm. Quasi-static tensile test was performed using servo-hydraulic testing machine. Metallographic section was also prepared in the longitudinal direction by mechanical grinding and polishing. Hardness was measured by Vickers method with 10 kg load. Microstructure was revealed by Nital etchant. It was observed by optical and scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

Microstructure of all samples was bainitic. Different salt bath temperatures resulted in different size of ferritic sheaves and different carbide particle size. There are representative micrographs in **Figure 1** from samples treated in the coolest and hottest salt bath and with lowest and highest alloying. Dependence on the temperature is clearly visible - the lower temperature the finer structure. However there was no significant difference in bainite appearance among three tested materials at given salt bath temperature while observing by light microscope or SEM with magnification 10 000x. Carbides formed at the ferritic sheaves boundaries, at the prior austenite boundaries and within ferritic sheaves.

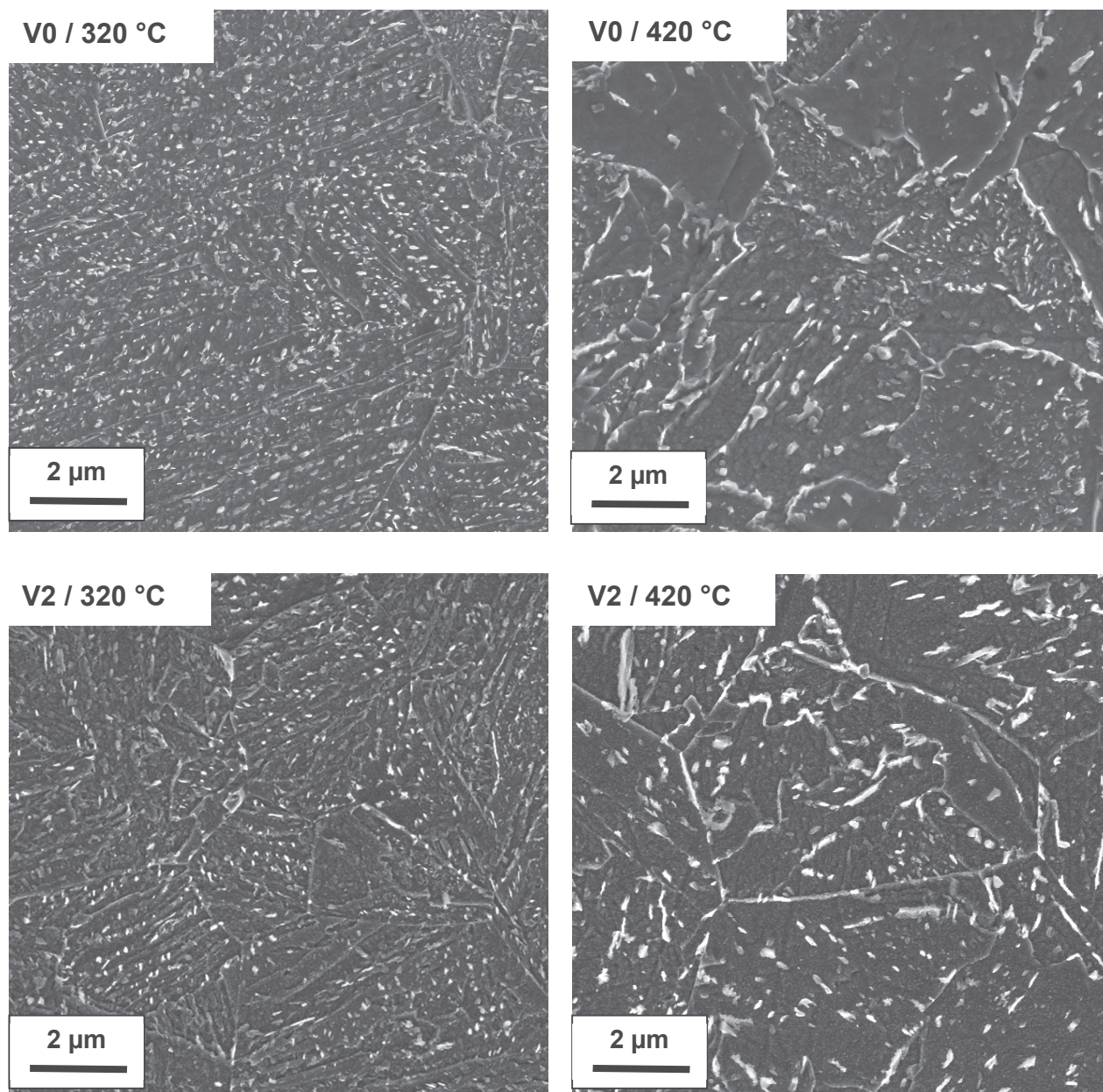


Figure 1 Microstructure of the samples V0 and V2 after cooling in 320 °C and 420 °C salt bath

Samples were examined by SEM also in higher magnification. **Figure 2** shows details of microstructure of all materials bainitized at SBT 380 °C. Micrographs show dark-grey ferrite matrix and bright cementite particles. Cementite particles have comparable size and appearance among the materials. Structures differ in presence of small particles in the ferrite matrix, less than 20 nm in diameter. Material V0 showed almost no small particles whereas ferrite in materials V1 and V2 was densely populated with them. This character of microstructure was observed at all SBTs. Interpretation of the small particles as copper precipitates manifestation is plausible. However it can't be stated that apparent diameter of the particles in SEM micrographs equals to the precipitate diameter measured by transmission electron microscopy (TEM). Etching could leave particle with different diameter than visible by TEM by lattice difference. SEM resolution is also at its limits to precisely determine diameter of these particles.

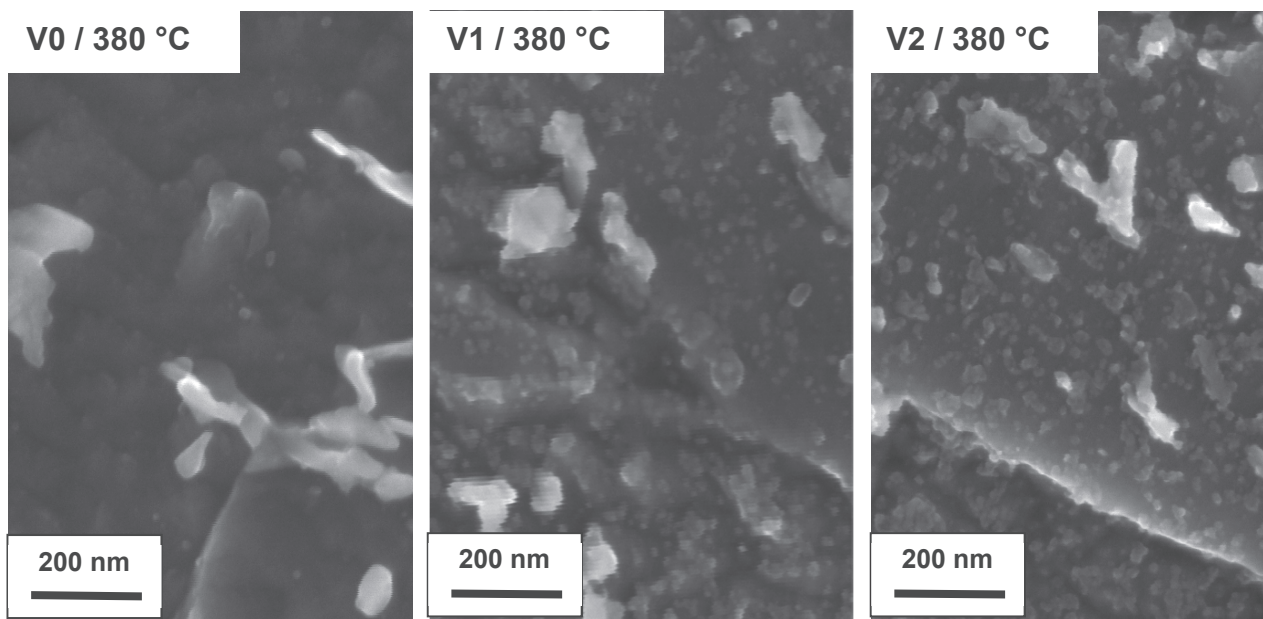


Figure 2 Microstructure of the test materials at higher magnification

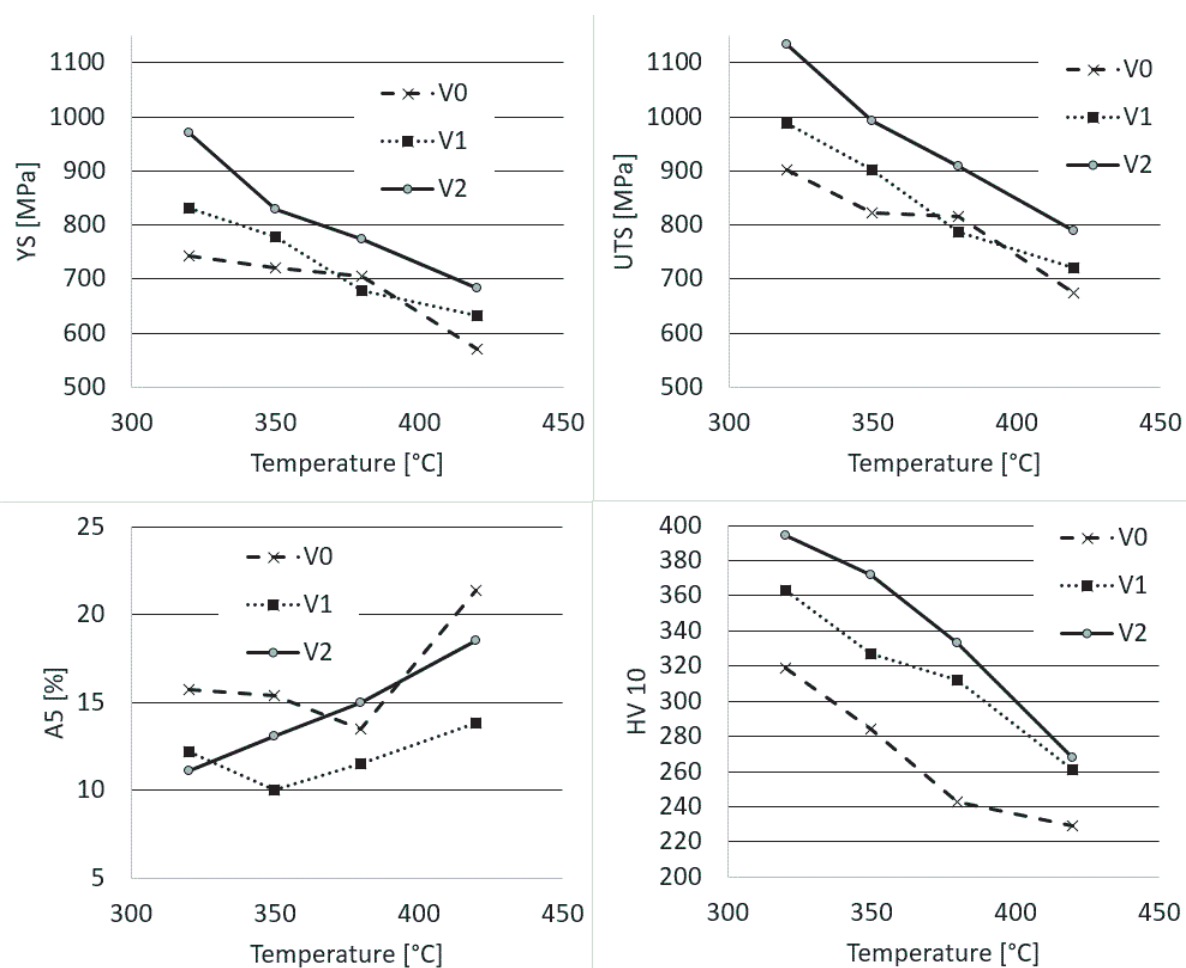


Figure 3 Mechanical properties of heat treated samples in dependence of salt bath temperature. Yield stress (YS), ultimate tensile strength (UTS), ductility (A5) and hardness HV10.

Mechanical properties of the samples are shown in **Figure 3**. Yield stress (YS), ultimate tensile strength (UTS) and hardness showed monotonous trend - decrease with increasing salt bath temperature. The ductility for the materials V0 and V1 had minimum at the salt bath temperature (SBT) 350 °C.

Comparison of materials V0 and V1 shows influence of copper alloying. UTS and YS increased by roughly 50 MPa except of SBT 380 °C, where material V1 has lower UTS and YS than V0, even though the hardness is significantly higher.

Addition of Mn caused another increase of strength, hardness and even ductility, which is comparable to the material V0 except of the lowest SBT 320 °C.

Solid solution strengthening causes ferrite YS increase by 37 MPa per 1 wt. % Cu and 30 MPa per 1 wt. % Mn. However other strengthening mechanisms have to be taken into account for the experimental material. Alloying can cause also change in grain size and dislocation free path given by cementite particles spacing inside the ferrite crystals. Finally, there is also desired precipitation hardening effect from Cu. Ferrite crystal size (or simply grain size) is given by dimensions of the bainitic ferrite sheaves. Both the ferrite crystal size and the carbide spacing in bainite is difficult to quantify. Thus, only visual comparison of the structures was performed (see **Figure 1**).

Samples treated at all SBT exhibited strengthening with increasing content of Cu and Mn with one exception. YS and UTS of V0 material at SBT 380 °C was higher, than for material V1 alloyed with additional 1 wt. % Cu. However hardness of V1 material was higher (see **Figure 3**). Samples V0 380 and V1 380 had also different character of stress-strain curve (SSC). Specimen V0 380 exhibited SSC without distinctive YS. However, there was a notable YS point in case of sample V1 380. There was no actual drop of stress at the YS but a sharp kink of SSC was present. Similar, but much less apparent kink was present also at the SSC of sample V2 380. Material V0 exhibited higher deformation strengthening at this temperature than other tested materials. All SSC from specimens treated at SBT 350 °C and 320 °C exhibited no distinctive YS. All SSC from temperature 420 °C exhibited distinctive YS.

There was increase of YS by 60 MPa by addition 1 wt. % Cu (V0 → V1) and another 50 MPa increase by addition of Mn from 1 to 2 wt. % (V1 → V2) for SBT 420 and 350 °C. These increments are slightly higher than ferrite solid solution strengthening known for these elements. Much higher increase of YS was measured for SBT temperature 320 °C. 90 MPa with Cu addition and further 140 MPa with increased Mn content. It indicates possible synergy of Mn and Cu alloying. Mn may affect Cu precipitation, so that Cu precipitates strengthen ferrite matrix more effectively.

4. CONCLUSION

It was found, that copper precipitates were formed during bainitic transformation and shortly after it. The precipitation occurred both in the material with copper and with copper and enhanced manganese content. Bainitization was carried out in salt bath at temperatures from 420 °C to 320 °C. Strengthening by additions of copper and further addition of manganese were only slightly higher than solid solution strengthening expectable from Cu and Mn at used concentrations. High strengthening was observed only at the lowest bainitization temperature 320 °C. Addition of 1 wt.% Cu caused YS rise by 90 MPa and it rose for additional 140 MPa after further 1 wt. % Mn addition. This may indicate that Mn supports Cu precipitation in form which strengthens the ferrite more effectively.

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