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Effect of Tempering Temperature on the Mechanical Properties of Cast L35HM Steel

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Abstract

A possibility to control the strength, hardness and ductility of the L35HM low-alloy structural cast steel by the applied tempering temperature is discussed in the paper. Tests were carried out on samples taken from the two randomly selected industrial melts. Heat treatment of the cast samples included quenching at 900 °C, cooling in an aqueous solution of polymer, and tempering at 600 and 650 °C. The obtained results showed that the difference in the tempering temperature equal to 50 °C can cause the difference of 121 MPa in the values of UTS and of 153 MPa in the values of 0.2%YS. For both melts tempered at 600 °C, the average values of UTS and 0.2%YS were equal to 995 MPa and 933 MPa, respectively. The values of EL and RA did not show any significant differences. Attention was drawn to large differences in strength and hardness observed between the melts tempered at 600 and 650 °C. Despite differences in the mechanical properties of the examined cast steel, the obtained results were superior to those specified by the standard.

Keywords: Heat treatment, Tempering, Quenching, Mechanical properties, Cast L35HM steel

1. Introduction

Cast L35HM steel belongs to the group of low-alloy steels for structural applications. It is used for castings operating under high mechanical loads, which demand the best combination of plastic and mechanical properties expressed by the high YS / UTS ratio [1,2]. According to PN-EN 10340: 2009 standard, castings made of this steel are used in various sectors of the building industry (cast wheels and cranes, buckets of excavators, cement cells, parts of construction machinery) and in civil engineering (railways, road infrastructure and pipeline network) [3]. Their chemical composition is chosen in such a way as to obtain after quenching and tempering the structure of tempered martensite uniformly distributed over the entire casting wall cross-section [1,4]. The parameter determining the ability of the material to form a martensitic structure is hardenability which, besides the chemical composition, also depends on the austenite grain size and homogeneity, on the presence of non-metallic inclusions, including carbides and nitrides, and on the type of the introduced inoculant (Ti, V, Nb, rare earth metals) [4-7]. If the casting wall comprises, instead of a homogeneous structure of the tempered martensite, products of the diffusion-induced austenite decomposition, the properties in the wall cross-section will not be uniform. In this situation, higher mechanical properties can be expected in the areas of a martensitic structure rather than in the mixed structure present mostly in the heavy sections and hot spots of the casting [4].

Another important parameter in the quenching and tempering process of low-alloy structural steel, contributing significantly to its mechanical properties, is the temperature of the tempering treatment. An increase in this temperature improves plastic properties, toughness included [8-13].

Nowadays, users of castings often expect not only the required mechanical properties but also small scatter of values in the successive batches of castings. The change in these characteristics is expressed by the DPMO number (defects per million opportunities), which is also a determinant of the quality of heat treatment carried out under the industrial conditions [14]. Therefore it is so important to get stable results in the industrial process of cast steel manufacture.

The paper presents the results of mechanical tests carried out on the cast L35HM steel, melted and heat-treated in an industrial environment.

2. Research methodology

The test material was taken from two different industrial melts. Melting was conducted in an electric arc furnace of 8.5 Mg capacity. From the melted material, clover-shaped test ingots were cast following the recommendations of PN-EN 1559-2:2014-12 standard [15]. The chemical composition of the test material was determined by emission spectrometry on a Foundry Master spectrometer. The results of chemical analysis are summarized in Table 1.

Test samples were cut out from the same areas in the test ingots.The cut fragments of the cast test ingots were quenched and tempered under the industrial conditions. For heating and soaking during the quenching process, a resistance-chamber furnace of the KS520/14 type operating in an atmosphere of air was used. The following quenching regime was adopted:

- heating with the furnace at a rate of 200 °/h to 900 °C;
- soaking at this temperature for 2 h;
- cooling in a 12 % aqueous solution of the polymer.

The quenched samples were divided into two groups and placed in furnace at a temperature of about 100 °C in an atmosphere of air. They were heated to a temperature of 600 °C and 650 °C and held for 2 hours. The selected temperatures of both quenching and tempering corresponded to the heat treatment parameters applied to this material in an industrial environment. Next they were taken out from the furnace and cooled in air. From thus prepared material, specimens (3 specimens for each tempering temperature) were machined for the static tensile test carried out according to PN-EN ISO 6892-1: 2010. The specimens were tested for the tensile properties at ambient temperature at a rate of 39 MPa/s. The study was completed with Brinell hardness measurements. Metallographic examinations were performed using a light microscopes (Neophot 32 and Leica MEF4M) and scanning electron microscope (JSM 7100F). Samples for X-ray diffraction were examined on a Siemens D500 diffractometer using CuK_{α} radiation ($\lambda_{K\alpha}$= 0.154 nm) for the phase analysis.

3. Results and discussion

Table 2 and Figures 1 and 2 give a short summary of the results of mechanical tests carried out on the cast L35HM steel. Samples from both melts (1 and 2) were characterized by the average mechanical properties and reduction of area much higher than the values recommended by PN-EN 10340: 2009. Only elongation after tempering at both 600 and 650 °C was slightly inferior to the minimum values specified by the standard.

As regards the strength parameters obtained in static tensile test and during hardness measurements, the observed changes in these values have confirmed the general principle that higher tempering temperature reduces strength and hardness but increases plastic properties. This allows the steel casting properties to be effectively shaped and adjusted to the conditions of further operation.

Table 1.
Chemical composition of investigated materials

	Chemical composition, wt. %								
	C	Si	Mn	P	S	Cr	Ni	Mo	Al
L35HM by PN-EN10340:2009	0.30 0.40	0.20 0.50	0.50 0.80	max 0.04	max 0.04	0.8 1.1	-	0.20 0.30	-
Melt 1	0.30	0.42	0.83	0.02	0.02	1.03	0.19	0.26	0.041
Melt 2 [16]	0.27	0.39	0.68	0.01	0.01	1.04	0.53	0.22	0.042

Table 2.
The average quenched and tempered properties of cast L35HM steel

	Treatment	UTS [MPa]	0.2%YS [MPa]	EL [%]	RA [%]
L35HM by PN-EN10340:2009	quenching 840÷870 °C; tempering 530÷670 °C	min 750	min 550*	min 14	min 30
Melt 1	quenching 900 °C, tempering 600 °C	1018	977	11	39
	quenching 900 °C, tempering 650 °C	966	889	12.5	42
Melt 2 [16]	quenching 900 °C, tempering 600 °C	972	889	11	33
	quenching 900 °C, tempering 650 °C	781	670	13	38

*value of the yield strength (YS)

Attention was drawn to the fact that there were large differences in the values of the tensile strength and yield strength obtained for the same grade of cast steel but originating from different melts. This is particularly evident at the tempering temperature of 650 °C. Depending on the tempering temperature, the differences between the tensile strength values obtained in individual melts of the tested cast L35HM steel were 46 MPa (which represents a change of 4.5 %) for tempering at 600 °C and 185 MPa (which represents a change of 19.2 %) for tempering at 650 °C. In the case of the yield strength, the reported differences were even greater, and amounted to 88 (which represents a change of 9 %) and 219 MPa (which represents a change of 24.6 %), respectively (Fig. 1). In contrast, the values of elongation and reduction of area were more stable for the tested melts and selected tempering temperatures (Fig. 2).

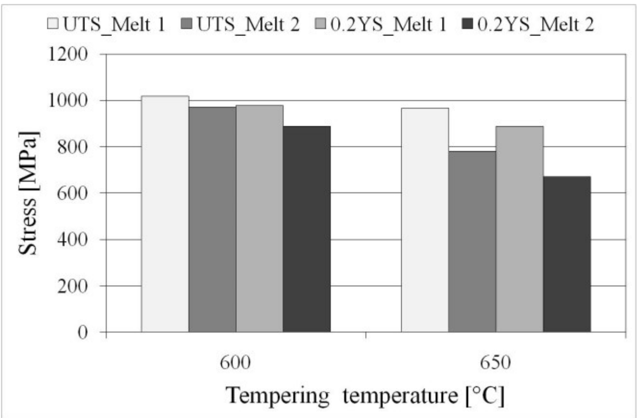


Fig. 1. Effect of tempering temperature on ultimate tensile strength (UTS) and 0.2% yield strength (0.2%YS)

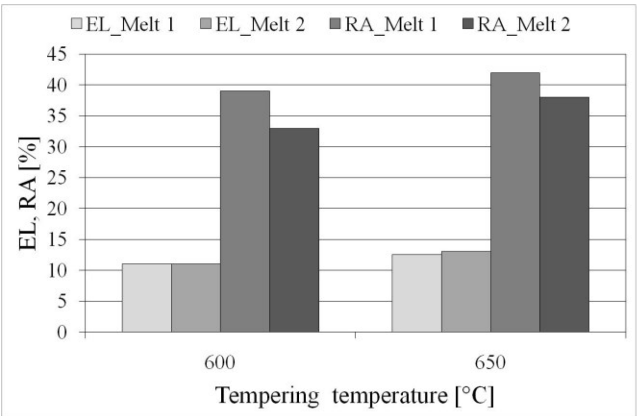


Fig. 2. Effect of tempering temperature on elongation (EL) and reduction of area (RA)

Figure 3 shows the tempering temperature-hardness relationship observed in the tested cast steel. It was found that like 0.2%YS and UTS also hardness of the material from both industrial melts was decreasing with the increasing tempering temperature, although the results obtained after tempering at 600 and 650 °C were higher than the standard values (180 ÷ 200 HB). At higher tempering temperatures, the differences in the hardness of the cast L35HM steel samples taken from the two randomly selected melts were even more pronounced.

Depending on the melt from which the test sample was taken, hardness of the tested cast steel tempered at 600 °C was by approximately 88 units (melt 2) and 116 units (melt 1) higher than the upper hardness limit set out by the standard, while hardness of the test material tempered at 650 °C differed from the standard values by about 51 units (melt 2) and 95 units (melt 1). The results of hardness measurements obtained on samples taken from the same cast L35HM steel melt but tempered at different temperatures have proved that with the increasing temperature of tempering, hardness of the tested material is decreasing (by 37 HB, i.e. 13 % for melt 2, and by 21 HB, i.e. 7 % for melt 1).

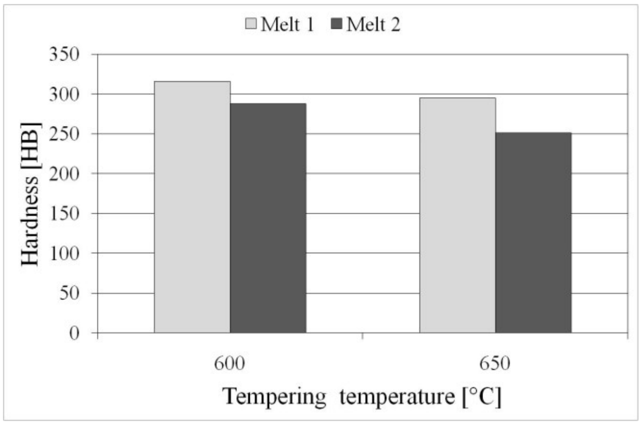
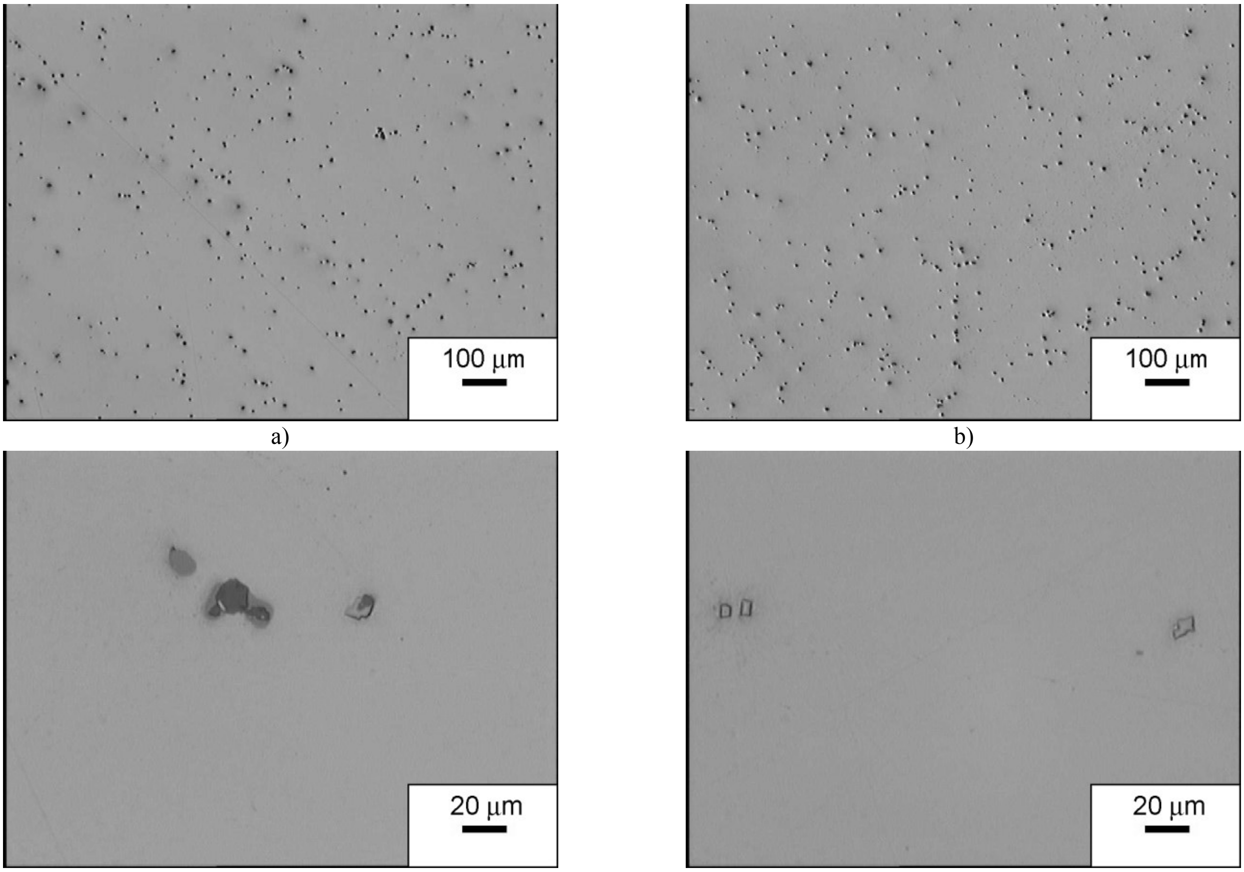


Fig. 3. The tempering temperature - hardness relationship observed in cast L35HM steel

Looking for possible causes of differences in the properties of cast L35HM steel from two selected melts, thorough examinations of the non-metallic inclusions were undertaken. Based on the obtained results, the occurrence of complex globular inclusions, typical of cast steel, uniformly distributed in the examined polished metallographic sections, was noted. Additionally, at a 2000x magnification, the presence of characteristic polygon-like shaped nitrides, occurring most often as single separate inclusions, was reported (Fig. 4).



a) b) c) d)

Fig. 4. Non-metallic inclusions in investigated cast steel: a, c - melt 1 and b, d – melt 2

Further microstructural studies showed that heat-treated microstructure of the examined cast steel was characterized by a ferritic matrix with numerous carbide precipitates (Fig. 5). The X-ray studies of the cast L35HM steel have confirmed the presence of reflections coming from ferrite and cementite (Fig. 5, 6). The precipitates of cementite are very small so it does not have a significant diffractive effect.

Microscopic observations did not reveal any major differences in the microstructure of the tested material that might be claimed responsible for so significant differences in the resulting mechanical properties of cast L35HM steel (Fig. 5). Thus, the only reasonable explanation for differences in the properties of the tested material is the presence of inclusions accumulated in the cross-sections of samples used in the static tensile test and variations in the size of prior austenite grains [10, 12, 13].

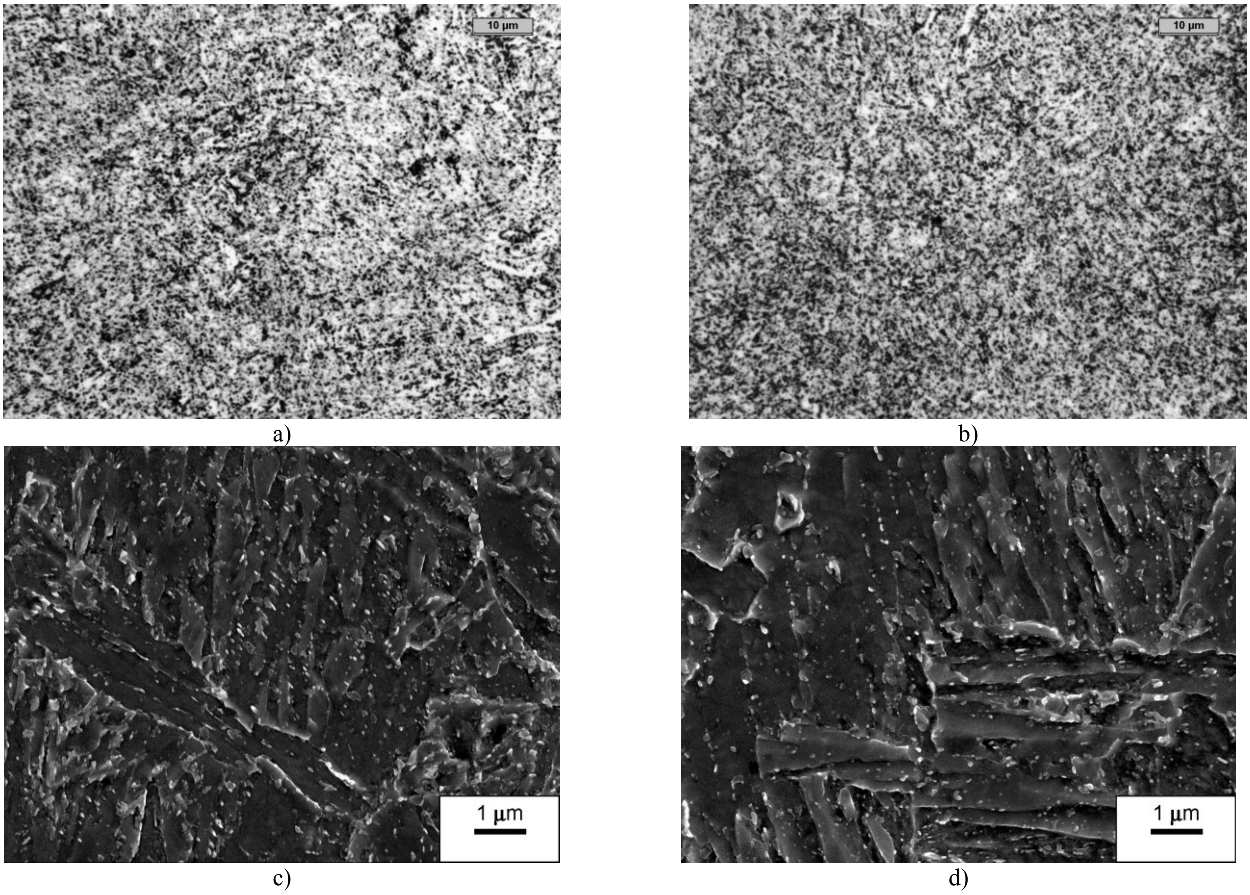


Fig. 5. Microstructure of investigated cast steels after quenching and tempering at 600 °C: a, c - melt 1 and b, d – melt 2

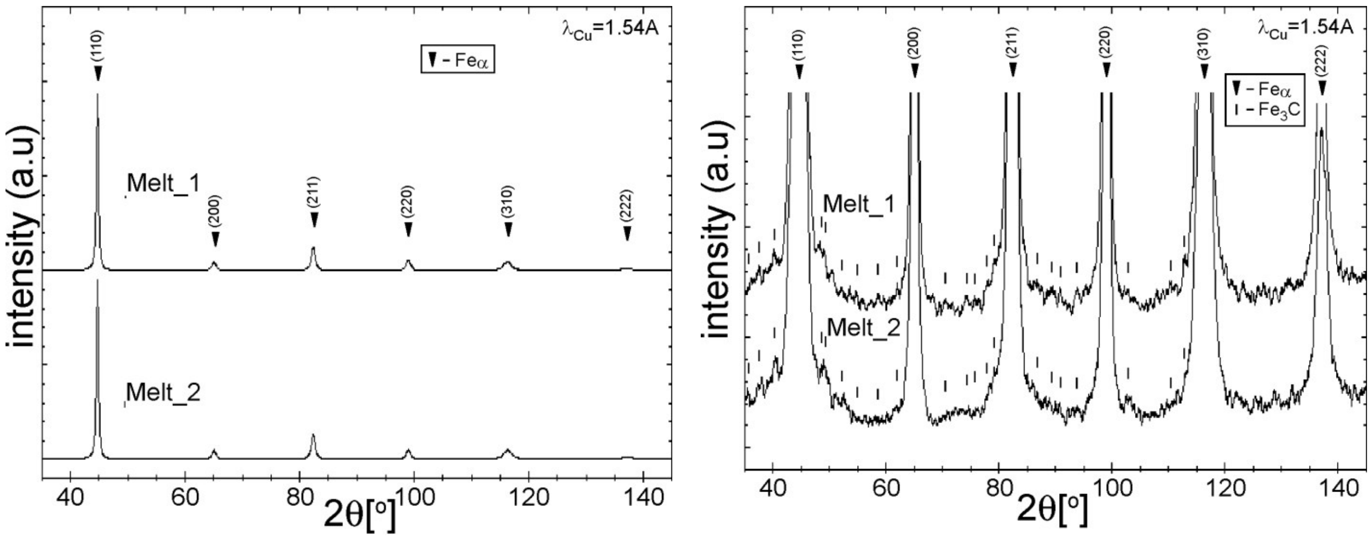


Fig. 6. The X-ray diffraction patterns of the L35HM cast steel after quenching and tempering at 600 and 650 °C

4. Conclusions

- Studies have demonstrated the effect of tempering temperature on the mechanical and plastic properties of the examined cast L35HM steel.
- Quenching and tempering at 600 °C gave better strength properties and hardness (far in excess of the values specified by the standard) than quenching and tempering at 650 °C. The average value of UTS = 995 MPa, 0.2%YS = 933 MPa and hardness 302 HB.
- The tempered microstructure of the tested cast steel contained mostly ferrite and cementite.
- The non-metallic inclusions in both cast steel melts had a globular shape and were evenly distributed in the matrix of the tested material. In addition to these inclusions, also single polygon-shaped precipitates, typical of nitrides, were observed.
- The precipitates of cementite were very small and as such did not provide a significant diffraction effect.
- In order to fully justify the resulting properties of cast steel, in addition to the heat treatment, it is necessary to closely monitor the liquid metal preparation technology and mould pouring conditions.

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