RELATION BETWEEN THE GRAIN SIZE DEVELOPLMENT AND MECHANICAL PROPERTIES OF 34CrMo4 STEEL AFTER FOUR TYPES OF TREATMENT

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Abstract

Steel 34CrMo4 is world widely used steel type for the variety of products, for example forgings, castings, shafts, bars etc. Desired mechanical properties of mentioned steel can be achieved by various treatments such as in a metallurgical process by titanium, niobium, vanadium, zircon or nitrogen microalloying. Another suitable way how to achieve desired mechanical properties is use of different heat treatment modes due to excellent hardenability and temperability of steel 34CrMo4 or combination of these methods in thermomechanical forming. To achieve the best combination of mechanical properties, the grain size is the one of the most important microstructural parameters. In this article, the development of 34CrMo4 steel grain size together with the microstructure after four treatments of the material including as hot rolled state, after normalization annealing, normalization annealing with subsequent quenching and tempering and as final treatment of quenching and tempering were evaluated in relation to achieved values of mechanical properties after each treatment. Except the grainsized and microstructural investigation, as it was mentioned, also the evaluation of mechanical properties was a part of the experimental procedures. This procedure revealed that the most favorable and balanced mechanical properties (tensile strength of 1172 MPa vs. 61 $J.cm^{-2}$ of CVN (at - 50 °C) and elongation of 16.1 %) in case of the treatment based on the quenching and tempering processes applied after the hot forming were achieved. Other treatment types also showed favorable results of mechanical properties however always lower in comparison with the above mentioned treatment.

Keywords: steel 34CrMo4, grainsized, mechanical properties, heat treatment

1. INTRODUCTION

The development od materials, especially steels, and the increase of their mechanical properties is one of the crucial targets in the wide range of applications fields, such as constructional materials, heavy industrial, aircraft and automotive materials and components for all designers to achieve lighter constructional solutions and designs. There is a variety of possible solutions how to achieve such goal. The most important and most commonly used solutions are, the metallurgical process by alloying and microalloying of steel, thermo-mechanical treating and heat treating [1 - 3]. This paper is aimed at the evaluation of influence of four treatment types to the microstructural parameters, especially grain size development and resulting mechanical properties of steel 34CrMo4. The main emphasis was put on the influence of the heat treating of this steel by annealing, annealing with subsequent quenching a tempering and as the last type of treatment, was only quenching and tempering. The influence of the each treatment type on the mechanical properties and microstructure caused by the grain size development will be investigated.

2. EXPERIMENTAL PROCEDURES

Chemical composition of final products, high pressure steel cylinders (HPSC) made of steel 34CrMo4 microalloyed by nitrogen, was analysed by use of the optical emission spectrometer Spectrolab 2000. The production cycle of HPSC manufacturing was based on the reversed extrusion of the heated up billet up to 1150 – 1200 ˚C, subsequent reversed hot rolling on mandrel in range of temperature 990 – 1070 ˚C. After the reversed hot rolling the delay for the cooling of semi-product before the fast air cooling was applied to avoid martensitic transformation. Next step of the production was rotation forming applied as procedure for shaping the cylinder's neck (half spherical part of the cylinder). The extraction of all specimens needed for mechanical testing and microstructural testing were extracted of HPSC in all four states (as rolled, annealed, annealed + quenched and tempered, quenched and tempered).

The first set of HPSC (further marked as HT1) contained cylinders after the hot forming processes extrusion, broaching and neck shaping in range of temperatures 990 – 1200 ˚C, the delay for the cooling of semi-product on air to 600 ˚C before the fast air cooling was applied to avoid martensitic transformation from austenitic state of microstructure. HPSC of second set (further marked as HT2) were treated by normalization annealing based on the heating at 890 ˚C for 50 minutes and subsequently cooled by ambient air cooling (2.5 – 7 ˚C/s). Cylinders representing the third set (further marked as HT3) underwent treatment based on the normalization annealing as it is described above with subsequent quenching (30 – 35 ˚C/s) from temperature 890 ˚C and tempering at 560 ˚C. The last, fourth set of cylinders (further marked as HT4) was treated by quenching and tempering using the same quenching mode as HT3, however tempering was realized at 540 ˚C. Preparation of specimens for mechanical testing contained cutting and machining specimens for the tensile properties testing, notch toughness testing, hardness and microstructure investigation. All specimens were extracted from exactly identic areas of all investigated HPSC. Subsequently, the evaluation of mechanical properties was carried out. This process was based on the yield strength (YS) and tensile strength (TS), elongation (El.), notch impact energy (CVN) at – 50 ˚C and hardness (HBW) and micro-hardness (HV0.2) testing. Complete testing of tensile properties was carried out using the Zwick/Roell Z 250 machine according to EN ISO 6892-1 standard. The testing of notch impact energy was tested by use of RKP 450 Charpy Impact Testing Machine According to ISO 148-1 standard and hardness measuring was realized on the hardness testing machine M4U750 according to EN ISO 6506-1 standard and micro hardness was measured by use of LECO 2000 device according to ČSN ISO 3887.

After the mechanical properties testing, the metallographic observation was realized on specimens after grinding and polishing by use of the light microscope Neophot 21 and basic metallographic parameters, such as micro purity according to ČSN ISO 4967, method A standard and the grain size evaluation according to ČSN EN ISO 643 standard by use of image analyser NIS-Elements AR Analysis were carried out. The essential determination of resulting microstructures was carried out on specimens after grinding, polishing and etching in Nital. As the last part of the material investigation, the microstructural analyses were carried out using the scanning electron microscope SEM JEOL JSM-6490 equipped with X-ray analyser EDA.

Table 1 Chemical composition of used heat of 34CrMo4 steel (wt. %)

C	Si	Mn	Cr	Mo	S	P	N
0.37	0.28	0.80	1.15	0.24	0.002	0.011	0.0121

3. RESULTS AND DISCUSSION

Results of chemical analysis of final HPSC are shown in Table 1 and revealed significantly low values of segregation elements, especially S and P. The HPSC are commonly manufactured from the steel CrMo steel types, usually 34CrMo4, 42CrMo4 or similar. In this case the steel 34CrMo4 was used as an input material and showed a high portion of elements supporting transformation to ferrite and it is also generally accepted, that austenite decomposition is delayed in Mo and Cr containing matrixes to an increase of hardenability [4]. In frame of industrial production possibility, maximal martensite and partially acicular ferrite (AF) nucleation supported by possible nucleable locations on particles based on the Mn and S and segregation banding elimination is the general aim of the production. With the given Mo addition the martensite and also AF formation could be taken into account, because of the cooling rate during the HT 3 and HT4 plus the Mo presence modifies the CCT curves, enlarges ferrite and the AF areas and pearlite formation shifts to longer times. It is also why lower cooling rates could support the AF formation [4].

a) b) c) d)

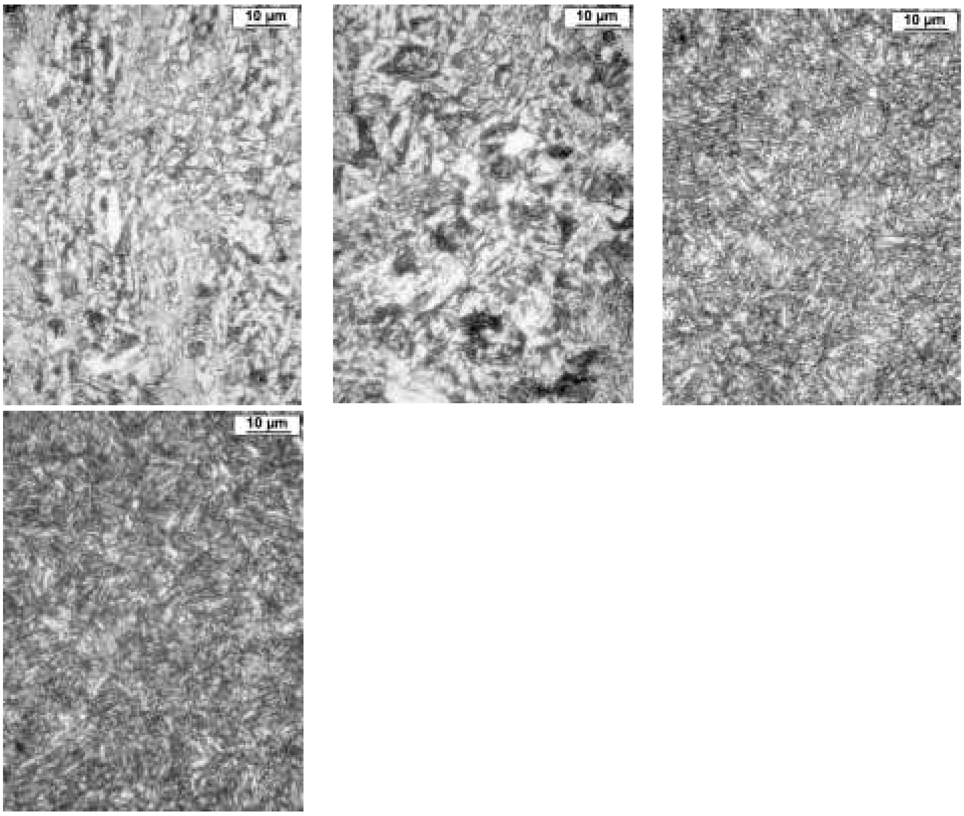


Fig. 1 Microstructure image of decarburized layer of outer surfaces, a) HT1, b) HT2, c) HT3, d) HT4

Achieved mechanical properties fully correspond with applied heat treatment modes and obtained microstructures, which are shown in Fig. 1. However in case of HT2 and HT3 significant decarburization of mainly outer surface layer up to 0.5 mm and inner surface up to 0.3 mm, see Fig. 2, where the micro hardness profile shows the thickness of decarburized layers of HT1 – HT4 and Fig. 3 that shows the decarburization of outer surfaces of specimens after HT1 – HT4, due to high mobility of C during the heating at 890 ˚C and slow cooling by ambient air during the procedure of normalization annealing.

a) b) c) d)

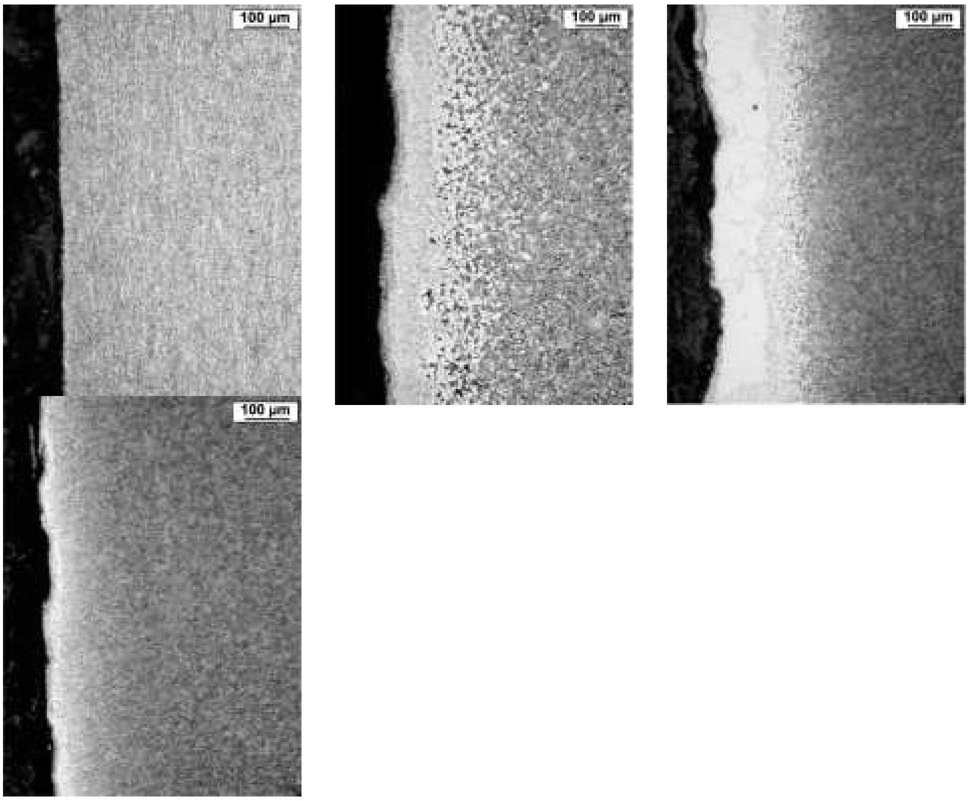


Fig. 2 Microstructure image of decarburized layer of outer surfaces, a) HT1, b) HT2, c) HT3, d) HT4

Resulting mechanical properties (YS, TS, El, CVN and HBW) are listed in Table 2 and proved that the final achieved microstructure is the most influencing parameter of the entire experimental procedure together with the significant influence of the homogeneity of microstructure across the profile (wall thickness) of HPSC. In case of HT1 where the fully bainitic microstructure obtained only by air cooling after the reversed hot rolling was obtained, the decarburized layer was significantly reduced same as it was in case of HPSC after the quenching and tempering where the decarburized layer was reduced to minimum due to the blocking of C mobility by the fast cooling around 35 ˚C/s during the quenching procedure and water mist cooling after the tempering process. The decarburized layers in case of HT2 and HT3 contributed to the lower values of CVN because of the inhomogeneous distribution of strength during the Charpy test between the surfaces layers and middle section comparing to homogeneous microstructure of HT1 and HT4. The tensile testing of mechanical properties (YS, TS, El. and HBW) values are not affected by the decarburized layers due to the necessary turning of round bars specimens, therefore achieved values in Table 2 are influenced (gained) directly by the obtained microstructure in the middle section of specimens

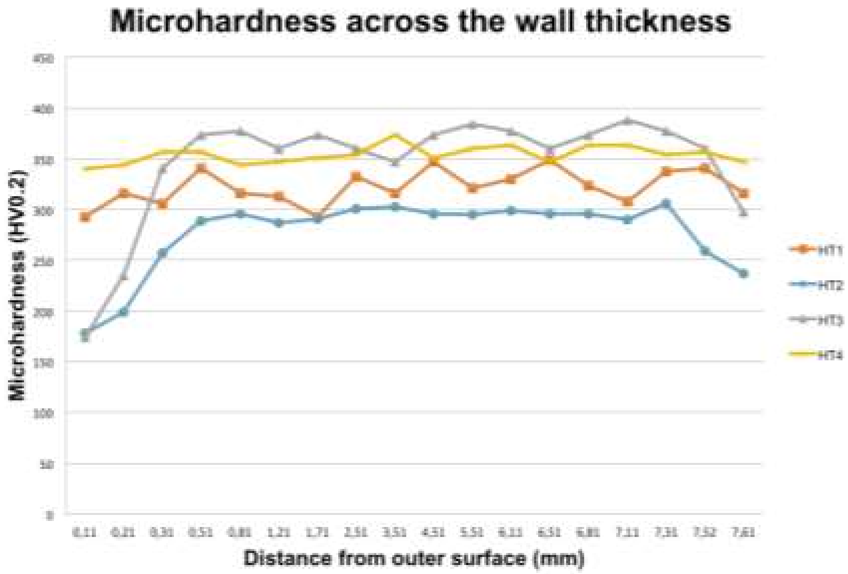


Fig. 3 Micro hardness profile across the SPSC after four types of treatment results

Table 2 Resulting mechanical properties of HPSC after four types of treatment

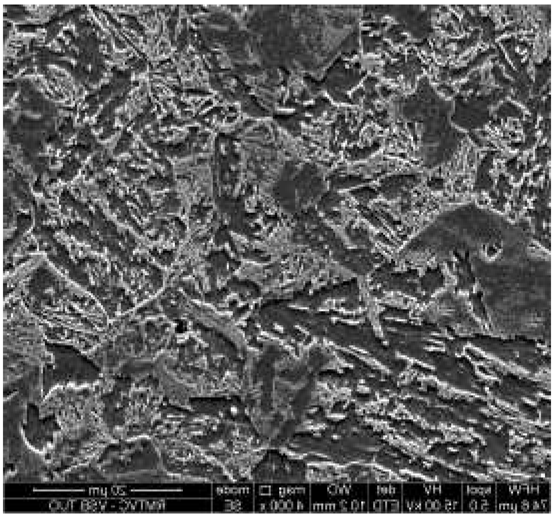
Set of HPSC	YS [MPa]	TS [MPa]	El. [%]	CVN $_{-50\ transverse}$ [$J{\cdot}cm^{-2}$]	HBW (2.5/187.5) [-]
HT1	824	1102	17.3	14	303
HT2	778	992	18.6	10	291
HT3	1142	1191	16.7	50	360
HT4	1105	1172	16.1	61	350

Results of investigated microstructural parameters (micro purity and grain size) are listed in Table 3 and show that the used heat proved significantly high level of cleanness, especially zero values of sulphitic, banded oxitic and coarse globulitic inclusions. Other types of inclusions, especially globular oxides were present in microstructure in outstanding minority presence. The grain size evaluation revealed resulting values of grain size, which fully correspond with applied treatment. The finest grain size was gained in the HPSC only after the hot forming process of reversed extrusion and broaching (HT1) thanks to the elimination of long lasting high temperature heating, therefore reduction of grain size growth as it was in case of applied treatments HT2 and HT3 where the growth of grain size was caused by the high temperature heating during the normalization annealing with slow air cooling, 2.5 – 7 ˚C/s. HPSC after HT4 showed second finest grain size what was caused by the elimination of intermediate step of normalization annealing compared to the HT3 or directly HT2. Resulting grain sizes are directly connected together with the resulting microstructures to the resulting mechanical properties, see Table 2. The grain size influences mainly the CVN as it was proved that the CVN of HPSC after the HT1 was of 2 $J.cm^{-2}$ higher than it was in case of HT2 even though the microstructure of both HPSC specimens was similar. However the resulting values of CVN were not significantly different, the most obvious difference was achieved in case the HT4 compared to the HT3 where the resulting microstructure was exactly the same together with the significantly similar mechanical properties except the CVN that was extraordinary higher in case of HT4 what was caused mainly by the finer grain size and partial reason of non-decarburized layer of outer and inner surface of HPSC CVN specimens.

Table 3 Results of micro purity and grain size investigation

Set of HPSC	Sulphides fine/coarse [-]	Banded oxides fine/coarse [-]	Silicates fine/coarse [-]	Globular oxides fine/coarse [-]	Coarse globular inclusions fine/coarse [-]	Grain size [-]
HT1	0/0	0/0	0/0.3	1/0.2	0	9,8
HT2	0/0	0/0	0/0	1/0.2	0	9.1
HT3	0/0	0/0	0/0	1/0.2	0	8.9
HT4	0/0	0/0	0/0	1/0.5	0	9.6

a)



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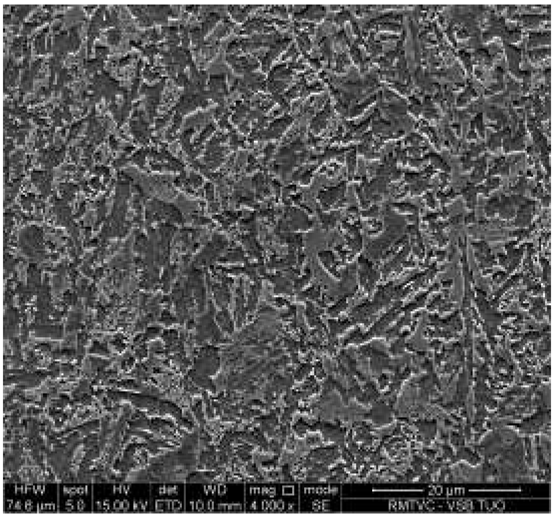

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d)

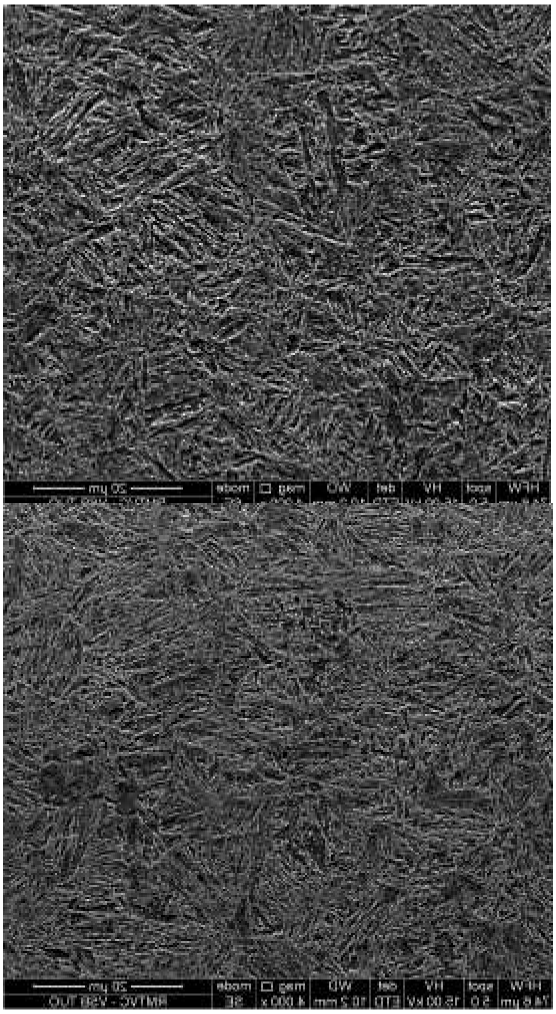

Fig. 4 SEM images of achieved microstructures, a) HT1, b) HT2, c) HT3, d) HT4

Fig. 4 presents the microstructure of specimens after HT1 – HT4 captured by use of SEM to investigate the obtained microstructure by all four types of treatment and verified that the microstrctructure of specimen HT1 was based on the mix of the mainly bainitic and additionally proeutectoid ferritic and pearlitic phases that fully corresponds to the cooling by continuously cooled air flow. The representative specimen of HT2 shows the matrix based on the proeutectoid ferritic and pealitic phases mainly with the minority bainit phase what was resulting due to the slow cooling on the air. The specimens after the HT3 and HT3 showed mainly martensitic matrix with minority phase of low bainite and due to the CCT curve [4] more likely acicular ferrite due to the influence of Mo on CCT curve of this steel type. Martensitic mixrostrcuture obtained by the quenching and tempering processes in case of HT3 and HT4 revealed numerous spheroidic carbide particles, which are typical for the process of tempering above 500 ˚C.

CONCLUSION

The most balanced values of mechanical properties were achieved in case of HPSC where the HT4 was applied. Comparing to the HT3, higher values of CVN were achieved, what is directly showing finer resulting grain size of value 9.6. Lower tensile strength was in case of HT4 cause by the higher tempering temperature compared to the HT3. The best value of the grain size proved that the normalization annealing does not influence the resulting microstructure and the grain size in the desired favorable values. Also, the normalization annealing causes the high temperature mobility of carbon and causes the significant decarburization that could negatively influence resulting CVN values. The best solution of HPSC heat treating is the conventional mode based on quenching and tempering processes.

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