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PLASTIC DEFORMATION AND HEAT TREATMENT OF THIN WALLED CENTRIFUGALLY CAST HIGH STRENGTH CrMoNb STEEL TUBES

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Abstract
This work deals with effects of hot plastic deformation process and subsequent heat treatment on structure and mechanical properties of centrifugally cast (CC) high strength CrMoNb steel tubes. Plate samples, taken from CC tubes, were homogenized and subsequently hot rolled. One serie of samples was soft-annealed (SA) and other series oil-quenched and tempered (QT) between 373-923 K. Primary and secondary structures, non-metallic inclusions in radial direction and prior austenite grain size were analyzed using bright-field and polarized light microsopy. Experimental mechanical properties of SA and QT samples were modeled by means of polynomial functions and correlated with structure properties.

Keywords: *Centrifugal casting, high strength steel tubes, hot plastic deformation, heat-treatment, structure and mechanical properties*

1. INTRODUCTION

Centrifugal casting (CC) of metals and alloys is a core technology in the development of hollow products and its progress has led towards as-cast products with superiour physico-mechanical properties than conventional castings and dimensions near to those of the final products [1,2,3,4,5,6]. Further improvements of physical and mechanical properties of CC products can be achieved through an additional treatment, e.g. microalloying, plastic deformation, heat treatment etc.

Studies related to a hot plastic deformation and/or heat treatment of the Nb-free and Nb-containing CC high strength CrMo steel tubes are rarely found in literature. Niobium is known as a very influencing alloying element by which austenitisation, recrystallization, grain growth, phase transformation, and precipitation behavior can be controlled efficiently and by which the mechanical properties can be varied in a wide range. Niobium affects the transformation of austenite to ferrite and to bainite and thus volume fraction and stability of the retained austenite. Steels that contain additions of niobium show elevated yield and tensile strength values and only a slight decrease in ductility [7].

Our previous investigations have included analysis of distribution of chemical elements [8], the type and distribution of nonmetallic inclusions and structure in as-cast CC CrMo and CrMoV high strength steel tubes of different diameters and wall thicknesses [9] and properties of heat treated CC CrMoNb steel tubes [1]. The aim of this paper is to examine and, for the first time, to report on a rather general level, dependence of structure and mechanical properties on hot plastic deformation and subsequent heat treatment of plate-like samples taken from thin walled CC CrMoNb steel tubes in axial direction. It is important to notice that due to a lack of equipment to assess the possibilities for rotary forging of CC CrMoNb steel tubes the hot plastic deformation experiments were carried out instead.

2. EXPERIMENTAL

The average chemical composition of CC samples used in this study is shown in Table 1. Unlike the 4140 (AISI designation) i.e. 42CrMo4 (EN designation), CC CrMoNb steel has a higher content of Cr and contains the micro-alloying element Nb.

Table 1 - Chemical composition of CC CrMoNb steel [wt.%]

C	Mn	Si	S	P	Cr	Mo	Nb	Ni	Cu	Al	O	N
0.44	0.70	0.42	0.022	0.020	2.70	0.20	0.11	0.092	0.097	0.075	0.0370	0.020

Cylindrical parts of CC CrMoNb steel tubes, with dimensions of ϕ128/ϕ78x1400 mm, were homogenized (austenitized) at 1323 K for 2 h. After, they were furnace-cooled down to 573 K and air-cooled to room temperature. Hot deformation (rolling) process on laboratory scale (Faculty of Technology and Metallurgy, Belgrade) was performed on plate-like samples with starting dimensions of 115/50/16 mm that were taken from homogenized CC cylindrical parts in axial direction. The deformation was carried out by use of rollers with 240 mm in diameter, 12° grip angle, 0,8 m/s rolling speed and at 1473 K in six rolling passes. Between two or three passes hot-worked samples were additionally heated to avoid significant drop in interpass temperature due to air-cooling. After last rolling pass, samples were cooled from finishing temperature (1123 K -1223 K) down to room temperature in air when had dimensions approximately 170/51/10 mm. The degree of deformation after six rolling passes was 40 % while single-pass degree of deformation was somewhat less than 10 %, on average scale.

In order to 1) investigate structure and mechanical properties in spheroidized condition, 2) redistribute stresses developed after cooling from finishing temperature of rolling, and 3) reduce hardness of as-hot-rolled plates, prior to their quenching and tempering, samples were soft-annealed at 993 K for 2 h. One serie of soft-annealed samples (SA) was cut and prepared for structure analysis and mechanical testing, while other SA samples of similar dimensions were additionally quenched and tempered (QT). QT samples were annealed at 943 K for 30 min and subsequently oil-quenched at 298-308 K with intensive oil mixing. Afterwards, samples were tempered in series at 473 K, 573 K, 673 K, 773 K, 823 K, 873 K, and 923 K. In all cases tempering time was 1 h. After tempering each sample was oil-cooled down to room temperature.

Prior to structure analysis (Military Technical Institute, Belgrade), samples were grinded with SiC abrasive paper and polished down to 1 μm by use of diamond particle suspensions. Effects of hot deformation process on dendrite (primary) structure were studied on SA samples by employing a deep chemical etching in Oberhoffer's reagent (Figure 1). Prior austenite grain size (PAGS) was determined according to recommendations of ASTM E 112 and SRPS C.A3.004 standards. Grain boundaries were revealed in 15% HCl reagent (Figure 2). Secondary structure was analyzed on both SA and QT samples and revealed by use of 3% Nital reagent (Figure 3). Structure was observed by use of bright-field light microscopy (BF-LM) with vertical illuminating source. Although not presented here, distribution of non-metallic inclusions in radial direction was analyzed by means of bright field and polarized light microscopy (BF- and P-LM).

Ex-situ mechanical testing (Military Technical Institute, Belgrade) was performed on standard test specimens made from SA and QT samples taken in axial (rolling) direction. Properties of macrohardness (HV_{30}), yield strength ($R_{p0.2}$), tensile strength (R_m), elongation (Z), area reduction (A_5) and impact energy (KU) were measured as a function of tempering temperature. Tensile testing was carried out on Instron 8033 device (100 kN), while impact energy was determined with Charpy pendulum Tinius Olsen (348 Nm). Macrohardness measurements in radial direction (perpendicular to rolling direction) were obtained by using the Wolpert device.

3. RESULTS AND DISCUSSION

Typical results obtained after structure analysis and mechanical testing are shown in Figures 1-3 and Figure 4, respectively. Judging by appearance of more dispersive primary structure (Figure 1a), near-surface regions were affected to a greater extent by the hot deformation process than central parts where a coarser dendritic-like structures were occasionally observed (Figure 2b).

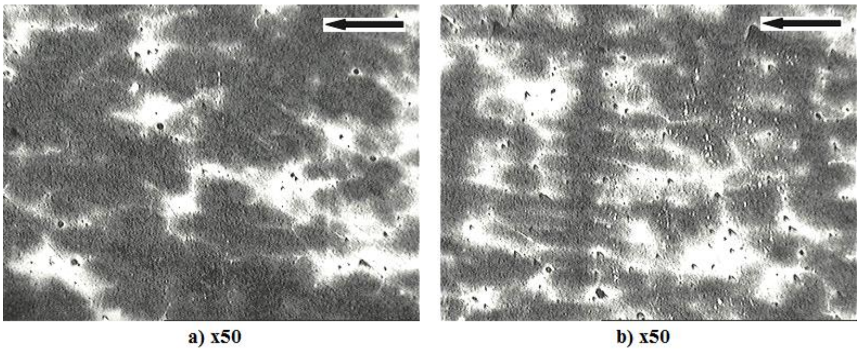


Figure 1 – Primary structure of SA samples; cross-sectional view; a) near-surface region (1-2 mm) and b) central part (2-5 mm); arrows point at rolling direction; Oberfoffer's reagent.

The austenite grain size index (G) in as-cast condition was varying between 3 and 8. After hot rolling and soft-annealing SA samples had G = 8 (Figure 2a) and more homogeneous austenite grain size distribution. Subsequent heat treatment resulted in a further significant austenite grain refinement (Figure 2b, G = 12).

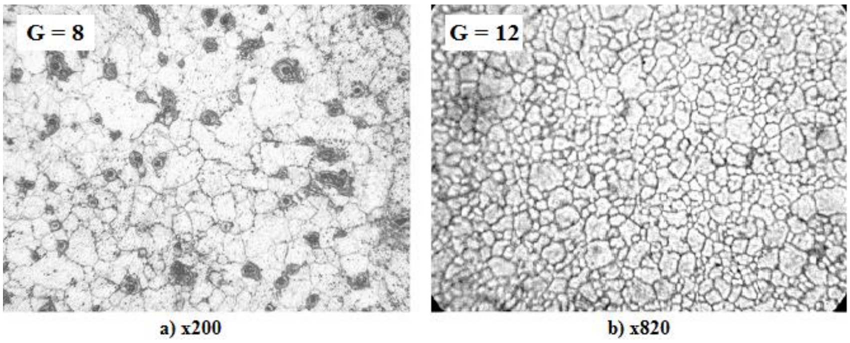
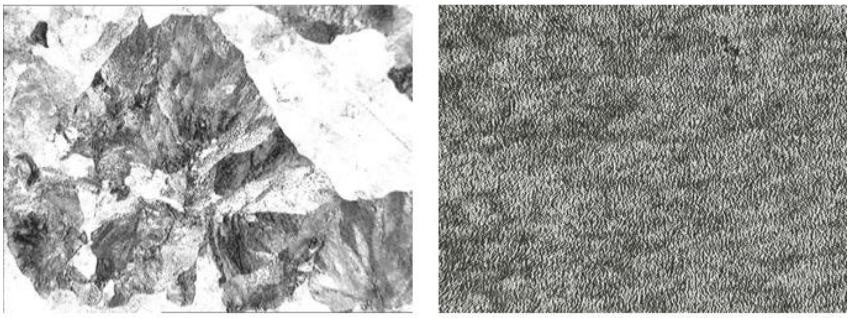
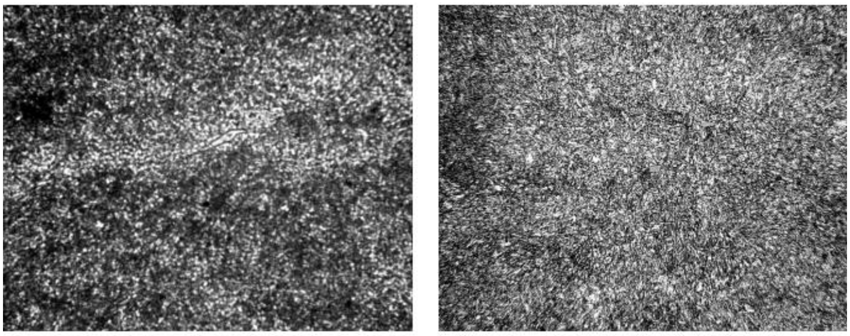


Figure 2 – Prior austenite grain size of a) SA samples and b) QT samples tempered at 573 K; cross-sectional view; perpendicular to rolling direction; G – grain size index (ASTM E112); 15% HCl.

Secondary structure in Figure 3a, after homogenization, consisted of pearlite (dark color) in various sizes and smaller amounts of ferrite (light color). Undissolved carbides and carbonitrides were present, also. After homogenization and spheroidization SA samples contained partially recrystallized bainite, dispersive pearlite and smaller amounts of ferrite, as well as somewhat coarser carbides and carbonitrides (Figure 3b). Later structure can be the result of small single-pass degree of deformation (<10%), low finishing temperature of rolling (<1323 K) and Nb presence. QT samples, tempered up to 673 K, were composed of tempered martensite, dispersive carbides and carbonitrides (Figure 3c). At higher tempering temperatures (up to 873 K) additional presence of bainite was observed (Figure 3d), as well as dispersive pearlite and ferrite at 923 K. Partitioning of substitutional solutes in CrMo steels (Cr, Mo, Mn etc.), e.g. between martensite, retained austenite and cementite, practically does not occur for a longer periods of time up to 723 K, according to Ref. [10]. By considering the previously mentioned, the additional presence of Nb, and short tempering time (1h), applied in this work, the stability of bainite structure up to the highest tempering temperatures can be possibly explained.



a) $HV_{30} = 231$; x200   b) $HV_{30} = 238$; x100



c) $HV_{30} = 580$; x750   d) $HV_{30} = 365$; x750

Figure 3 – Secondary structure of a) homogenized, b) SA, and QT samples tempered at c) 573 K and d) 873 K; cross-sectional view; perpendicular to rolling direction; 3% Nital.

In Figure 4 changes in mechanical properties are consistent with changes in structure properties. The slopes of almost all curves are noticeably different at tempering temperatures above (673-773) K range, marking the transition when probably diffusion (partitioning) of substitutional solutes becomes relatively significant. This transition is maybe somehow connected to bainite appearance. The toughness properties (HV_{30}, $R_{p0.2}$, R_m) mark the highest values below (673-773) K transition range, while ductility properties (A_5, Z and KU) the lowest. Impact energy of only 9 J is achieved below appointed transition range, while acceptable limit of 27 J has been reached just below the highest tempering temperature (923K). The low ductility is probable reason why the rare occurrence of micro-cracks has been sometimes observed during studying of secondary structure. The origin of micro-cracks still remains unknown. It is assumed that these properties are directly connected with conditions applied during the homogenization and hot deformation procedure.

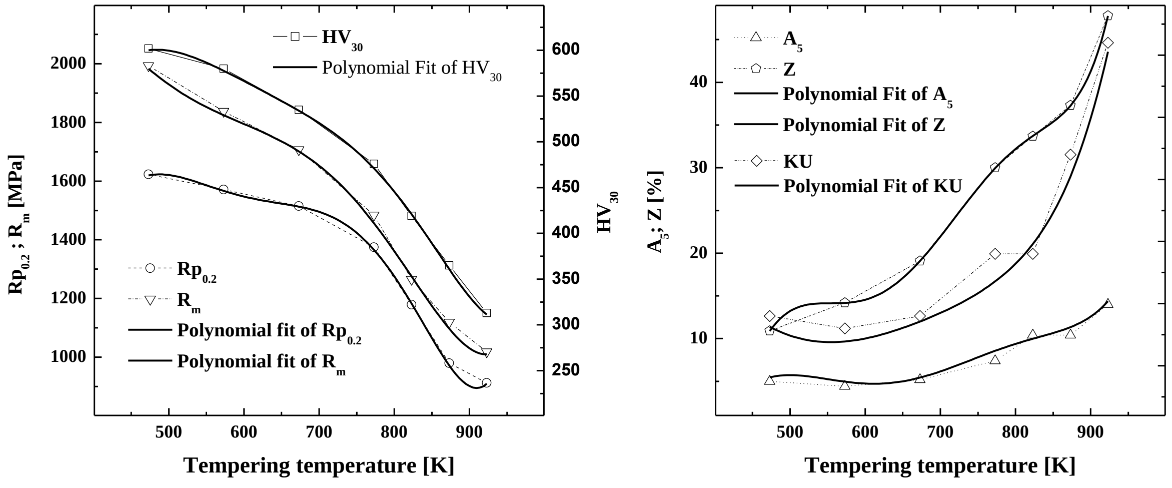


Figure 4 – Room temperature a) hardness (HV_{30}), yield ($R_{p0.2}$) and tensile (R_m) strength and b) area reduction (A_5), elongation (Z) and impact energy (KU) of QT samples as a function of tempering temperature.

4. CONCLUSIONS

Here it was demonstrated the influence of hot deformation process and subsequent quenching and tempering on room temperature structure and mechanical properties of plate-like samples taken from thin walled centrifugally cast Nb-containing CrMo high strength steel tubes. The research was conducted in order to assess the possibilities for further improvement of mechanical properties of as-cast CC CrMo steel tubes by use of rotary forging technology and the results of this preliminary research show that there is a great potential to significantly improve them. The mechanical properties are in consistence with changes in structure properties. It was achieved a remarkable level of toughness properties with e.g. yield and tensile strength of approximately 1600 and 2000 MPa, respectively. However, the level of ductility properties was low and for the mentioned strength levels e.g. impact energy was approximately 9 J. It is assumed that insufficient single-pass degree of deformation and homogenization procedure are possible reasons for such poor ductility level. For this reasons the roles of Nb and higher level of Cr (in comparison to AISI 4140) in centrifugally cast CrMo steel during homogenization, hot deformation and tempering yet need to be clarified. The link between Nb and baintite structure appearence, also. Ongoing research is dealing with the influence of hot deformation and tempering on the structure and mechanical properties of thick walled Nb-free and Nb-containing centrifugally cast CrMo steel tubes.

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