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Mechanical properties and corrosion resistance of steel X210CrW12 after semi-solid processing and heat treatment

Łukasz Rogal^{a,4}, Jan Dutkiewicz^{a,1}, Zbigniew Szklarz^{b,2}, Halina Krawiec^{b,2},
Marcin Kot^{c,3}, Sławomir Zimowski^{c,3}

^aInstitute of Metallurgy and Materials Science of the Polish Academy of Sciences, 25, Reymonta St., 30-059 Krakow, Poland

^bAGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Al. Mickiewicza 30, 30-059 Krakow, Poland

^cAGH-University of Science and Technology, Fac Mech & Robot, 30, Mickiewicza St., 30-059 Krakow, Poland

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ABSTRACT

Semi-Solid Metal Processing (SSM) is one of the modern methods of steel forming. SSM of hot rolled X210CrW12 tool steel was conducted at 1250 °C, in order to obtain about 30% of liquid phase. The microstructure consisted of globular austenitic grains surrounded by eutectic mixture (ferrite, austenite and M_7C_3 carbides). The average hardness of as-SSM samples was 470 HV₅, while the coefficient of abrasion resistance reached $7.9 \cdot 10^{-6} \text{ mm}^3/\text{Nm}$. The compression strength of thixo-casts of X210CrW12 steel reached 4850 MPa at the plastic strain of 34%, although the yield stress was only 810 MPa. The X210CrW12 alloy just after thixo-casting revealed disadvantageously small wear resistance due to a large amount of metastable austenitic structure. A heat treatment consisting of 2 h tempering at 555 °C and additional low temperature tempering at 250 °C led to the hardness increase up to 650 HV₅ as well as to the improvement of abrasion resistance to $1.8 \cdot 10^{-6} \text{ mm}^3/\text{Nm}$. The compression strength and plastic strain decreased to 3140 MPa and 8.9%, respectively, while the yield stress increased up to 2050 MPa. Such very good mechanical properties were due to a complex microstructure consisting of globular grains containing the tempered martensite, fine perlite and M_7C_3 carbides surrounded by eutectic mixture. Tempering at 630 °C for 2 h led to the transformation of primary austenitic grains into perlite and carbides. It caused a decrease in hardness down to 495 HV₅ and the compression strength to 2300 MPa, and the deterioration of abrasion resistance to $7.4 \cdot 10^{-6} \text{ mm}^3/\text{Nm}$. The corrosion measurements revealed that the X210CrW12 steel directly after SSM was susceptible to the pitting corrosion in 0.1 M sodium chloride solution. The corrosion resistance of thixo-casts after tempering at 555 °C/2 h slightly decreased compared with the as-thixoformed samples.

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1. Introduction

Thixoforming or Semi-Solid Metal Processing (SSM) is the technique of shaping the metal components in the semi-solid

state taking advantage of the thixotropic behavior of metal alloys, related to the non-Newtonian flow of semi-solid slurry. It is possible, when the microstructure consists of globular grains of solid solution surrounded by the liquid phase. It

E-mail address: l.rogal@imim.pl (Ł. Rogal).

¹ Tel.: +48 122952801; fax: +48 122952804.

² Tel.: +48 12 617 40 62.

³ Tel.: +48 12 617 34 20.

⁴ Tel.: +48 126172826; fax: 48122952804.

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leads to a decrease of viscosity under shear stress [1]. Such an unusual behavior of metal alloys in the semi-solid state was examined in order to obtain methods of material processing as an alternative to conventional technologies of production. The industrial application of the technology was initiated on aluminum alloys A380 [2], and later introduced for high melting point alloys such as AISI 304 and 440C ones [3,4]. A further intensive research led to the development of two methods of forming: rheoforming (directly from the liquid state during the solidification) or thixoforming (after heating from the solid state to semi-solid one) [4,5]. Only Mg and Al alloys have found industrial applications so far [6–9]. In the case of steel a lot of technological problems arise: a die material, oxidation effects and the temperature control in the semi-solid state [10]. Recently, several types of steels have been selected for SSM such as 100Cr6, C38, T15, M2, H13, X210CrW12, X220CrVMo13-4, HS 6-5-2 [10–14]. Some of them, e.g. C38, 45Mn5, C80, 100Cr6, needed a modification of their chemical composition in order to adapt them for the SSM processing [15]. The X210CrW12 steel was formed from the semi-solid state using thixoeextrusion, thixocasting [16–18], thixoforging [19] and rheoforging [20]. Mechanical properties of as-SSM processed steels are poor due to their initial austenitic structure [11]. A heat treatment like tempering or hardening and tempering was used to improve the mechanical properties using a controlled cooling rate from the semisolid state [20–24]. In the X210CrW12 steel, the as-SSM microstructure consisted of the metastable austenite and eutectic mixture [25]. Uhlenhaut et al. [21] determined the conditions of austenite decomposition during cooling of X210CrW12 steel from a temperature close to solidus (1210 °C) to the ambient temperature. The maximum hardness of 614 HV₁₀ was obtained for the cooling rate of 10 °C/min. The relationship between hardness, abrasion resistance and tempering time at 490 °C, 540 °C and 595 °C was investigated in [21]. The highest abrasion resistance along with optimal hardness was observed in the X210CrW12 steel after tempering at 490 °C for 120 h [21]. Masek et al. [26] measured the hardness as a function of tempering temperature for the X210Cr12 steel after thixoforming at a low processing force. Although the corrosion resistance is one of the important properties of structural alloys, there is no information about corrosion of the as-SSM X210CrW12 steel in the literature. The present work is a continuation of the research of Ł. Rogal and J. Dutkiewicz published in [22]. The aim of the study has been a complex characterization of the mechanical properties of X210CrW12 steel thixo-casts, combined with the corrosion resistance examinations of as-SSM samples and after heat treatment.

2. Experimental Procedure

2.1. Feedstock Material and Preparation of Thixo-cast Samples

The X210CrW12 tool steel used was produced by Batory Steel Works in Poland. The steel was hot rolled near 1050 °C and annealed at 840 °C (the feedstock for thixoforming). Its chemical composition was 2.1% C, 10.5% Cr, 0.7% W, 0.4% Si and 0.4% Mn (all in wt.%). The steel after austenitization at 970 °C for 2 h, water cooling and tempering at 300 °C for 2 h, described as X210CrW12 HR was applied as a reference material for the

corrosion resistance analysis. The thixo-cast samples of the rectangular prism shape (50 mm × 25 mm × 10 mm) were obtained using a specially built prototype device. The piston velocity was 1 m/s. The locking force of the machine was 800 kN. A billet of X210CrW12 steel (diameter 30 mm and height 30 mm) was heated in an induction furnace. The temperature of feedstock was measured with an S type thermocouple. The sample reached the temperature of 1250 °C after 4 min. The billet was then moved to a cylinder of a high-pressure die-casting machine and pressed out (35 kN) by the piston into the die, made of M2 steel, preheated to 200 °C and covered with a BN layer. The average rate of cooling from temperature 1250 °C to 200 °C was measured in the die to be about 90 °C/s. Various heat treatments of thixo-casts were applied, which consisted in single tempering at 230 °C, 320 °C, 420 °C, 525 °C and 630 °C for 2 h. Additional double tempering was carried out at 555 °C for 2 h and at 250 °C for 2 h.

2.2. Microstructure and Measurements of Mechanical Properties

The samples subjected to microstructure examinations were polished and etched in Nital (the as-SSM samples along with the heat treated ones) and in LB III solutions (10 g of NH₄F·HF, 1 g of K₂S₂O₅ and of 100 ml of hot distilled water) for the deformed samples. The metallographic studies were carried out using Leica DM IRM microscope equipped with Leica QUIN image analysis software. The analysis of fracture was obtained using a Scanning Electron Microscope, FEI SEM XL30. The microstructure and electron diffraction studies were performed using Transmission Electron Microscope (TEM) Philips CM20. The X-ray investigations of the phase composition were performed using Co-Kα filtered radiation using Philips PW 1710 diffractometer. The standard deviation was estimated based on three analyses. The samples for TEM were electropolished using Struers Tenupol-5 jet polisher in electrolyte consisting of 20% HClO₄ and 80% CH₃OH at subzero temperatures. The hardness measurements were carried out in accordance with ASTM E 92 standard under the load of 50 N, using a Zwick/ZHU 250 tester (HV₅), and 0.2 N with CSM Instruments Micro-Hardness tester (HV_{0.02}). The measurement error was estimated from three analyses, which allowed the determination of standard deviation. The compression test was performed using the INSTRON 3382 machine. The X210CrW12 steel thixo-cast samples of size 5 × 5 × 7.5 mm were compressed following the PN-57/H-04320 standard. The wear properties of the steel thixo-casts were evaluated before and after the heat treatment using a ball-on-disc apparatus (dry condition) with silicon nitride (Si₃N₄) balls of 6 mm in diameter as the counter body in accordance with ASTM G99-95. The investigations were conducted at established test parameters: wear track of 6 mm diameter, rotation speed of 60 rpm, normal load of 10 N (F_N) and total number of cycles 11,500, and distance of wear track 500 m (s) at temperature 22 ± 2 °C. After the tests, the profiles of wear tracks were measured with a stylus profilometer and the A_V area of the worn material was calculated. Wear rate W_V was calculated after each test from the equation:

$$W_V = V / F_N \cdot s \quad (1)$$

where: worn volume of material V is given by

$$V = A_V \cdot 2 \cdot \pi \cdot r \quad (2)$$

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