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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH-ALLOYED 23Cr-5Mn-2Ni-3Mo CAST STEEL

MIKROSTRUKTURA I WŁAŚCIWOŚCI MECHANICZNE WYSOKOSTOPOWEGO STALIWA 23Cr-5Mn-2Ni-3Mo

The article presents the microstructure and mechanical properties of cast duplex stainless steel type 23Cr-5Mn-2Ni-3Mo. It has been shown that the structure of the tested cast steel is composed of ferrite enriched in Cr, Mo and Si, and austenite enriched in Mn and Ni. In the initial state, at the interface, precipitates rich in Cr and Mo were present. A high carbon content (0.08%C) in this cast steel indicates that probably those were complex carbides of the $M_{23}C_6$ type and/or σ phase. Studies have proved that the solution annealing conducted at 1060°C was not sufficient for their full dissolution, while at the solutioning temperature of 1150°C, the structure of the tested material was composed of ferrite and austenite.

Partial replacement of Ni by two other austenite-forming elements, which are Mn and N, has ensured obtaining mechanical properties comparable to cast duplex 24Cr-5Ni-3Mo steel of the second generation. Basing on the results of static tensile test, a twice higher yield strength was proved to be obtained, compared to the cast austenitic 18Cr-9Ni and 19Cr-11Ni-2Mo steel commonly used in the foundry industry. In addition to the high yield strength (YS = 547 ÷ 572 MPa), the tested cast steel was characterized by the following mechanical properties: UTS = 731 ÷ 750 MPa, EL = 21 ÷ 29.5%, R.A. = 43 ÷ 52%, hardness 256 ÷ 266 HB. Fractures formed in mechanical tests showed ductile-brittle character.

Keywords: duplex stainless cast steels, microstructure, solution annealing, mechanical properties

W artykule przedstawiono mikrostrukturę i właściwości mechaniczne, kwasoodpornego staliwa ferrytyczno - austenitycznego 23Cr-5Mn-2Ni-3Mo typu duplex. Wykazano, że struktura badanego staliwa składa się z ferrytu δ wzbogaconego w Cr, Mo i Si oraz austenitu wzbogaconego w Mn i Ni. W stanie wyjściowym na granicy międzyfazowej występują wydzielenia wzbogacone w Cr i Mo. Wysoka zawartość C (0.08%) w tym staliwie wskazuje, że prawdopodobnie są to złożone węgliki $M_{23}C_6$ i/lub faza σ. Wykazano, że temperatura przesycania 1060°C nie jest wystarczająca do ich całkowitego rozpuszczenia. Natomiast w temperaturze przesycania 1150°C struktura badanego materiału składa się z ferrytu i austenitu.

Częściowe zastąpienie Ni przez dwa inne pierwiastki austenitotwórcze jakimi są Mn i N zapewniło uzyskanie porównywalnych właściwości mechanicznych do staliwa duplex 24Cr-5Ni-3Mo drugiej generacji. Na podstawie przeprowadzonej statycznej próby rozciągania wykazano dwukrotnie wyższą granicę plastyczności w porównaniu do często stosowanego w przemyśle odlewniczym austenitycznego staliwa 18Cr-9Ni i 19Cr-11Ni-2Mo. Poza wysoką granicą plastyczności ($Rp_{0,2}$ = 547 ÷ 572 MPa), badane staliwo charakteryzowało się następującymi właściwościami mechanicznymi: R_m = 731 ÷ 750 MPa, A_s = 21 ÷ 29,5%, Z = 43 ÷ 52%, HB = 256 ÷ 266. Przełomy po badaniach wytrzymałościowych wykazywały charakter ciagliwo-kruchy.

1. Introduction

Microstructure of the Cr-Ni duplex stainless steel and cast steel is composed of austenite and ferrite [1÷3]. The volume fractions of these two constituents depend on the content of the elements stabilizing ferrite (Cr, Mo, Si, Nb) and austenite (Ni, C, N, Cu), and next on the wall thickness of the casting and type of the heat treatment applied [2,4÷6]. A particular group among these steels constitute duplex steels with high nitrogen content (0.2÷0.3%N). Nitrogen in Cr-Ni stainless steels affects the morphology of phases present in the microstructure [7,8] and improves the corrosion resistance of these steels (it expands the range of the passivation potential, reduces the passivation current density and the rate of pitting corrosion), but only when it is fully dissolved in solid solution and does not form precipitates [7÷9]. In turn, according to [9], the presence in the microstructure of nanoprecipitates of CrN refines the structure and improves the mechanical properties of these steels, mainly as regards the yield strength. Additionally, nitrogen as an alloying element delays the formation of brittle σ phases. Ferritic – austenitic (F-A) steels, besides good pitting and stress corrosion resistance in a medium containing chloride ions, offer a favourable combination of mechanical and performance properties [1,4,12]. First of all, they show

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a much higher yield strength than the conventional austenitic grades resistant to corrosion [2÷4]. This combination of properties makes these alloys readily used for elements operating mainly in the extractive industries of oil and natural gas and in installations for the desalination of sea water [1,3]. On the other hand, ferritic – austenitic (F-A) type Cr-Mn-Ni steels have good corrosion resistance in environments containing, among others, lactic acid or acetic acid. Therefore this group of materials has been used mainly for installations operating in the food industry.

The aim of this study is to present the mechanical properties of cast chromium - nickel duplex type steel with nickel content reduced to 2%, and manganese content increased up to 5% and up to 0.2% nitrogen.

2. Materials and methods

Tests and studies were carried out on high-alloyed Cr-Ni cast duplex steel, where nickel was partly replaced by the increasing addition of Mn and N. The chemical composition of the tested material is shown in Table 1. The index of pitting corrosion resistance PRE_N for this cast steel is 36.7. The test material was melted in a laboratory electric induction furnace. The charge to the furnace was composed of scrap Cr-Ni alloy, armco iron, metallic Cr and Ni, and ferroalloys (FeSi, FeMn, FeMo). Nitrogen was introduced into the bath as a nitrided FeMn. Two "Y" type specimens were made. The specimens before tests were subjected to solution annealing carried out at 1060°C and 1150°C.

TABLE 1

Chemical composition of the investigated cast steel

C	Si	Mn	Cr	Mo	Ni	N	P	S	Al
wt. %									
0.08	0.67	4.96	23.3	2.95	2.16	0.227	0.006	0.008	0.02

PRE_N=%Cr + 3.3%Mo + 16%N= 36.7 [1]

Metallographic examinations were performed using light microscope and scanning electron microscope (JSM-7100) with EDS detector. For simulation of the solidification process, a Thermo-calc computer program was used. Ferrite content in the examined material was determined with an MPD 100A ferritoscope. Hardness of the examined cast steel was measured with Brinell hardness tester. Microhardness of phases present in the microstructure was measured with an attachment to the Hanemann light microscope.

Static tensile tests were carried out on a Zwick Z250 machine according to PN-EN ISO 6892-1 standard.

3. Discussion and results

Microstructure of the tested cast steel with nickel content reduced to 2% and manganese content raised to 5% and up to 0.2%N is composed of ferrite and austenite (Fig. 1, 2). According to calculations made by Thermo-calc, ferrite δ is the first one to precipitate during the crystallization process at a temperature of 1450°C. Austenite starts crystallizing at 1325°C, i.e. slightly above the solidus temperature (1323°C). Austenite precipitation from the residual liquid phase at the end of crystallization may indicate the occurrence of a peritectic L+δ→γ reaction taking place as a result of the microsegregation of Cr, Mo, C, N, Ni and Mn between the liquid and solid phases (the reaction L+δ→γ is backed up by, among others, the increased content of N and high content of C in the examined cast steel).

$M_{23}C_6$ carbides and σ phase are formed at temperatures of 1000°C and 890°C, respectively. Therefore it can be assumed that the tested cast steel solidifies as a nearly ferritic one, and at the end of solidification a peritectic reaction occurs. This course of solidification has been confirmed by calculations of the Cr_{eq} (Cr_{eq} = %Cr + 1.37%Mo + 1.5%Si) and Ni_{eq} (Ni_{eq} = %Ni + 22%C + 0.31%Mn + 14.2%N) equivalents as well as Cr_{eq}/Ni_{eq}. The obtained value of Cr_{eq}/Ni_{eq} = 3.27 exceeds 1.95 thus indicating that the crystallization process takes place in the tested material according to a ferritic model [13].

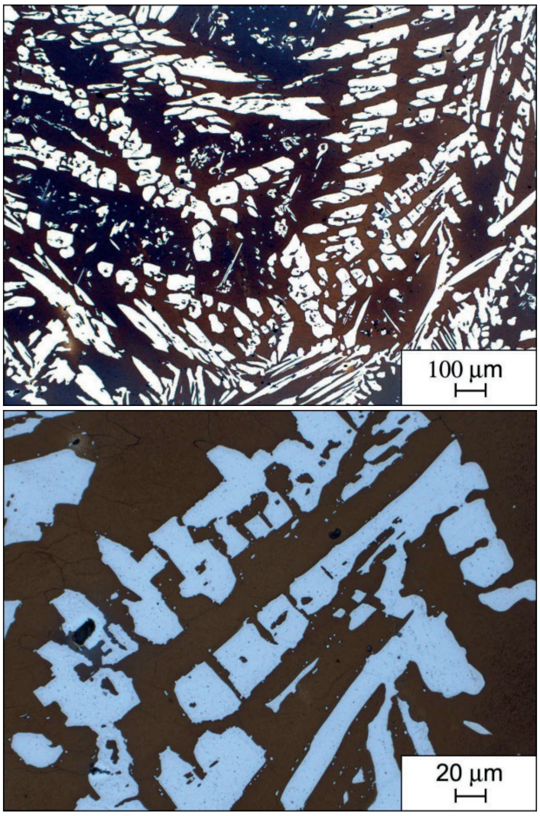
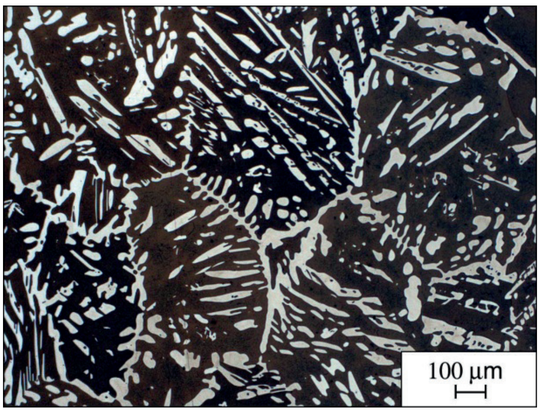


Fig. 1. Microstructure of the investigated cast steel after solution annealing at 1060°C, light microscope



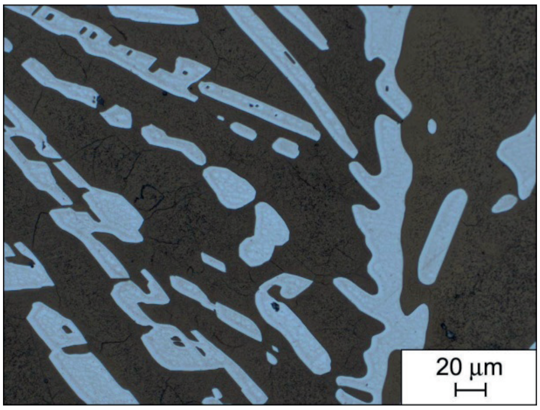


Fig. 2. Microstructure of the investigated cast steel after solution annealing at 1150°C, light microscope

The volume fraction of δ ferrite in the initial state showed considerable variations depending on the place where the head of the ferritoscope was applied. At the edge of the sample, lower ferrite values were reported than in the areas more distant from the surface. The average ferrite fraction in the initial state was approximately 54% and thus was within the limits set for duplex steels [1,3]. After solution heat treatment an increase in the volume fraction of ferrite up to about 60% was reported.

Studies conducted by scanning electron microscopy have proved that the structure of the examined material with 0.08% C contains in the initial condition, in addition to ferrite and austenite, also precipitates rich in Cr and Mo, which most likely are complex chromium carbides. After the solution annealing carried out at 1060°C, a few of such precipitates were still observed at the ferrite/austenite interface (Fig. 3, 4). On the other hand, their presence was not detected after the solution heat treatment carried out at 1150°C. Chemical analysis in the microregions of ferrite and austenite has confirmed the effect of Cr, Mo and Si microsegregation towards ferrite and reduced concentration of both these elements in the areas of austenite (Fig. 5). On the other hand, in austenite, the increased content of Mn and Ni was recorded (Fig. 6). Also was confirmed the beneficial effect of the presence of nitrogen on reduced division of Cr between ferrite and austenite. It was also demonstrated that the chemical composition of ferrite and austenite after the solution heat treatment at 1060°C and 1150°C did not show any significant differences (Table 2). In turn, comparing the morphology of austenite it has been found that with the increasing temperature of solution annealing, the precipitates of austenite undergo partial dissolution, which increases the ferrite content [14].

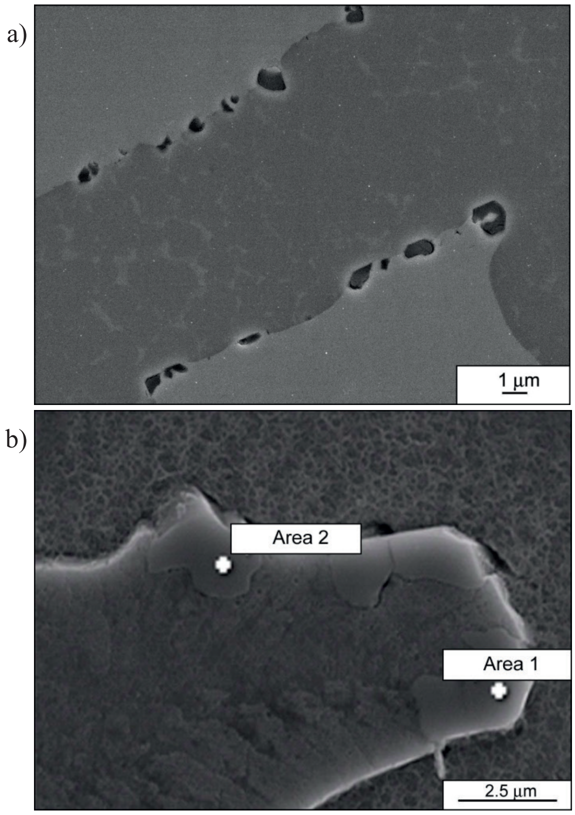
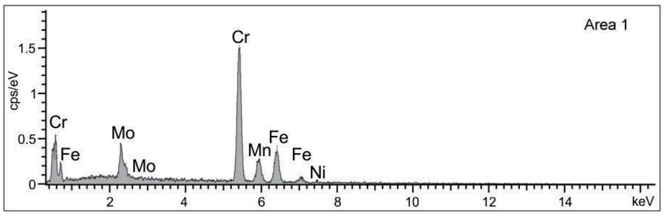


Fig. 3. SEM image of the investigated cast steel after solution annealing at 1060°C



Area	Chemical composition, wt. %					
	Cr	Mo	Mn	Ni	Si	Fe
1	60.5	8.5	4.1	1.4	0.1	25.4
2	32.7	4.3	5.1	2.7	0.7	54.5

Fig. 4. X- ray spectrum with the energy dispersion (EDS) and the chemical composition of areas 1, 2 from Fig. 3b

TABLE 2

The chemical composition of ferrite and austenite in the investigated stainless cast steel

Heat treatment	phase	Average content, wt. %					
		Cr	Mo	Mn	Ni	Si	Fe
As cast	A	21.9	2.3	5.8	3.1	0.6	66.3
	F	23.8	3.7	4.7	2.7	0.7	64.4
1060°C	A	22.7	2.4	5.3	2.8	0.5	66.3
	F	23.4	5.7	4.6	1.9	0.7	63.8
1150°C	A	22.6	2.6	5.5	2.9	0.6	65.8
	F	23.5	4.9	4.3	2.4	0.7	64.2

*/ *A-austenite, F-ferrite,*

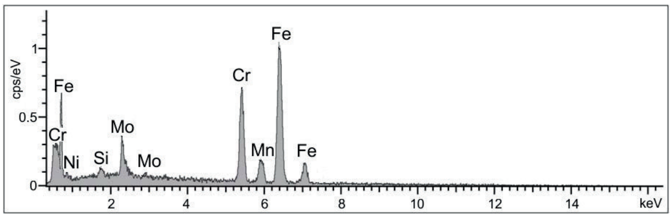


Fig. 5. X- ray spectrum with the energy dispersion (EDS) from ferrite - sample after solution annealing at 1060°C

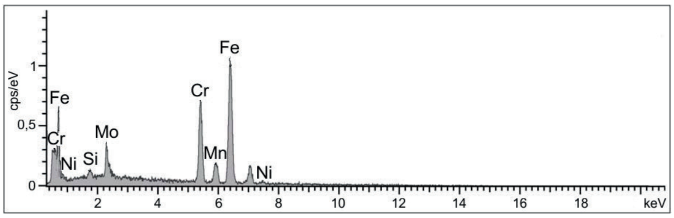


Fig. 6. X- ray spectrum with the energy dispersion (EDS) from austenite - sample after solution annealing at 1060°C

Hardness measurements of the examined cast steel have demonstrated an effect of the conducted heat treatment on this parameter (Fig. 7). In contrast, microhardness of ferrite and austenite after solution heat treatment at 1060°C and 1150°C did not show any more significant differences. Microhardness of ferrite was 315 μHV_{20}, on an average, while microhardness of austenite was higher and amounted to 338 μHV_{20}. The increase in the microhardness of austenite may result from the strengthening interstitial solid solution elements such as C and N. In the initial condition, the microhardness of both phases was slightly lower.

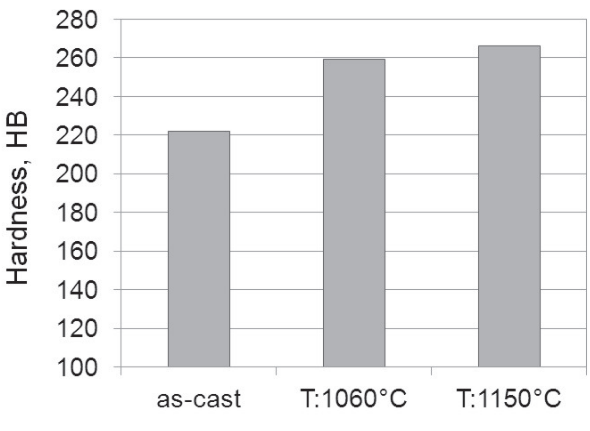


Fig. 7. Hardness of the investigated cast steel in as cast conditions and after solution annealing at 1060°C and 1150°C

Static tensile tests were next conducted on the examined material to determine its basic strength parameters. The study used 7 standard samples. Tensile strength values were in the range of 731 ÷ 750 MPa, the values of the yield strength were in the range of 547 ÷ 572 MPa with elongation of 21 ÷ 29.5%. The measurement results are shown in Fig. 8. Compared to cast 24Cr-5Ni-3Mo duplex steel, the tested material has similar plastic properties (EL, R.A.), but somewhat lower tensile strength.

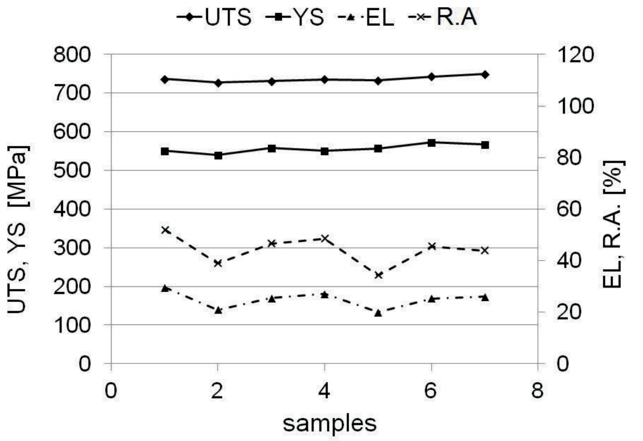


Fig. 8. Mechanical properties of cast stees after solution annealing at 1060°C

Fractures observed in samples after the mechanical tests have been of ductile-brittle nature with prevalence of ductile areas characterized by numerous small dimples occurring mostly around the precipitates (e.g. Al_2O_3 i MnS) as a result of the process of deoxidation and desulphurization. Locally, on the fracture surfaces, characteristic "faults" or "steps" were observed, around which the areas of cracks were accumulated (Fig. 9).

a) b)

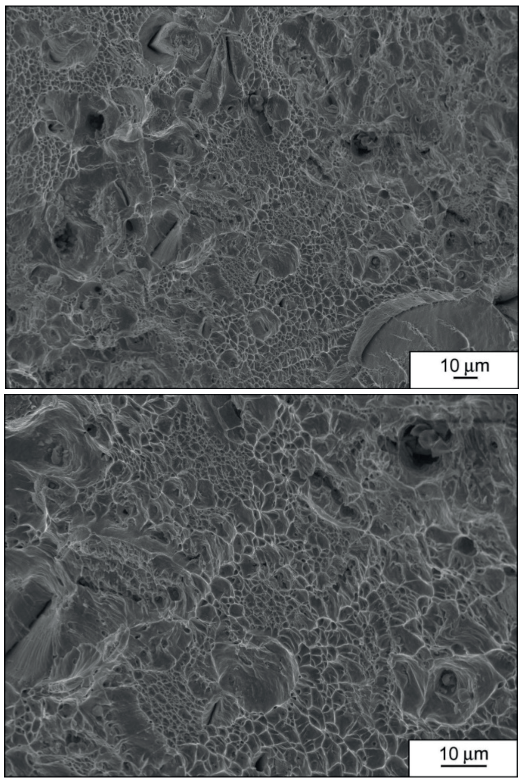


Fig. 9. Photographs of the investigated cast steels – sample fractures

4. Conclusions

- Microstructure of 23Cr-5Mn-2Ni-3Mo cast steel is composed of ferrite enriched in Cr, Mo and Si, and austenite enriched in Mn and Ni. Additionally, in the initial state, at the interface, the precipitates rich in Cr and Mo have been observed; in small amounts they occurred also after the solution heat treatment at 1060°C.

- The temperature of the solution annealing of the tested cast steel did not affect the microhardness of phases occurring in the structure of this cast steel grade.
- Subjected to solution heat treatment, the examined cast dual-phase steel had the following mechanical properties: UTS = 731 ÷ 750 MPa, YS = 547 ÷ 572 MPa, EL = 21 ÷ 29.5%, R.A. = 43 ÷ 52%, hardness 256 ÷ 266 HB.
- Fractures obtained after the static tensile test had a ductile-brittle character with visible globular precipitates of oxides and sulphides. Ductile cracks were also noted in the fractures.
- The beneficial effect of the presence of nitrogen on reduced division of Cr between ferrite and austenite was also confirmed.

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