Archives of Materials Science and Engineering

Volume 41
Issue 2
February 2010
Pages 69-76

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

The high alloy precipitation hardening martensitic steels and their suitability for welding

S.J. Pawlak [a,*], S. Dudek [b]
[a] Institute for Ferrous Metallurgy, ul. K. Miarki 12-14, 44-100 Gliwice, Poland
[b] WSK Rzeszów S.A., ul. Hetmańska 120, 35-078 Rzeszów, Poland
* Corresponding author: E-mail address: spawlak@imz.pl

Received 17.12.2009; published in revised form 01.02.2010

ABSTRACT

Purpose: Present work was aimed at developing welding technology applicable for hot and cold rolled strips made of high alloy martensitic steels. Electron beam (EB) and TIG welding processes parameters were worked out for strips of the 2N11K13H3M, N19M4T, H11N10M2T and PH13-8 steel grades (unconventional maraging and precipitation hardening stainless steel grades).

Design/methodology/approach: The heats of the steels were laboratory vacuum melted, forged and then hot and cold rolled. Welding process parameters were experimentally selected. Quality of the welds was evaluated by several non-destructive techniques and metallographic examination. Hardness distribution and tensile properties of welded strips were analyzed, and post weld heat treatment was proposed.

Findings: All four steel grades studied were suitable for the electron beam welding and optimum process parameters were worked out for the 3 mm strips. The suitability of the steels to welding using the TIG process was tested with 1.5 mm strips. Apart from the high cobalt maraging steel, which was not available in the form of thin strips, the other steels were welded successfully in TIG process. After welding, strength of the steels could be largely restored by full heat treatment.

Research limitations/implications: Further research is needed on weld microstructure evolution, affected by welding processes, to improve fracture properties of welds.

Practical implications: Welding technology of the hot and cold rolled strips of the four steel grades, high alloy martensitic grade, was developed, which along with very high mechanical properties and ductile fracture modes, make the steels suitable for advanced structural applications.

Originality/value: Progress achieved in welding technology development is of practical value for manufacture of the structural elements, made of high alloy martensitic steels in the form of hot and cold rolled strips.

Keywords: Metallic alloys; Welding metallurgy; Martensitic steels; Heat treatment

Reference to this paper should be given in the following way:

S.J. Pawlak, S. Dudek, The high alloy precipitation hardening martensitic steels and their suitability for welding, Archives of Materials Science and Engineering 41/2 (2010) 69-76.

MATERIALS

1. Introduction

High alloy martensitic steels studied in the present work, have well over 20% of the alloying elements and belongs to the two broad categories, the high-nickel maraging steels and the chromium-nickel precipitation hardening (PHSS) steels. In recent years there is the trend to substitute traditional quenched and tempered steels - which require surface protection - and use materials with good corrosion resistance, such as PHSS steels or titanium alloys. The new materials, to be suitable for advanced structural applications, should have technological advantages, as ease in fabrication and good weldability, as well as improved mechanical properties [1-6]. The materials are also selected on the bases of the relative strength, i.e. strength divided by density, and the structural efficiency - a factor combining yield stress, fracture toughness and density [7,8]. Maraging steels and PHSS steels with low carbon content are generally considered to have good weldability. However in practice often problems emerge, as susceptibility to cold and hydrogen cracking, problems with reactivity of precipitation hardening elements, or coarse microstructure in the melt area or heat affected zone (HAZ) [9-17]. For the weldability assessments of the high alloy martensitic steels studied, the tungsten inert gas welding (TIG) and electron beam welding (EB) processes has been selected.

The TIG process is most commonly used to weld thin sections of stainless steel, the low carbon high alloy martensitic steels and non-ferrous alloys. The process grants the operator greater control over the weld than competing procedures such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, the TIG process is comparatively more complex and difficult to master. Compared to EB welding the TIG process is much cheaper.

Electron beam welding process is one of most important welding processes used in aviation industry, especially for high precision assemblies. Electron beam of very high power density – about 100 W/cm^2, allow for deeper welds than are possible with other method. For similar thickness, width of weld and HAZ done with EB welding method is smaller than with TIG or plasma welding [9]. The EB welding process offers important advantages for many manufacturing applications, giving clean, reproducible, high integrity joints, with good mechanical properties.

2. Material and methodology

2.1. Material

All of the experiments were made with four laboratory vacuum melted high alloy martensitic steels. Two melts were maraging grade steels based on the Fe-Ni-Mo (cobalt-free) and Fe-Ni-Co (high-cobalt) matrix and two precipitation hardening stainless steels (PHSS) based on the Fe-Cr-Ni matrix, Table 1. After melting the ingots were forged and then hot and cold rolled to strips with thickness of 3 mm and 1.5 mm, respectively.

Table 1.
Chemical compositions of the high alloy martensitic steels studied, (wt.%)

El.	N19M4T Co-free maraging steel	2N11K13H3M high-Co maraging steel	H11N10M2 T PHSS steel	PH13-8 PHSS steel
C	0.03	0.24	0.02	0.05
Mn	0.14	0.13	0.14	0.20
Si	0.06	<0.05	0.06	0.10
P	0.010	0.010	0.010	0.008
S	0.010	<0.010	0.010	0.010
Cr	-	3.8	10.5	11.65
Ni	17.5	11.1	11.7	7.9
Co	-	11.5	-	-
Mo	4.5	1.2	1.46	2.13
Ti	1.1	-	1.34	-
Al	0.04	0.02	0.05	0.96

2.2. Methodology

All the TIG test welds were done with semiautomatic welding station. Test sample was mounted on copper backup with copper clamp (chillers). In the TIG welding following process parameters were controlled: current, arc voltage, welding speed and type of inert gas. In the EB welding process, made inside vacuum chamber, electron gun was working with 120 kV accelerating voltage. Other parameters were adjusted to strip thickness and steel grade. Weld quality was evaluated by non-destructive and metallographic examination. To reveal internal defects, the following non destructive methods were used: acoustic, magnetic and high voltage X-ray. For detection of the surface defects, the fluorescent penetrant method (FPI) was used.

3. Results and discussion

3.1. Microstructure, properties and heat treatment of the base materials

The 2N11K13H3M high cobalt maraging steel is particularly complex alloy in terms of composition and hardening mechanism. To find proper ageing temperature, the study on the ageing behavior has been made for that steel. The effect of ageing treatment on the hardness of 2N11K13H3M steel is shown in Fig. 1. Before ageing the steel was annealed at 980ºC and refrigerated at -78ºC. From Fig. 1 it can be inferred that proper ageing temperature is at about 480ºC. Lower ageing temperatures were not studied, as it is known that maraging steels are prone to embrittlement at temperatures close to 450ºC.

The X-ray diffraction studies of the electrolytic extracted residues were made, which revealed that ageing at 480ºC for 3 hours, leads to precipitation of the hexagonal carbide Mo_2C and η-MoC phase, also hexagonal. The diffractions patterns were very complex, indicating presence of other phases, presumably intermetallics of iron with cobalt, and possibly M_6C carbide.

Prolonged ageing at 480, 510 and 540ºC, give rice to martensite-austenite reaction, so called reversion, Table 2, which is the principal mechanism of the steel softening.

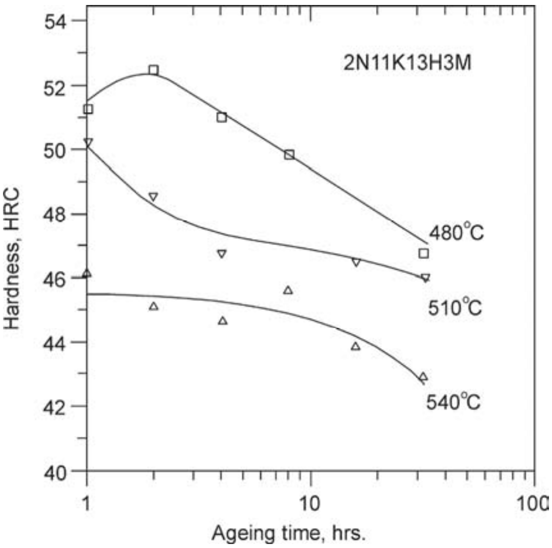


Fig. 1. Effect of ageing on the hardness of 2N11K13H3M steel grade

Table 2.
Effect of ageing treatment on the retained austenit content in the high cobalt maraging steel

Heat treatment*	Retained austenite [vol. %]
A + R + 480ºC, 32 hrs	10.8 ± 1.7
A + R + 510ºC, 32 hrs	18.0 ± 1.4
A + R + 540ºC, 32 hrs	27.6 ± 1.2

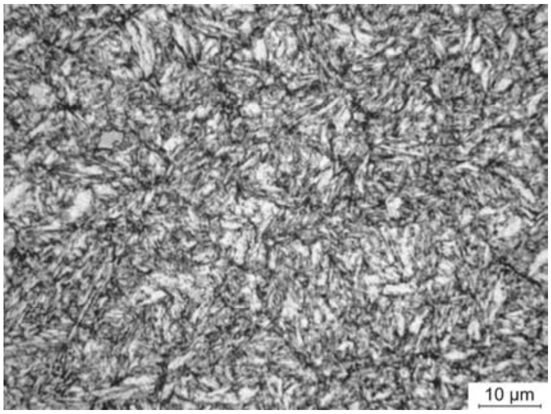
*A + R = annealing + refrigeration

Similar studies, as for the 2N11K13H3M, were made for the N19M4T and H11N10M2T steels, also involving tensile property changes for broad ageing temperature range [18,19]. The study showed that pronounced improvement in tensile elongation of the steels, occurs only when they are aged at temperatures as high as 550-600ºC. Despite very high ageing temperature the strength loss was only moderate. Such treatment with high overaging may be considered as the alternative post weld heat treatment, when welding joints with exceptionally high reliability are required. In the previous works the effects of metallurgical factors on the structure, fracture mode and properties of the high cobalt and cobalt free maraging steel has been studied, with the aim to better understand structure-property relations and enhance mechanical properties of the steels [18-20]. It was found that after cooling from annealing temperature the retained austenite was persistent in the 2N11K13H3M high cobalt steel and PHSS steels, but not in the N19M4T cobalt-free steel. To get rid of the retain austenite the refrigeration treatment was applied after annealing. Final stage in the heat treatment of all the steels studied was ageing, producing high strength as a result of the precipitation hardening reaction. Typical heat treatments of the steels studied are given in the Table 3.

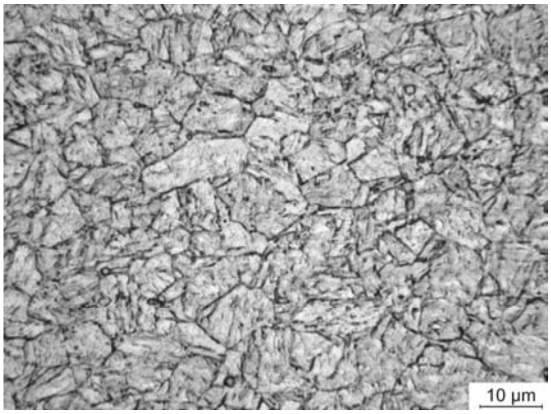
Table 3.
Typical heat treatment of the steels studied

Steel grade	Annealing	Refrigeration	Ageing
2N11K13H3M	885°C	-78°C, 3 h	480°C, 3 h
N19M4T	815°C	-	480°C, 3 h
H11N10M2T	985°C	-78°C, 3 h	510°C, 3 h
PH13-8	930°C	-78°C, 3 h	540°C, 3 h

a)



b)



c)

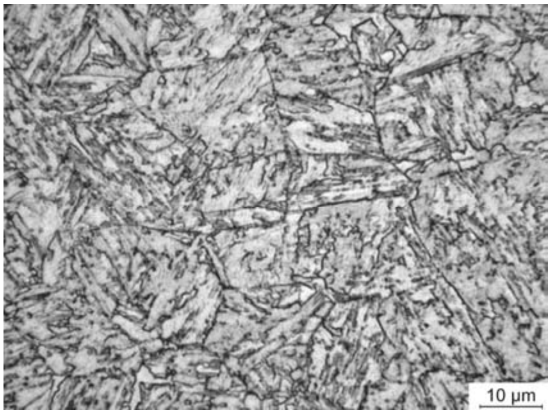


Fig. 2. Light microscopy microstructures of the high alloy martensitic steels after full heat treatment: a) 2N11K13H3M, b) N19M4T, c) H11N10M2T

This heat treatment is the optimal treatment for the forged and hot rolled products, such as bars and strips. In the case of cold rolled strips, used in the cold work state, the refrigeration treatment may be not needed and only ageing is applicable [20]. The martensite microstructures obtained after full heat treatments of the high alloy steels studied are given in Fig 2.

3.2. Welding technology with tungsten inert gas (TIG) process

The TIG arc welding process was applied to the 1.5 mm strips in the annealed condition. The arc welding process parameters established after numerous trials were following (typical values): welding current 45 A, arc voltage 8.6 V, welding speed – 250 mm/s. As a shielding gas the high purity argon (99.995%) was used. After TIG welding all strips were fully heat treated in the proper conditions for each steel grade. Two additional ageing temperatures were also applied to verify the applicability of the bulk material heat treatment to the welded joints, Table 4.

Table 4.
Heat treatment of the TIG welded steels

Steel grade	Annealing	Refrigeration 3 hrs	Ageing 3 hrs
N19M4T cobalt-free maraging steel	815°C	-	480°C 510°C 540°C
H11N10M2T PHSS steel	980°C	-78°C	480°C 510°C 540°C

The effect of heat treatment on the tensile properties of TIG welded strips of N19M4T cobalt-free maraging steel and H11N10M2T PHSS steel is presented in Table 5 and in Figs. 3 and 4. The tensile elongations values were not included in the Table 5, as these are considered as being uncertain, resulting from less than perfect geometry of the tensile specimens in the weld region (the original geometry of the welded specimen was preserved - not corrected by mechanical working). For the same reason the yield stress values of the welded specimens, have lesser accuracy then the tensile strength values.

Table 5.
Tensile properties of the 1.6 mm thick strips heat treated after TIG arc welding

Ageing temperature	YS MPa	UTS MPa	Remarks
N19M4T cobalt-free maraging steel			
480ºC	1415	1454	HAZ cracking
510ºC	1360	1396	-
540ºC	1290	1336	-
H11N10M2T PHSS steel			
480ºC	1326	1388	Cracking at weld/HAZ border
480ºC	1347	1411	Cracking at HAZ
480ºC	1336	1400	-
510ºC	1340	1387	-
540ºC	1165	1265	-

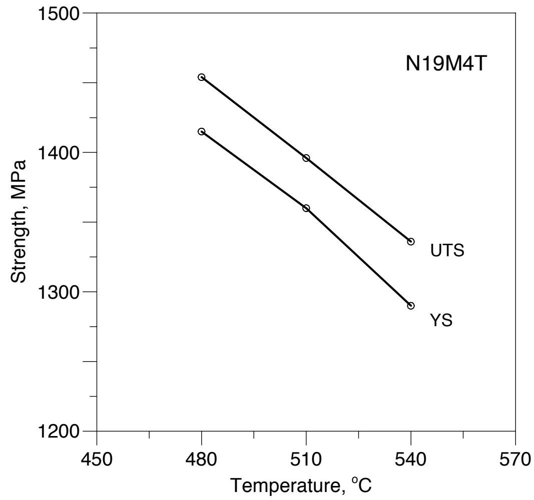


Fig. 3. Effect of ageing temperature on the tensile properties of the TIG welded N19M4T cobalt-free maraging steel

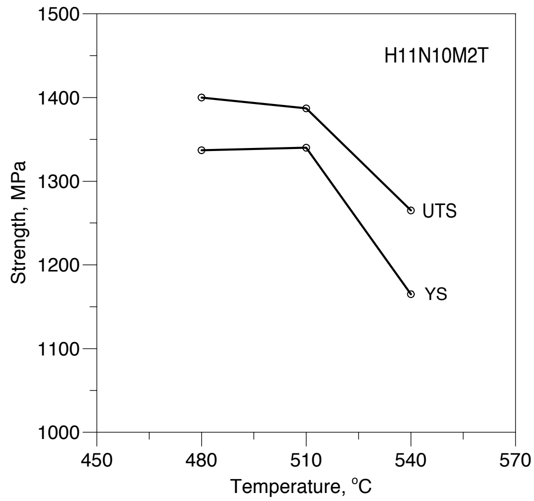


Fig. 4. Effect of ageing temperature on the tensile properties of the TIG welded H11N10M2T PHSS steel

Apart from strength it is important to analyze the plastic properties of the welded joints. Bearing in mind uncertainty in the tensile elongation values, the fracture modes of broken tensile specimens may provide good judgment in that respect. The scanning electron microscopy (SEM) fractographic investigation showed that welded strips of the N19M4T cobalt-free maraging steel and H11N10M2T PHSS steel were essentially fully ductile, Figs. 5-6, despite that cracks were localized in the heat affected zone (HAZ) or on the HAZ-weld border. Ductile appearance of the fracture surfaces of welded strips, at very high tensile strengths level, shows that both steels are characterized by good weldability at the selected TIG process parameters studied. As can be seen from Figs. 3 and 4, the ageing temperature for the N19M4T cobalt-free maraging steel may be selected as 480ºC and 510ºC for the H11N10M2T PHSS steel, producing the tensile strengths of about 1450 MPa and 1400 MPa, respectively.

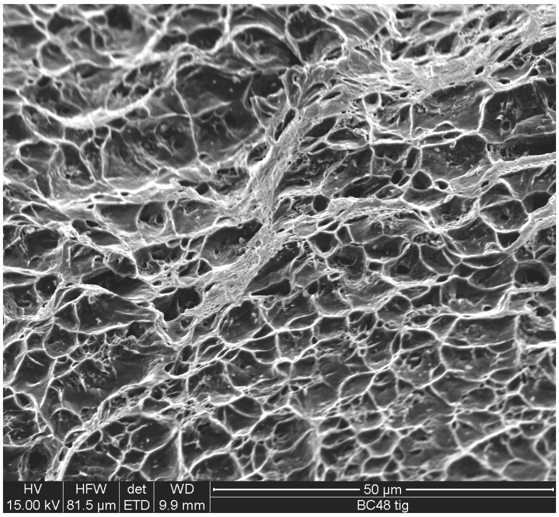


Fig. 5. SEM fracture appearance of the broken tensile TIG welded specimen of the cobalt-free maraging steel after full heat treatment, with ageing at 480ºC

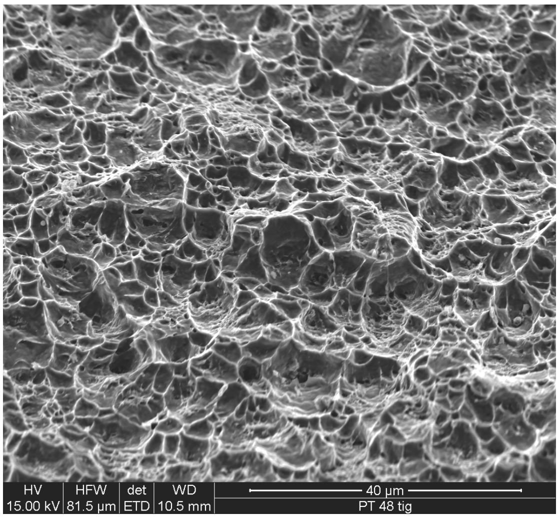


Fig. 6. SEM fracture appearence of the broken tensile TIG welded specimen of the H11N10M2T PHSS steel after full heat treatment, with ageing at 480ºC

3.3. Welding technology with electron beam (EB) process

The electron beam welding tests with the cobalt-free, high cobalt steels and H11N10M2T PHSS steels were conducted on the hot rolled strips, 3.5-4.0 mm thick. Welding process parameters were established after large number of trials, and normally were: beam current J = 18 mA, welding speed V = 20 mm/sec and deflection current (x and y) - 0.30 mA. Two weld passes were made in all test – normal welding pass and so called cosmetic pass with lower current and beam focus.

The X-ray photographs of the EB welds revealed porosity in some welds, Fig. 7.

a) b) c)

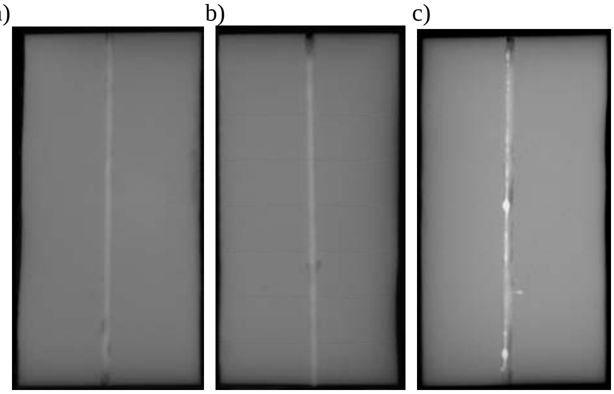


Fig. 7. The X-ray photographs of the EB welds: a) 2N11K13H3M high cobalt maraging steel, b) N19M4T cobalt-free maraging steel, c) H11N10M2T PHSS steel

Example of typical weld appearance of the high cobalt maraging steel are shown in the Fig. 8.

a) b)

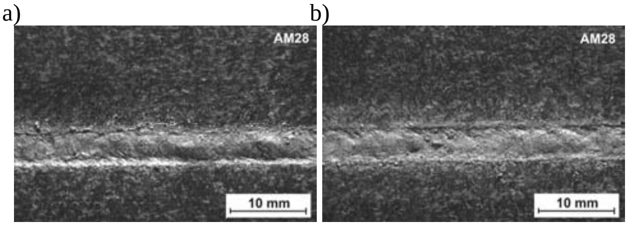
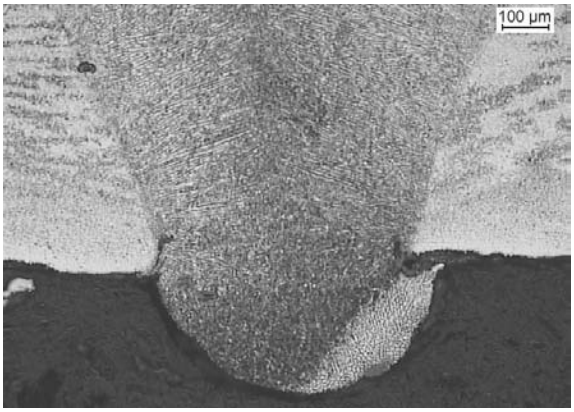


Fig. 8. Typical EB weld appearance of the 2N11K13H3M high cobalt maraging strip of 3 mm thickness: a) face side, b) root side

Visual inspections of the welds from face and root sides showed lack of cracks, undercut or porosity. Excess under fill were occasionally detected on the face side, Fig 8. For welds made without filler material this is considered normal, especially for thin strips. Closer metallographic examination of the high cobalt maraging steel welds, occasionally revealed defects in the form of the globular porosity and non regular excess penetration – too high root of weld as well as weld discontinuity. Microscopic investigations also revealed lack of side fusion, and cracking at the weld root edge, Fig. 9.

Nature of the revealed defects indicated that they may be minimized or eliminated entirely in future test, after gaining some practical experience. It was learned that the EB welding requires very high surface purity and perfect geometrical matching of the welded surfaces. It was found that essentially, welds were sound and the EB welding process can be applied to all three investigated steels. Hardness distribution across the raw EB welds (i.e. without any post weld treatment) are presented in Fig. 10a, whereas data for the heat treated strips in Fig. 10b. The heat treatment applied was the same as the one used to hot rolled strips, as given in Table 3.

a)



b)

c)

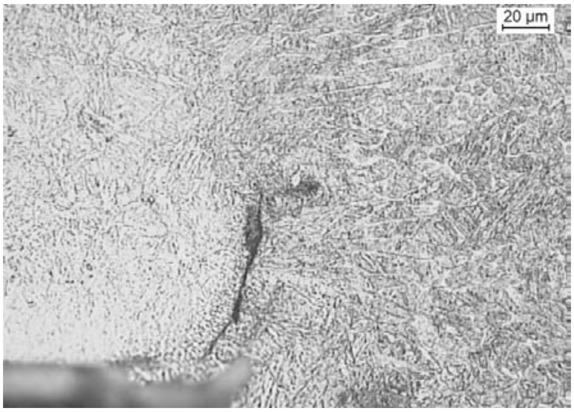
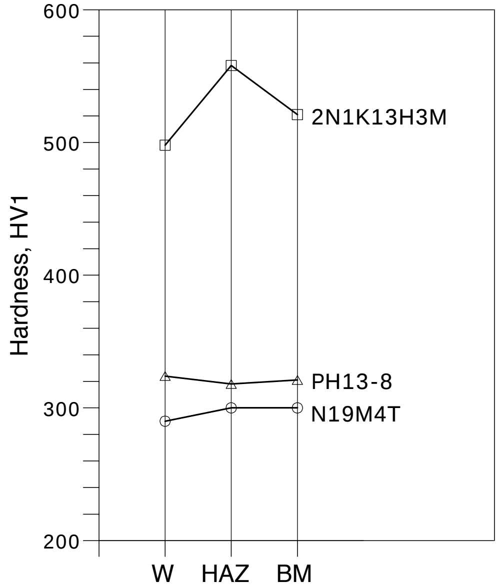


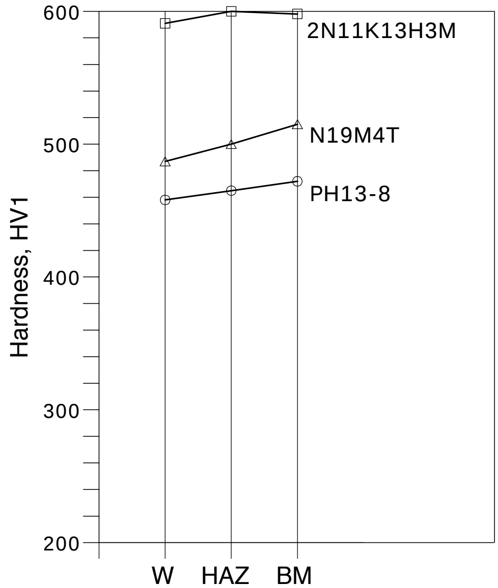
Fig. 9. Structure at the root edge the EB weld of high cobalt maraging steel. Defects in the form of cracks, lack of side fusion and excess penetration are observed

For the 2N11K13H3M high cobalt maraging steel, the hardness across the weld was very uniform (about 600 HV), Fig. 10b. This corresponds well with the weld microstructures, which were also uniform, at least at small magnification, Fig. 11. Despite that uniformity, the tensile test specimens usually broke in the heat affected zone.

a)



b)



Legend: W - weld, HAZ - heat affected zone, BM - base metal

Fig. 10. Weld hardness distribution after electron beam welding of the steels studied: a) raw welds, b) heat treated welds

Tensile properties evaluation of the EB welded joints of the high cobalt maraging steel in the form of hot rolled 3 mm strips are presented in Table 6.

a)

b)

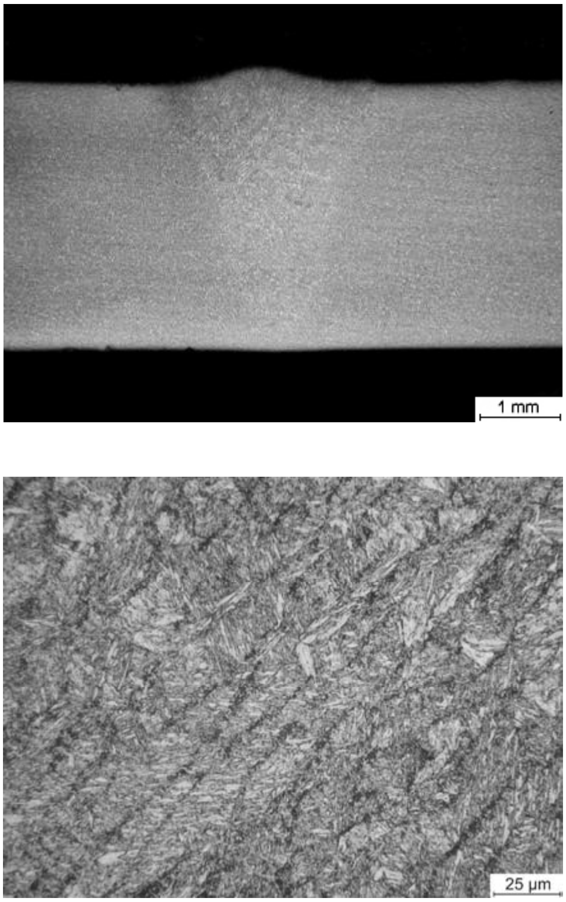


Fig. 11. EB weld of the 2N11K13H3M high cobalt maraging steel after full heat treatment, a) macrostructure, b) microstructure of the fusion zone

Table 6.
Tensile properties of the 2N11K13H3M high cobalt maraging steel, heat treated after electron beam welding of 3 mm strips

Heat treatment 885ºC, -78ºC and ageing at:	YS MPa	UTS MPa	Elongation A_{25}, %	Remarks
480ºC	1360	1545	3.2	HAZ cracking
510ºC	1360	1416	6.6	-

After ageing at 480ºC, the ultimate tensile strength was 150 MPa lower than typical one used to bulk steel products [18,19], but the cross sections of the welded specimens in the weld area were somewhat lower then for the parent strip, and the strip size was used in the tensile strength calculations.

The example of EB weld microstructure of the H11N10M2T PHSS steel after full heat treatment is given in Fig. 12. Compared to the 2N11K13H3M high cobalt maraging steel, the H11N10M2T PHSS steel have much coarse microstructure, both in the fusion zone and in base metal. The same observation was also true for the N19M4T cobalt-free maraging steel.

a)

b)

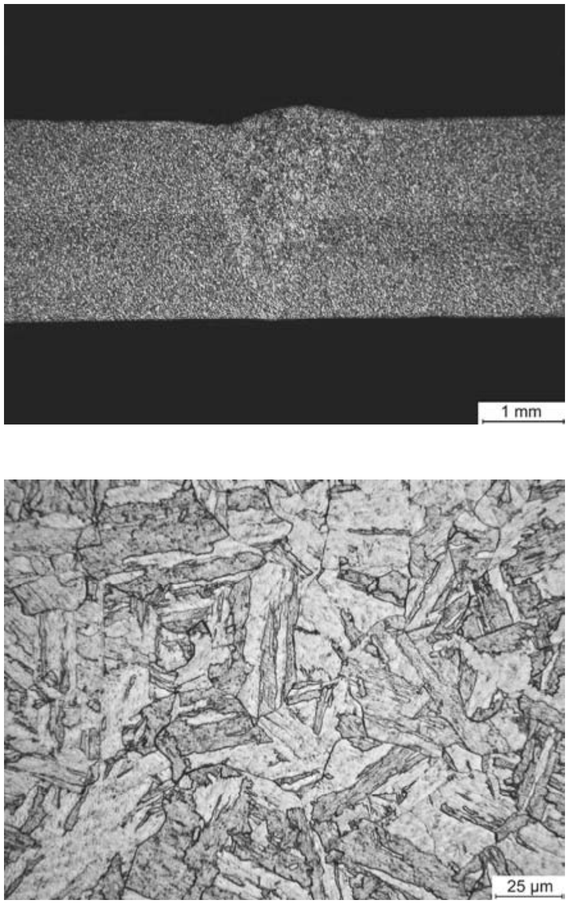


Fig. 12. EB weld of the H11N10M2T PHSS steel after full heat treatment, a) macrostructure, b) microstructure of the fusion zone

4. Conclusions

Progress was achieved in the material and welding technology development for the martensitic high alloy steels, unconventional maraging steel grades (2N11K13H3M, N19M4T) and precipitation hardening stainless steel grades (H11N10M2T, PH13-8). Welding tests were conducted on the hot and cold rolled strips with thickness of about 3 mm and 1.5 mm, respectively (the high cobalt maraging steel was not available in the form of thin strips).

All four steel grades were suitable for the electron beam welding. The EB welding and heat treatment parameters developed for the 2N11K13H3M high cobalt maraging steel assured very uniform microstructure and hardness (about 600 HV) from the base metal across the weld. At tensile strength of about 1550 MPa, the cracked surfaces were ductile, and were located either in the weld area or in the base metal. For the N19M4T cobalt-free maraging steel, welded in EB process, microstructures obtained after full heat treatment were acceptable (but not so uniform as for 2N11K13H3M steel) and hardness dropped only marginally from base metal through HAZ to the weld.

The TIG welded thin strips of N19M4T cobalt-free maraging steel and the H11N10M2T PHSS steel - after post weld heat treatment - have the tensile strength about 1450 MPa and 1400 MPa, respectively. Fracture surfaces of the tensile specimens were ductile, and cracks were located in the heat affected zone, or on border line between HAZ and edge of weld.

The welds quality was evaluated by non destructive methods: FPI, acoustic, magnetic and high voltage X-ray as well as metallographic examination, which revealed various defects and weld inconsistencies. The nature of the defects indicated that they may be minimized or eliminated after some practice.

Acknowledgements

This work was supported by the Polish Ministry of Science and Higher Education, grant No. R07 034 02.

References

[1] D.G. Lee, K.C. Jang, J.M. Kuk, I.S. Kim, The influence of niobium and aging treatment in the 18% Ni maraging steel, Journal of Materials Processing Technology 162-163 (2005) 342-349.

[2] N.G. Pokrowskaja, Contemporary high strength structural steels for aerospace industry, Physical Metallurgy and Heat Treatment of Metals 12 (2000) 23-26 (in Russian).

[3] Technological Cooperation Forum - Pratt & Whitney Canada, Warsaw Technical University, May 12, 2006 (unpublished document).

[4] L.A. Dobrzański, Metal Engineering Materials, WNT Warsaw, 2004 (in Polish).

[5] M. Hetmańczyk, L. Swadźba, B. Mendala, Advanced materials and protective coatings in aero-engines applications, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 372-381.

[6] S.J. Pawlak, Correlation between ductility and the second phase particles parameters in vacuum melted maraging steels, Proceedings of the International Symposium "Metallography", Strbske Pleso, Slovakia, 1986, Vol. 3, 26-30.

[7] L.A. Dobrzański, Engineering materials and material design. Principles of materials science and physical metallurgy, WNT, Warsaw, 2006 (in Polish).

[8] Y. Katz, N. Tymiak, W.W. Gerberich, Local approach contributions into the global view of the mechanical crack-tip environment formulation, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 162-165.

[9] S. Dudek, W. Karliński, A. Poznańska, M. Snieżek, Properties of electron beam welded 300M steel, Transactions of the Institute of Aviation 172-173/1-2 (2003) 55-58.

[10] E. Tasak, Welding Metallurgy, JAK, Cracow, 2008 (in Polish).

[11] Metals Handbook, Welding, Brazing and Soldering 6, ASM, Materials Park, USA, 2007.

[12] J. Brózda, M. Zeman, Wrong heat treatment of martensitic steel welded tubes caused major cracking during assembly of resuperheaters in a fossil fuel power plant, Engineering Failure Analysis 10/5 (2003) 569-579.

[13] M. Opiela, W. Krukiewicz, Hydrogen embrittlement of welded joints of the heat treatable XABO 960 thick plate, Protection Against Corrosion 11 (2008) 406-410 (in Polish).

[14] W. Ozgowicz, A. Kurc, G. Nawrót, Identification of precipitations in anodically dissolved high-strength microalloyed Weldox steels, Archives of Materials Science and Engineering 31/2 (2008) 95-100.

[15] J.S. Seo, H.J. Kim, H.S. Ryoo, Microstructural parameter controlling weld metal cold cracking, Journal of Achievements in Materials and Manufacturing Engineering 27/2 (2008) 199-202.

[16] C.H. Kim, H.S. Lim, J.K. Kim, Position welding using disk laser-GMA hybrid welding, Journal of Achievements in Materials and Manufacturing Engineering 28/1 (2008) 83-86.

[17] J. Nowacki, Structure and properties of large dimension vacuum brazed joints of 14-5 PH steel and WC - Co sinters, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 713-719.

[18] S.J. Pawlak, W. Zalecki, Microstructure, properties and hot deformability of the new maraging steels, Journal of Achievements in Materials and Manufacturing Engineering 29/1 (2008) 31-38.

[19] S.J. Pawlak, Microstructure and properties of high-cobalt and cobalt-free maraging steels, Journal of Achievements in Materials and Manufacturing Engineering 27/1 (2008) 31-34.

[20] S.J. Pawlak, H.J. Krztoń, Cold worked high alloy ultra-high strength steels with aged martensite structure, Journal of Achievements in Materials and Manufacturing Engineering 36/1 (2009) 18-24.