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Microstructure and properties of vacuum melted high cobalt and cobalt-free maraging steels

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Materials

ABSTRACT

Purpose: Steel cleanliness, microstructure and fracture mode have been studied, with the aim of enhancing mechanical properties and toughness of the high cobalt and cobalt-free maraging steels.
Design/methodology/approach: To fully evaluate all relevant metallurgical factors affecting steel mechanical properties and toughness, broad range of the experimental techniques was used: quantitative metallography, X-ray diffraction, TEM and SEM fractography.
Findings: Purity of the laboratory vacuum melted steels was similar to that of foreign industrial steels of the aircraft quality. It was showed that cobalt-free maraging steel could achieve properties comparable to the steel with very high cobalt content. Fracture surface morphologies were highly dependent on the steel grade and type of the mechanical test. In higher strength, the high cobalt steel
fractures were generally more flat and more ductile than in the Co-free steel, particularly in the impact test.
Research limitations/implications: Further comparative studies of the high cobalt and cobalt-free maraging steels are required on the properties, fracture modes and service properties of a selected parts.
Practical implications: Very high mechanical properties and fracture toughness values obtained for the steels studied, are suitable for advanced structural applications.
Originality/value: Detailed evaluation of the metallurgical purity, microstructure and fracture modes, allowed for better understanding of the microstructure-property relationships in selected high strength steels. The results obtained are of practical value for the development and production of the high strength steels with improved properties.
Keywords: Metallic alloys; Maraging steels; Mechanical properties; Microstructure

1. Introduction

In the development of the high strength steel for the advanced structural applications a considerable degree of control is needed over many metallurgical factors as chemical composition, cleanliness, microstructure and heat treatment [1-10]. In the constant strive to increase both strength and toughness, steel grades evolved from the quenched and tempered medium carbon Cr-Ni-Mo steels to high alloy maraging steels, with prominent "classical" composition of 18Ni-9Co-5Mo-Ti [11-13]. Currently the AM100 (0.23C-11.5Ni-13.4Co-1.5Mo) steel is gaining more favor [14-16]. The more general trends, leaner and eco-friendly technology is prevailing recently in many industries [17, 18]. For the steel development it means leaner compositions and fewer steps in manufacture.

2. Results and discussion

Most of the experiments were made with the 25 kg laboratory vacuum melted 19Ni-4Mo-1Ti and 0.23C-11.5Ni-13.4Co-1.5Mo maraging steels. Mean volume fractions of inclusions in the Co-free and the high cobalt heats were 0.086% and 0.022%, respectively. To efficiently measure geometric parameters of very small inclusions in very pure steels, a special method has been developed, using digital quantitative image analyzer [19]. The basic geometric parameters of the inclusions are shown in Table 1. Analogous measurements were also made for two foreign industrial melts of the aircraft quality [20], which showed that the purity (0.056 vol. % on average), was close to that of the laboratory melts (0.054 vol. %).

Table 1.
Geometric parameters of the inclusions in the laboratory melted Co-free steel, with inclusion volume fraction of 0.086%

Parameter	Mean µm	Std. dev. µm	Min. µm	Max. µm
Equivalent dia.	1.05	0.53	0.46	3.75
Length	1.54	1.08	0.52	9.37
Thickness	0.60	0.28	0.21	1.86
Aspect ratio	2.72	2.09	1.06	20.33

The specimens for the mechanical and microstructural testing were prepared from forged 32 mm dia. bars. Heat treatment of the Co-free steel involved annealing and ageing, while the high cobalt steel after annealing was subjected to refrigeration treatment at 80°C. Both steels were aged at 480ºC for 3 hrs. Light microscopy microstructures of the steels after full heat treatment are shown in Fig.1. The transmission electron micrograph (TEM), Fig. 2a, shows martensite with the lath substructure of high dislocation density. At high magnifications very small precipitates were observed in aged steels, Fig. 2b, but electron diffraction attempts to identify their structure were unsuccessful.

Other approach to identify the particles present in the steel after full heat treatment was X-ray diffraction of the chemically extracted residues. On the diffraction pattern of high cobalt steel the reflections from hexagonal Mo_2C carbides were observed as well as MoC (also hexagonal). Supposedly the M_6C carbide (M stands for metal) was also present in the residues. In the Co-free steel the basic constituent of the residues was the Fe_2Mo intermetallic phase. The other phases found were NiTi, Ni_3Ti, TiC and possibly the FeMo sigma phase.

The mechanical properties of the steels after full heat treatment are presented in Table 2.

Table 2.
Mechanical properties and toughness of the aged steels

Steel	YS MPa	UTS MPa	R.A. %	Charpy J	K_{1c} $MPa \cdot m^{1/2}$
High cobalt	1716	1912	53	39	70.1 ±5.5
Co-free	1624	1705	48	15	82.3 ±1.6

The cobalt-free maraging steel, has only about 100 MPa smaller yield strength, but much higher fracture toughness K_{1c} value than high-Co steel. To compare two steels, taking into account both strengths and toughness, "the structural efficiency" parameter was defined as $(K_{1c}/YS)^2$ - which has a unit of mm. This parameter is directly proportional do the allowable crack size, according to the fracture mechanics principle. On the bases of this criterion the Co-free seems to be better than the high cobalt grade, Fig. 3b, but definite judgment would only be made when yield strengths of the two steels were closer.

a)

b)

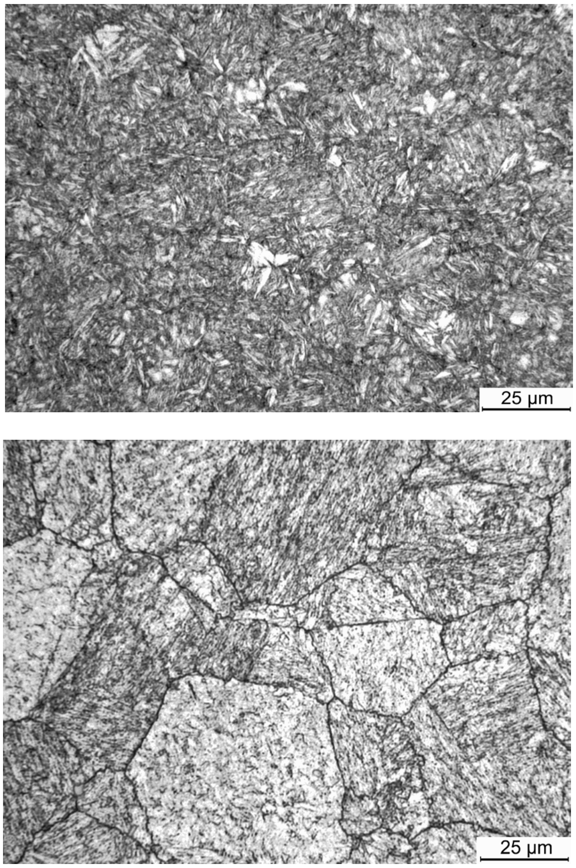

Fig. 1. Micrographs of the aged high cobalt (a) and the Co-free steel (b)

a) b)

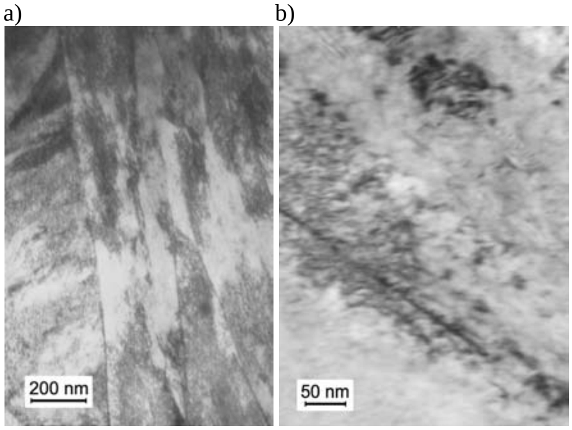

Fig. 2. TEM micrograph of the aged high cobalt steel showing lath martensite (a) and precipitates in martensitic matrix (b)

a)

b)

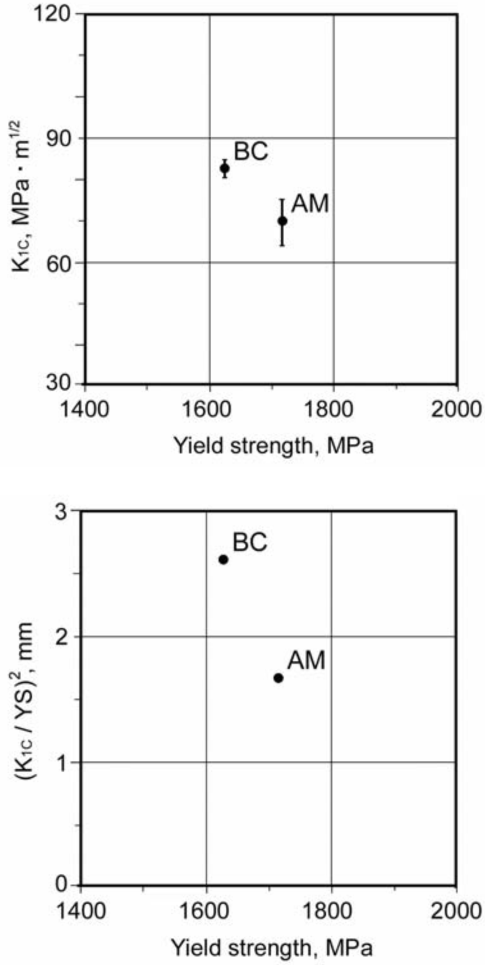

Fig. 3. Yield strength *vs* fracture toughness (a) and "structural efficiency" parameter (b) of the Co-free steel (BC) and the high cobalt steel (AM)

Fracture surface morphologies observed by SEM were strongly dependent on the steel grade and type of the mechanical test (quasi-static straining, impact bending and precracked quasi-static bending). After tensile testing of the aged specimens fracture surfaces in both steels were fully ductile, characterized by very deep voids.

The fracture surfaces of the fracture toughness (K_{1c}) specimens of the high cobalt steel were flat, made of shallow ductile micro voids, Fig. 4a, and occasionally intercrystalline tears were seen. In case of the Co-free steel fracture surfaces were more complicated. Apart from ductile areas, large part of the surface was essentially intercrystalline, but with not clearly developed microsurfaces of the grain size facelets, Fig.4b. These microsurfaces were often connected by ductile transcrystalline shears. The surface of K_{1c} tested specimens were so flat and uniform that profilometric measurements could be made using Taylor-Hobson instrument. Roughness values, Ra, for the high cobalt and the Co-free steel, were 4.3 µm and 10.3 µm respectively.

a)

b)

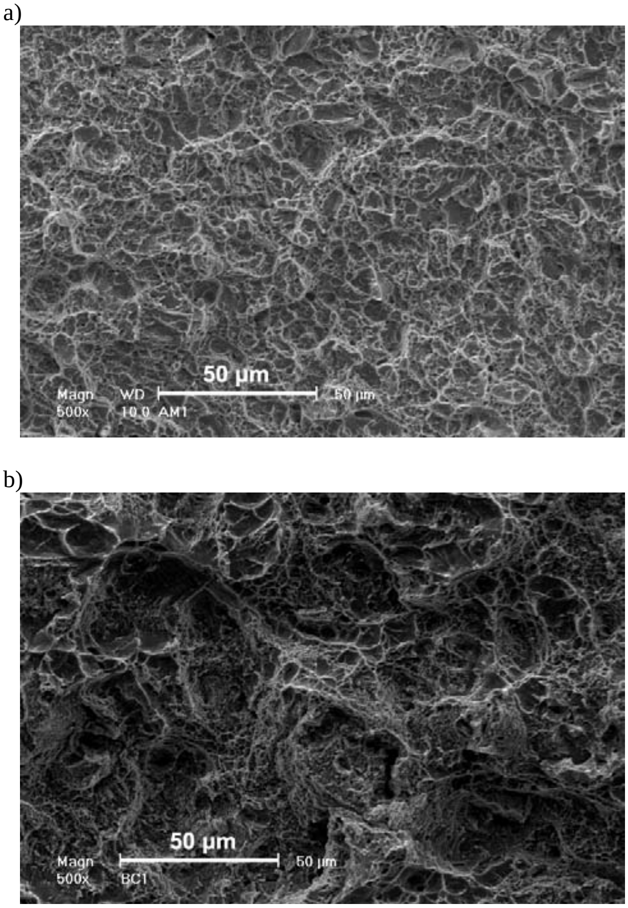

Fig. 4. SEM fractograph of the K_{1c} specimens of the high cobalt (a) and the Co-free steel (b)

The surfaces of the Charpy impact tested specimens were not so flat as that of K_{1c} tested specimens, and more intercrystalline fracture constituents were found in both steels, particularly in the cobalt-free steel.

3. Conclusions

Cleanliness of the laboratory vacuum melted steels were similar to that of the foreign industrial steels of the aircraft quality. Very high strengths and fracture toughness values obtained by the steels studied, make them adequate for many advanced structural applications. The 19Ni-4Mo-1Ti cobalt-free maraging steel with yield strength of over 1600 MPa and K_{1c} over 80 $MPa \cdot m^{1/2}$, has higher "structural efficiency" - a factor combining both yield stress and K_{1c} values - than 0.23C-11.5Ni-13.4Co-1.5Mo high cobalt grade.

Fracture surface morphologies were highly dependent on the steel grade and type of the mechanical test. In the high cobalt steel the fractures were generally more ductile and more flat than in the cobalt-free steel. The work is in progress on the fracture mode implications for the service properties of parts made of the steels studied.

Acknowledgements

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