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Journal of Nuclear Materials 271&272 (1999) 445–449

journal of nuclear materials

Tensile and impact behaviour of BATMAN II steels, Ti-bearing reduced activation martensitic alloys [1]

G. Filacchioni *, E. Casagrande, U. De Angelis, G. De Santis, D. Ferrara, L. Pilloni

ENEA CR Casaccia, Innovation Department, New Materials Division, Technology and Material Qualification Section, via Anguillarese 301, 00060 St. Maria di Galeria, C.P. 2400-00100 Rome, Italy

Abstract

Two series of Reduced Activation Ferrous alloys (RAF) have been produced and studied by Casaccia's Laboratories. These martensitic alloys are named BATMAN steels. They are among the few presently developed RAF materials to exploit Ti as a carbide forming and grain size stabilizing element instead of Ta. In this work their mechanical properties are illustrated. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

Ti-stabilised steels have received less attention than Ta-stabilised Reduced Activation Ferrous alloys (RAF). Therefore, few data are available about Ti-alloying effects on microstructure or mechanical behaviour of 7–9% Cr martensitic steels.

The ENEA's activity on Ti-bearing steels named BATMAN, started eight years ago at Casaccia's Laboratories. Two series of alloys were developed, the whole production covering a wide range of chemical compositions. By analysing properties of such steels, the effect of some elements in a martensitic structure has been clarified.

Owing to their mechanical behaviour, two compositions have been chosen as the most promising: Cast Nos 1953 and 1955 are now among the EU official candidates.

In this article, a number of mechanical properties of BATMAN alloys are reported and compared with those of other RAF steels.

2. Experimental details

2.1. Material

The present generation of alloys, named BATMAN II family, has been conceived taking into account the results we obtained in testing the first production of Ti-bearing RAF, the so-called BATMAN 91X steels [1–3]. The chemical composition for each group of alloys is reported in Tables 1 and 2. The most significant difference is the reduced amount of Mn, Ti and N. Reasons for such modifications have been reported and discussed elsewhere [4,5]; briefly, the reduced Mn allowed a wider useful range of tempering temperatures while reduced contents of Ti and N hinder the formation of coarse, blocky primary precipitation of TiN.

All mechanical tests were carried out on specimens machined from 6 to 15 mm thick plates, double-normalized plus tempered. Grain sizes were within ASTM No 8–10 (25–10 μm) and post-tempering Vickers hardness ranged from 205 to 225 kg/mm^2.

2.2. Tensile testing

Pin loaded specimens were tested on a closed loop servo-mechanical Mayes ESM100 load frame; specimens had a 16 mm^2 cross section and a 22.6 mm gauge length ($L_0/\sqrt{S_0} = 5.65$). Test temperature ranged from ambient

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* Corresponding author. Tel.: +39-06 3048 3142; fax: +39-06 3048 4864; e-mail: gianni.filacchioni@info1.casaccia.enea.it

[1] This work has been performed in the frame of the European Blanket Project-Structural Material Programme.

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PII: S0022-3115(98)00755-7

Table 1
Chemical composition of BATMAN 91X steels (previous generation)

Cast No. (%)	C (%)	Cr (%)	W (%)	Ti (%)	V (%)	Mn (%)	B (ppm)	Si (ppm)	N (ppm)	S (ppm)	P (ppm)	Ni (ppm)
27	0.1	8.9	1.45	0.20	0.21	3.1	40	490	340	140	90	710
28	0.09	8.94	1.51	0.01	0.24	3.51	91	320	340	140	70	520
29	0.08	8.98	0.96	0.24	0.26	3.76	61	390	320	150	60	420
30	0.11	9.27	1.53	0.29	0.32	3.81	83	390	270	140	80	410

For all casts: Al 100 ppm, Mo 200 ppm, Nb 100 ppm, Sb 50 ppm, Sn 100 ppm, Fe = bal.

Table 2
Chemical composition of BATMAN II steels (present generation)

Cast No.	C (%)	Cr (%)	W (%)	Ti (%)	V (%)	Mn (%)	B (ppm)	Si (ppm)	N (ppm)	S (ppm)	P (ppm)	Ni (ppm)
1951	0.12	8.45	1.45	0.12	0.17	1.34	70	330	70	12	50	260
1952	0.134	8.67	1.42	0.12	0.20	0.48	62	500	41	<20	50	340
1953	0.13	7.55	1.41	0.072	0.20	0.52	57	300	41	<20	50	290
1954	0.121	8.45	1.43	0.077	0.19	0.50	54	300	69	<20	50	290
1954b	0.077	7.68	1.38	0.065	0.20	0.50	54	280	26	18	60	210
1955	0.125	8.67	1.43	0.066	0.20	0.52	64	250	57	18	60	210
1956	0.14	8.59	1.42	0.12	0.20	1.48	<4	300	57	12	60	280

For all casts: Al < 85 ppm, Mo < 160 ppm, Nb < 25 ppm, Cu < 60 ppm, Sb < 45 ppm, Sn < 25 ppm, Fe = bal.

to 700°C and was monitored by K type thermocouples. Soaking time at temperature before testing was in the range of 10–15 min. A deformation-rate corresponding to 1.8%/min was used. Continuous data-logging provided a set of load versus ram displacement for analyzing the stress–strain curve.

2.3. Impact properties

Tests were performed either on full size Charpy ISO V or sub-sized KLST ($3 \times 4 \times 27$ mm^3, DIN 50115 standard) samples. A Tinius Olsen, 360 J (5.5 m/s, tup's velocity) or a Wolpert PW5, 50 J (3.85 m/s) were respectively used, both being fully instrumented pendulums. Actual test temperatures were evaluated from a series of master curves in which temperature evolution was related to measured cryogenic bath or oven temperature and time elapsed between extraction and impact. Accuracy of temperature estimation has been proven to be better than ±3%. Signals of load and tup displacement were also analysed for evaluating dynamic fracture toughness and dynamic yielding stress.

3. Results

The trends of tensile strength and elongation are plotted in Figs. 1 and 2. In each plot, the shaded area represents the envelope of the previous heats of Ti-bearing alloys. Flow–stress curves of present generation

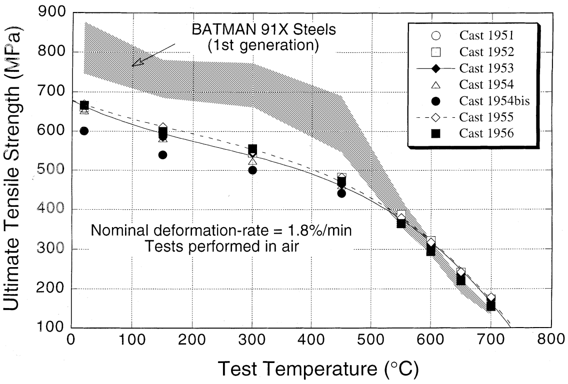


Fig. 1. Tensile strength of BATMAN steels.

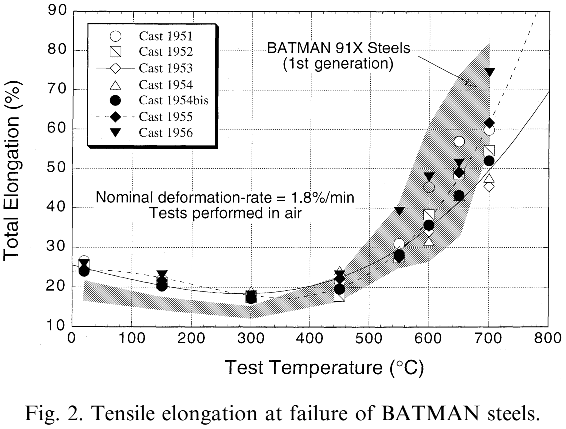


Fig. 2. Tensile elongation at failure of BATMAN steels.

steels have been analysed according to the Hollomon's strain-hardening correlation [6]

$$\sigma = K\varepsilon^{n}_{\text{plast}}. \tag{1}$$

True-stress, true-strain curves related to Cast 1955 are shown in Fig. 3.

The impact properties showed by sub-sized KLST specimens have been compared to those of BATMAN 91X series (Fig. 4) and data obtained on standard Charpy ISO V notched samples are reported in Fig. 5.

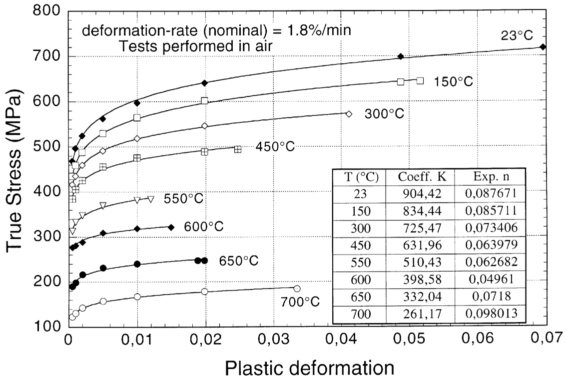
Exploiting the load-tup displacement curves, the dynamic fracture toughness (J_{d}) can be calculated taking into account the energies corresponding to maximum load, so that

$$J_{\text{d}} = \frac{2E_{\max}}{Bb}, \tag{2}$$

where $E_{\max}$ represents the energy at $F = F_{\max}$, B and b are respectively the specimen's width and the net ligament height. Thus an equivalent K_{d} will be determined as

$$K_{\text{d}} = \sqrt{J_{\text{d}}E} \tag{3}$$

being E the Young's Modulus. Dynamic fracture toughness values obtained on KLST specimens are shown in Fig. 6.



T (°C)	Coeff. K	Exp. n
23	904,42	0,087671
150	834,44	0,085711
300	725,47	0,073406
450	631,96	0,063979
550	510,43	0,062682
600	398,58	0,04961
650	332,04	0,0718
700	261,17	0,098013

Fig. 3. True-stress vs. true-strain curves of BATMAN II steel, Cast No. 1955 ($\sigma = K\epsilon^{n}$).

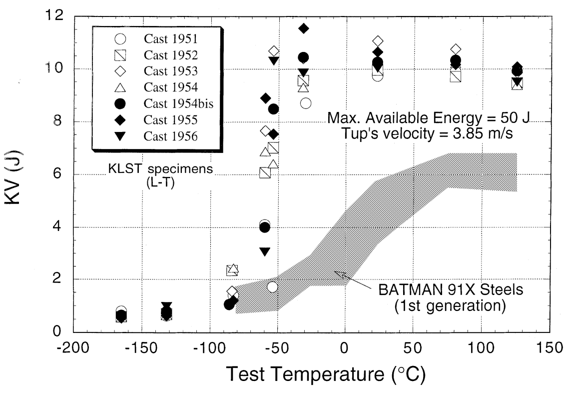


Fig. 4. Impact behaviour of BATMAN steels, tests performed on sub-sized DIN 50115 specimens.

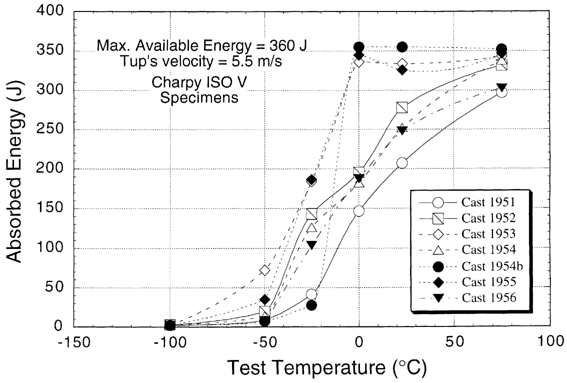


Fig. 5. Impact behaviour of BATMAN steels, tests performed on Charpy ISO-V specimens.

The calculation of dynamic yield stress was performed using the classic 3 point dynamically bent beam formula [7,8]

$$\sigma_y = 2.99\frac{F_{\text{gy}}W}{Bb^2}, \tag{4}$$

where F_{gy} representing the general yielding load and W the specimen's height. This formula is valid for a span to specimen's height ratio of 4 (usual for Charpy ISO V notched specimens), whereas for KLST samples ($S/W = 5.5$) the constraint factor must be raised from 2.99 to 4.11. Dynamic yield, for both standard or sub-sized specimens and 0.2% Proof stresses of two BATMAN steels are shown in Fig. 7.

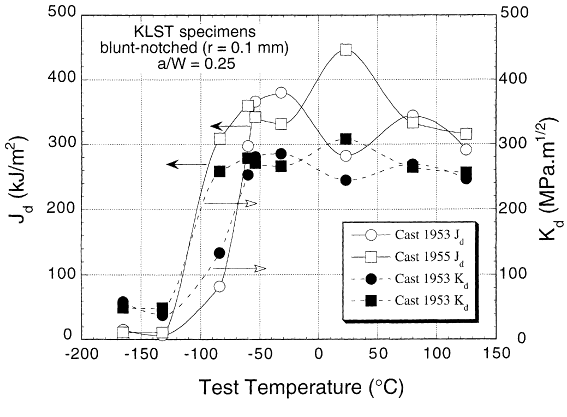


Fig. 6. Dynamic fracture resistance of BATMAN II steels as evaluated from blunt-notched samples' load–deflection curves.

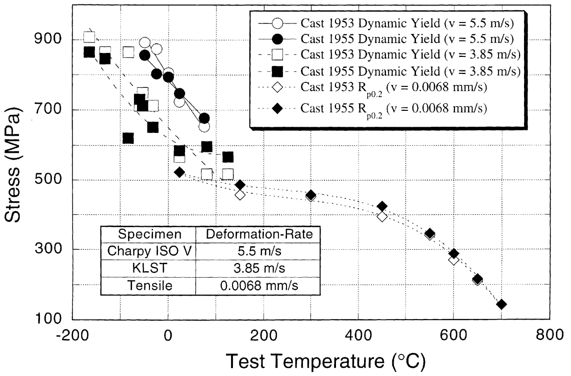


Fig. 7. Dynamic yield stresses and 0.2% PS of BATMAN II steels.

4. Discussion

The higher tensile strength of previous generation of Ti-bearing alloys is clearly evident up to 550–600°C, either in terms of UTS or proof stresses. This behaviour is due to the lower tempering temperature we used (700°C instead of 730°C), to the higher N content and, in a lesser extent, to the strengthening effect of a much higher Mn amount.

Total elongation of present generation is far superior up to 300–400°C, at more elevate temperatures elongation at failure are similar. In all cases, ductility is more than adequate.

Impact resistance is notably improved, USEs of sub-sized samples have to be raised to 10–11 J (a 50% gain in the worst evenience) and DBTTs lowered, at least by 50°C. Most probably, this improvement is due to the different precipitates size, morphology and distribution promoted by the higher tempering temperature and the revised chemical composition.

Analysing data obtained on standard specimens (Fig. 5), a negative effect of Mn and also B on impact properties was observed. Alloys 1951 and 1952 have the same composition but different manganese amounts: the former steel shows a lower USE and a higher DBTT. Regarding boron, the sole variable in the chemical composition of Alloys 1951 and 1956, it seems that a 70 ppm amount is sufficient to shift transition temperature beyond ambient.

Observing load–deflection curves (KLST samples), the best behaviours have been experienced by Casts No 1953 and 1955. These steels have very similar composition but chromium amount, so a decrease to 7.5% Cr (Alloy No 1953) does not affect strength, ductility or toughness. This evidence introduces new arguments for a reduction of such an element in the light of an improved weldability.

Comparison between Ti and Ta-stabilised RA steels showed that both alloy families have almost equivalent tensile strength and elongation at failure and, more or less, comparable transition temperatures (Figs. 8–10). Absorbed energies of BATMAN alloys in the upper shelf domain are within the range 320–350 J, the highest ever experienced in testing ferritic–martensitic steels Ref. [9,10].

5. Conclusion

Many others properties of Ti-bearing steels should be investigated to complete the knowledge of their global mechanical behaviour but the results we obtained are encouraging and lead us to some evidences and also to some speculations:

- tensile strength and ductility are adequate, estimated allowable stress (S_m stress as identified by RCC-MR and ASME N47 codes) being superior to that of conventional Grade 22 steels (2.25 Cr 1 Mo), almost equivalent to that of Grade 91 and just a little bit inferior to the one specified for 304 or 316 SA austeni-

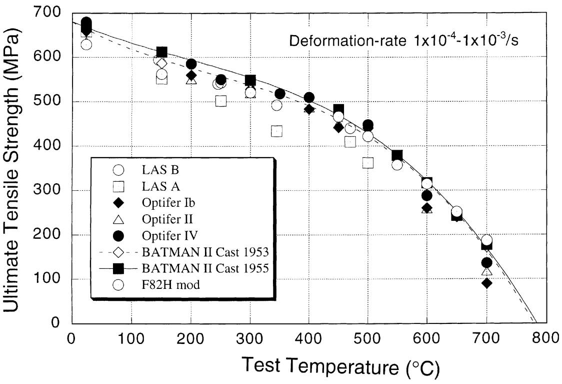


Fig. 8. Comparison of tensile strength of candidate RAF alloys.

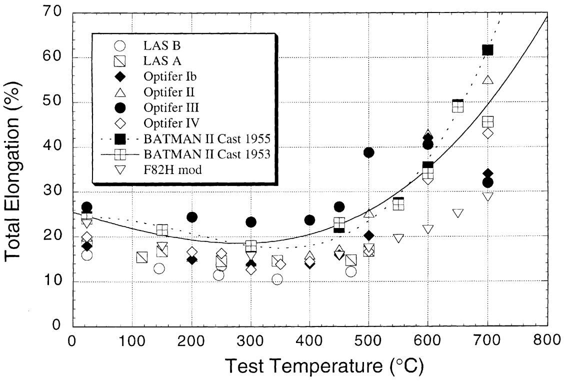


Fig. 9. Comparison between tensile elongation at failure of candidate RAF alloys.

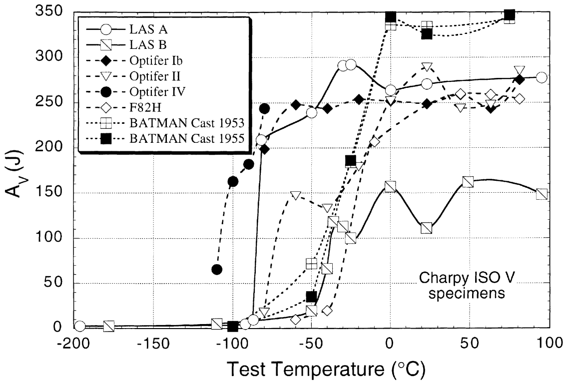


Fig. 10. Comparison between absorbed energies of candidate RAF alloys.

tic stainless steels at $T \geq 600$°C, this latter being the ultimate operative bound for a martensitic alloy.

- Impact properties and dynamic fracture toughness are comparable to those shown by other RAF alloys, both being tougher than conventional ferritic–martensitic steels in the unirradiated status.
- If the toughness is the key issue for a structural material in fusion environment, a rather wide margin still exists for improving the fracture resistance of BATMAN steels. The tempering temperature we used is roughly 100°C below the A_{c1} transformation point.
- A lower Cr amount could represent a solution for reducing crack susceptibility in welding process and the presence of a most effective stabilising element, Ti instead of Ta, could be a cure to reduce grain coarsening in the affected zone.

Nowadays, taking into account available data, RA 7–9% Cr, 1–2% W, V, Ta or Ti steels, seem promising structural materials for a MFR machine, almost as resistant as but much tougher than conventional 2.25–12% Cr ferritic–martensitic alloys [10]. In the meantime, data demonstrate a general equilibrium between properties of tantalum or titanium-stabilised steels in unirradiated status. A sound ranking will became possible just having a more complete data base covering prior to irradiation and post-irradiation features of base material and welded joints.

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