Influence of Chemical Composition and Tempering Treatment on Toughness of Bainitic 38MnV7 Steel

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Abstract. This work studies the influence of Mn and the V/N ratio on the toughness of 38MnV7 steel. Four steels with different Mn, N and Ti contents were studied. Lowering the Mn content to approximately 1.5% considerably enhanced toughness by reducing Mn segregation and consequently achieved a more uniform bainitic microstructure. Raising the N content to reach a V/N ratio of close to 5 enhanced the intragranular nucleation of bainite and thus also improved toughness. Isothermal transformation prevented the presence of retained austenite and allowed a complete bainitic transformation. One of the steels contained Ti to control austenite grain growth by the precipitation of TiN particles. However, the results showed that the presence of nanoparticles TiN did not improve the bainitic microstructure. In sum, the work has allowed the obtainment of a 38MnV7 steel with a toughness value (obtained in a Charpy V-Notch impact test) of close to 40 J, and higher than 50 J after tempering at 600 ºC. The steel shows a toughness of close to 20 J at -40 ºC. The optimal composition of the steel (in wt. %) was approximately: C=0.38; Mn=1.53; V=0.11; N=0.0217.

Keywords: Bainite, yield strength, toughness

1. INTRODUCTION

38MnV7 steel is used to manufacture automotive parts and reaches a strength of approximately 1000 MPa. However, toughness values recorded in Charpy impact tests vary strongly depending on whether the bainitic microstructure is obtained after continuous cooling (upper bainite) or by means of isothermal treatments (lower bainite) [1].

In both upper and lower bainite, the boundaries between bainitic ferrite laths within a packet are low angle boundaries that hinder dislocation movement but not crack propagation. In contrast, the boundaries between packets, or the prior austenite grain boundaries, are high angle boundaries that impede crack propagation [2].

The strengthening mechanisms that operate in bainite are well known, and a small bainite packet size means a small lath width, low dislocation density and a low number of carbide particles (Fe_3C) [3-6]. These properties are more easily achieved for lower bainite than for upper bainite.

The bainitic packet appears to be the microstructural unit controlling the cleavage resistance of low carbon bainitic steels, whose size is slightly smaller than the average unit crack path (UCP), and the critical stage in the fracture process appears to be the propagation of a Griffith crack from one packet to another [7,8].

Several attempts have been made to quantitatively relate the microstructure of bainite to its properties [4-6]. However, very few studies have considered the effect of Ti, V and Nb nitride, carbide and carbonitride precipitates on the mechanical properties of bainitic steel, especially its yield strength and ultimate strength [9].

In this work, four steels with different Mn, N and Ti contents and a similar V content have been studied with the aim of achieving a substantial improvement in toughness and simultaneously optimising the chemical composition.

2. EXPERIMENTAL PROCEDURE

The steels have been manufactured using electroslag remelting (ESR) equipment. Table 1 shows the chemical composition of the studied steels. Four ingots of the 38MnV7 family were manufactured with different Mn, Ti and N contents. All the steels are V-microalloyed with different V/N ratios, and steel MN7 also contains Ti. The steels were manufactured with a low Al (<0.010%)content in order that element did not to V and Ti picking up nitrogen.

Table 1. Chemical composition (% wt) of steels used.

Steel	C	Si	Mn	V	Ti	N
MN4	0.38	0.25	1.53	0.11	-	0.0217
MN5	0.38	0.26	2.08	0.12	-	0.0245
MN6	0.38	0.25	2.23	0.12	-	0.0118
MN7	0.36	0.25	1.80	0.105	0.029	0.0111

Taking into account that the refinement of bainitic packet size improves toughness, isothermal treatments were applied by heating the specimens to a temperature slightly above A_{c3} and cooling them to a temperature a little over M_s, where the bainitic microstructure was obtained by isothermal transformation.

The bainitic packet is smaller as the austenitisation temperature decreases, until both the bainitic packet and austenite grain size coincide [1,8,9]. In other words, when the austenite grain size is relatively large, each grain is transformed into several bainitic packets. As the austenite grain size decreases, the number of bainitic packets per austenite grain drops until a ratio of 1:1 is reached.

Taking the above into account, a new isothermal treatment was designed, consisting basically of adopting a higher austenitisation temperature, close to the end temperature of the $\alpha \rightarrow \gamma$ transformation in heating (A_{c3}), so that the austenite grain is as small as possible. This is followed by rapid cooling to a temperature above but close to the start of the martensitic transformation (M_s), which allows practically all of the austenite to be transformed into “lower bainite”. After a sufficiently long holding time

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for the bainitic transformation to take place, the specimens are then air-cooled. Finally, a tempering treatment is performed in order to reduce the stresses created by the bainitic transformation. Figure 1 shows a scheme of the isothermal treatment.

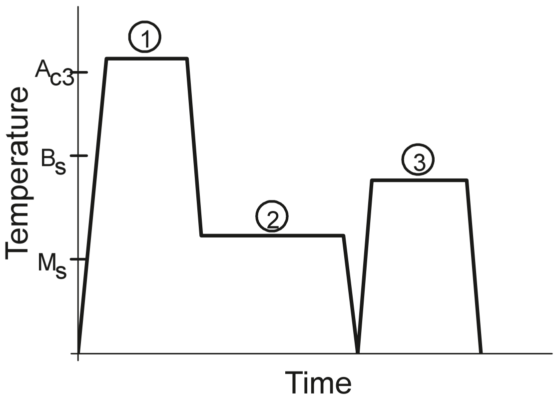

Figure 1. Scheme of isothermal treatments. (1) Austenitisation temperature; (2) Bainitic transformation temperature; (3) Tempering temperature.

Charpy impact tests verify the amount of energy absorbed during the high strain rate fracture of a material and are a measure of a material's resistance to brittle fracture. Charpy impact tests were performed according to ASTM standard E23 using test specimens of 10x10x55 mm in size with a V shaped notch 2 mm deep and a notch opening of 45°.

Tensile tests were performed according to standard EN-1002-1. Given that the steels used present high strength, the most important magnitude is their ultimate strength.

3. RESULTS AND DISCUSSION

3.1. Heat Treatments

First of all the critical transformation temperatures (A_{c3}, B_s, M_s) were determined. The bainitic transformation start temperature (B_s) and the martensitic transformation start temperature (M_s) hardly vary with the cooling rate, but the A_{c3} temperature varies with the heating temperature. B_s and M_s were determined by dilatometry (table 2) and A_{c3} was deduced from the transformation-time-temperature (TTT) diagram of 38MnV7 steel, with an approximate value of 780ºC [10].

Table 2. Experimentally determined values of B_s and M_s.

Steel	B_s (ºC)	M_s (ºC)
MN4	560	296
MN5	535	275
MN6	527	299
MN7	550	301

Accordingly, the thermal treatments applied to the studied steel specimens were as follows:
Austenitisation temperature: 820ºC / 30 min
Bainitic transformation temperature: 360ºC / 90 min
Tempering temperature: 600ºC / 60 min

The bainitic transformation temperature (360ºC) was chosen because it was sufficiently low to assure a complete transformation and was close to the nose temperature of the bainitic transformation curve, thus allowing the transformation to take place in a relatively short time. The tempering temperature (600ºC) was taken as the optimum softening temperature. In the present case the hardnesses achieved after the bainitic transformation were approximately 33 HRC for steel MN4 and 35 for the others. After tempering the hardness fell to approximately 28 HRC in all the steels.

3.2. Austenite Grain Size and Bainitic Microstructure

The austenitic grain size at the austenitisation temperature of 820ºC was measured applying standard ASTM E-112 and the results are shown in table 3.

Table 3. Austenite grain size (D_γ) at 820ºCx30 min.

Steel	MN4	MN5	MN6	MN7
D_γ (μm)	11	12	13	16

As was intended, all the steels shows a fine austenite grain size, which was somewhat larger in the case of steel MN7 containing Ti. The explanation for this behaviour is that at the austenitisation temperature (820ºC), which is lower than the solubility temperature of VCN type precipitates, the size of these precipitates (not dissolved) is smaller than the TiN type precipitates that have formed at high temperature during the solidification of the steel [11], where particle growth is easier due to the effect of Ostwald ripening [12-15]. Therefore, the pinning forces exerted by the particles on the movement of the grain boundaries are lower in the case of the TiN particles than with the VCN particles. Figure 2 shows the microstructure obtained by quenching in oil a steel MN7 specimen polished and etched in a saturated picric acid solution.

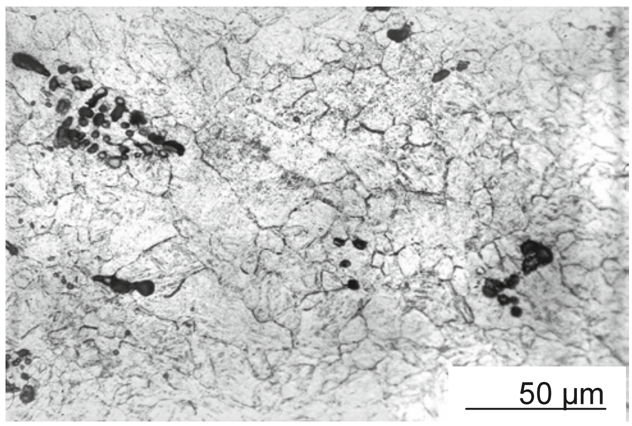

Figure 2. Austenite grain boundaries at 820ºCx30 min. Steel MN7.

The microstructure obtained after isothermal treatment showed a lower bainite (figure 3), much finer than that obtained in anisothermal treatment which yields a coarser higher bainite with a larger bainitic package [1].

In order to know the amount of retained austenite obtained after isothermal treatment, X-ray diffraction analysis was performed and in all cases yielded a result of 0%. The analysis shows the presence of 96.71% ferrite and 3.29% cementite. The measured lattice parameters correspond to ferrite and cementite, respectively.

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3.3. Toughness

Isothermally treated and tempered specimens were tested in the instrumented Charpy machine, using three specimens for each testing temperature and taking the average value as the test result. In this way, absorbed absorbed energy versus testing temperature curves were determined. Figure 4 also plots the curve corresponding to isothermal treatment without subsequent tempering. The value of 20 J, taken as the standard value for steel to be satisfactorily used at ambient temperature, has been marked on the graphs with the aim of identifying the temperature corresponding to that value.

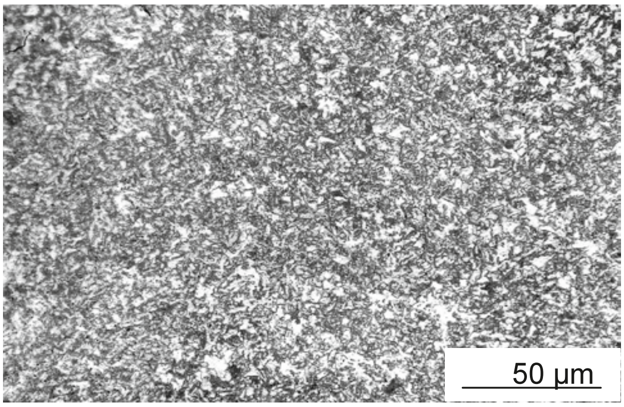

Figure 3. Bainitic microstructure. Heat treatment: Aust. Temp.= 820ºC; Transf. Temp.= 360ºC; HRC=33.

Therefore, taking the 20 J criterion as the impact transition temperature (ITT), the temperatures listed in table 4 have been determined. The steels showed excellent results, with very low transition temperatures for high strength steels. In particular, steel MN4 presented a transition temperature of -41ºC, which allows its use in any application in the most adverse conditions. The toughness of this steel may be considered excellent even in the case of isothermal treatment without tempering (figure 4), whose transition temperature was -29ºC, which is also an excellent value for the steel to be used in extremely challenging service conditions.

Table 4. ITT for 20 J in Charpy impact testing.

Steel	Tempered at 600ºC; ITT for 20 J (ºC)	Not tempered; ITT for 20 J (ºC)
MN4	-41	-29
MN5	-4	-
MN6	-5	-
MN7	-23	-

For steels MN5, MN6 and MN7, the absorbed energy was determined in not tempered state only at ambient temperature (figures 5-7), which makes it possible to see the increase in absorbed energy when tempering treatment is performed. This increase is approximately 10 J for steel MN4, which represents 40%, and 15 J for steels MN5 and MN6, which represents 200%, and is even higher for steel MN7. The effect of tempering is enormously efficient in improving the toughness of the lower bainite microstructure, and is even greater than has been estimated by other authors [2].

Steels MN4 and MN7, with low Mn contents, present the best toughness. Specifically, steel MN4 has the lowest Mn content (1.53% wt) and the highest toughness. Mn is an element that is easily segregated during solidification through the formation of dendrites, being segregated in the interdendritic spaces that subsequently solidify. Some Mn-rich zones are not totally transformed and in cooling after the bainitic transformation the small fraction of retained austenite will be transformed into martensite, which is barely detectable by optical microscopy, increasing the hardness and consequently decreasing the toughness [16].

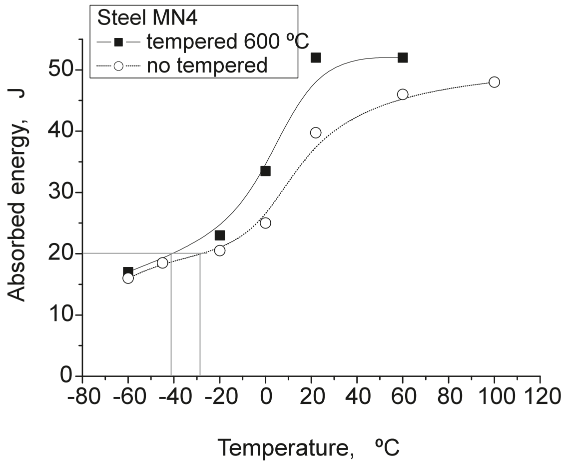

Figure 4. Charpy impact absorbed energy. Steel MN4.

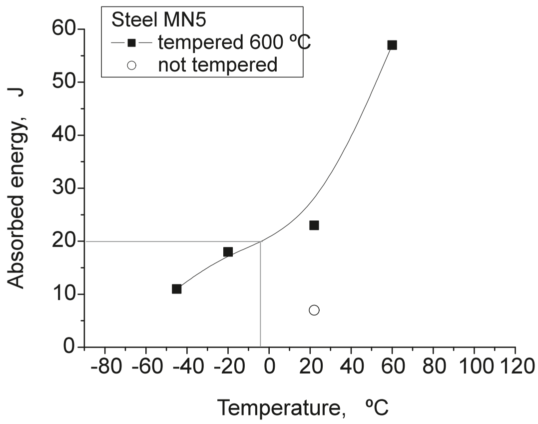

Figure 5. Charpy impact absorbed energy. Steel MN5.

Finally, steels MN5 and MN6, with higher Mn contents, presented the lowest toughness irrespective of the N content, which in steel MN5 was relatively high (0.0245%) and in steel MN6 was approximately half that value (0.0118%).

3.4. Tensile Mechanical Properties

Tensile mechanical properties were determined and the results are shown in table 5. The ultimate strength was higher than 900 MPa in all the steels. The yield strength was close to 850 MPa, except for steel MN4 in which case it was 760 MPa.

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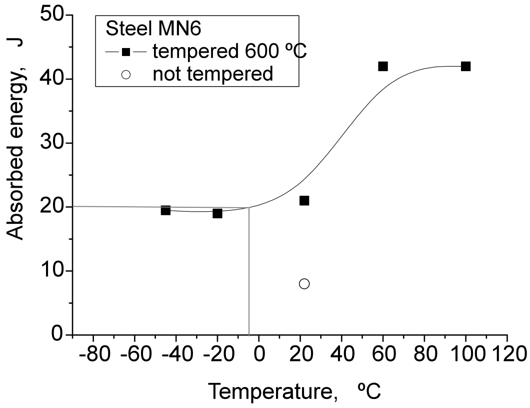

Figure 6. Charpy impact absorbed energy. Steel MN6.

Although steel MN4 presented a somewhat lower yield strength and ultimate strength than the other steels, its lower ultimate strength is compensated by its better toughness.

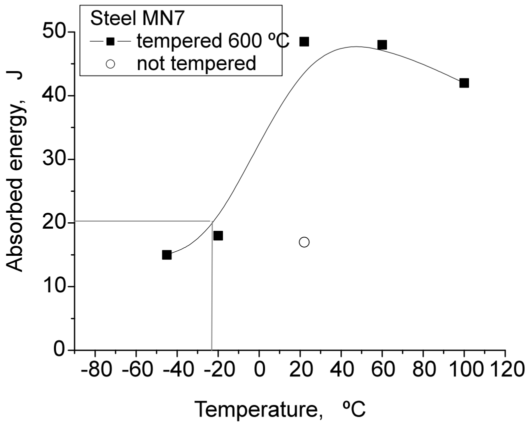

Figure 7. Charpy impact absorbed energy. Steel MN7.

Finally, isothermally treated steel MN4 showed ultimate strength and yield strength values of 954 MPa and 777 MPa, respectively, when not tempered and slightly higher values when tempered at 600ºC. The ductility of not-tempered steel MN4 is very similar to that of the tempered steel.

Table 5. Tensile mechanical properties for steels isothermally treated and tempered at 600ºC. Yield strength (R_p). Ultimate strength (R_m); Elongation (A); Reduction of area (RA).

Steel	R_p (MPa)	R_m (MPa)	A (%)	RA (%)
MN4	760 777*	905 954*	15 15*	49.2 52.5*
MN5	816	958	17.1	50.5
MN6	847	997	14.5	53.4
MN7	848	960	13.1	49.8

*not tempered

It should be noted that the nanometric CVN particles in these steels have contributed to raising the yield strength and ultimate strength by approximately 70 MPa [9]. The increase in yield strength has been calculated as a function of the precipitated volume fraction and the particle diameter using Orowan's expression [17], confirming its good prediction for bainitic steels [9].

4. CONCLUSIONS

The steels presented a J transition temperature below 0ºC for an absorbed energy of 20 J. Specifically, steel MN4 presents a transition of -29ºC when not tempered and -41ºC when tempered. These values indicate that steel MN4 can be used in the most adverse service conditions even in a not-tempered state.

In agreement with other authors, the lower Mn content of steel MN4, and thus its lower segregation index, seems to be the cause of its better toughness than the other steels.

The presence of Ti in steel MN7 has not led to an improvement in toughness, since at the low austenitisation temperature applied (820ºC) the austenite grain size was not smaller than in the other steels.Neither the N content or the V/N ratio have influenced the toughness.

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