

# IMPROVEMENT OF MECHANICAL PROPERTIES IN FE-MN-TI STEEL BY ALLOYING WITH CR AND MO

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## ABSTRACT:

Effects of 5 wt. % Mo and 4 wt. % Cr additions on the tensile properties and fracture mechanism of Fe-9Ni-5Mn-1.5Ti (wt. %) steel was investigated. Hardening behavior, tensile properties and fractographic features of the specimens aged for 7.2 and 14.4 ks at 793 K were examined. An ultimate tensile strength of 1795 MPa and total elongation of 3% obtained in the specimen aged for 7.2 ks while longer aging time resulted in lower strength and higher ductility. Dimpled ductile intergranular fracture mechanism was indicated by fractographic examinations of the aged specimens. Precipitation of Mo-enriched second phases at grain boundaries was found and responsibility of these phases for intergranular failure of the alloy was indicated. It was found out that Mo and Cr additions prevent premature brittle intergranular failure of the Fe-Ni-Mn-Ti alloy at aging temperature.

## KEYWORDS

Maraging, Intergranular Failure, High Strength, Grain Boundary, Precipitation

## INTRODUCTION

Fe-Ni-Mn maraging alloys have attracted increasing interest because of their economic aspects. Successive precipitations of f.c.t.  $\theta$ -NiMn intermetallic compound and reversion to f.c.c. austenite have been found in these alloys during isothermal aging [1]. Fe-Ni-Mn maraging alloys are ductile in the solution annealed condition but suffer from severe intergranular embrittlement along prior austenite grain boundaries (PAGBs) after aging [2]. The source of grain boundary embrittlement in these alloys has been attributed to grain boundary segregation and precipitation. For example, segregation of Mn atoms at PAGBs has been proposed to take place during isothermal aging [3]. Mun et al. [4] reported precipitation of f.c.c. reverted austenite particles at PAGBs in a Fe-8Mn-7Ni (wt. %) alloy. Lee et al. [5] reported precipitation of f.c.t.  $\theta$ -NiMn intermetallic phase at PAGBs in a Fe-10Ni-5Mn (wt. %) alloy. Hossein Nedjad et al. [6] found discontinuous coarsening of f.c.t.  $\theta$ -NiMn intermetallic precipitates at PAGBs during isothermal aging of a Fe-10Ni-7Mn (wt. %) alloy at 753 K.

A wide range of Fe-Ni-Mn-(Mo)-(Ti)-(Cr) alloys have been studied to investigate effects of alloying with Mo, Cr and Ti on the intergranular failure of Fe-Ni-Mn maraging alloys [7-12]. Two-stage hardening behaviors have been reported in Fe-Ni-Mn-Mo alloys due to precipitation of NiMn intermetallic compound at early stages of aging and precipitation of Fe<sub>2</sub>Mo Laves phase at later stages of aging [8, 11]. Successive precipitation of Ni<sub>3</sub>Ti and Fe<sub>2</sub>Mo has been reported in Fe-9Ni-5Mn-5Mo-1.5Ti-3Cr (wt. %) maraging alloy [10]. It has been found out that Cr does not contribute directly in the age hardening of Fe-Ni-Mn-Mo-Ti-Cr alloys while augmentation of Ni<sub>3</sub>Ti and Fe<sub>2</sub>Mo precipitation has been identified [10].

It has been found out that Mo addition partially enhances strength and ductility of Fe-Ni-Mn alloys which depends strongly on the aging temperature and time. For example, Squires et al. [7] reported that Fe-6Ni-5Mn-5Mo (wt. %) alloy shows a mixed transgranular-intergranular, brittle transgranular cleavage and intergranular fracture when aged at below 723, 723~748 and above 748 K, respectively. The intergranular failure above 748 K has been attributed to precipitation of  $M_6C$  and  $Fe_2Mo$  films at grain boundaries. Heo [11] has reported a ductile-brittle-ductile transition in Fe-9Ni-5Mn-5Mo (wt. %) alloy during isothermal aging below 773 K while age hardening at higher temperatures resulted in improvement of tensile ductility and loss of strength. The brittleness of this alloy has been attributed to segregation of Mn at grain boundaries at early stages of aging and augmented segregations of Ni and Mo have been proposed to increase grain boundary strength at later stages of aging [11].

Asayama et al. [13] reported beneficial effect of Cr addition to prevent intergranular failure in Fe-Ni-Ti maraging. Heo and Lee [10] have investigated effect Cr addition up to 3 wt. % on the tensile properties and fracture mechanism of Fe-9Ni-5Mn-5Mo-1.5Ti (wt. %) alloy. It has been found that Fe-9Ni-5Mn-5Mo-1.5Ti-3Cr (wt. %) alloy shows ductile-brittle-ductile transition during isothermal aging below 773 K while enhanced tensile properties and ductile transgranular fracture have been shown in a specimen aged for 7.2 ks at 793 K. Alloying with Ti has also been found to suffer Fe-Ni-Mn alloys by more severe grain boundary embrittlement [14, 15].

The contribution of this paper is to investigate effects of 4 wt. % Cr and 5 wt. % Mo additions on the grain boundary precipitation, tensile properties and fracture mechanism of Fe-9Ni-5Mn-1.5Ti (wt. %) alloy.

## 1. EXPERIMENTAL PROCEDURE

Heats of nominal compositions Fe-9Ni-5Mn-5Mo-4Cr-1.5Ti (wt. %) were prepared in a vacuum arc remelting furnace using electrolytic iron, electrolytic manganese, electrolytic chromium, nickel shots (CP), ferromolybdenum and ferrotitanium. Table 1 gives chemical

Table 1) Chemical composition of the alloy studied (wt. %)

Fe	Ni	Mn	Mo	Cr	Ti
Bal.	9.1	5.0	5.1	3.8	1.4

composition of the alloy. A homogenizing treatment was performed at 1473 K for 10.8 ks in an argon atmosphere followed by hot forging for 50% at 1273~1373 K. Hot rolling to 50 % reduction was also carried out at 1173~1173 K before solution annealing treatment at 1323 K for 3.6 ks. Sheet type tensile specimens of dimension 2×6.25×25 mm (ASTM E8-M) were machined from the solution annealed material then aged for 7.2 and 14.4 ks at 793 K. Hardness measurements were made by Vickers method of 30 kgf load. Tensile properties were measured using Instron type tensile test machine at a crosshead speed of 1 mm/min. Fractographic features were studied by a scanning electron microscope equipped with energy-dispersive x-ray spectroscopy (EDS).

## 2. RESULTS AND DISCUSSION

Figure 1 shows changes in the hardness of the alloy versus isothermal aging time at 793 K. Solution annealed material has a hardness of 320 HV. Aging treatment at 793 K results in substantial hardening of this alloy where a maximum hardness of 600 HV is obtained after aging for 7.2 ks. However, a two-step hardening is illustrated in the age hardening curve at 1.8 and 7.2 ks which are proposed to correspond to precipitation of  $Ni_3Ti$  and  $Fe_2Mo$ , respectively. A typical hardness reduction due to over-aging at longer aging times is also

observed.

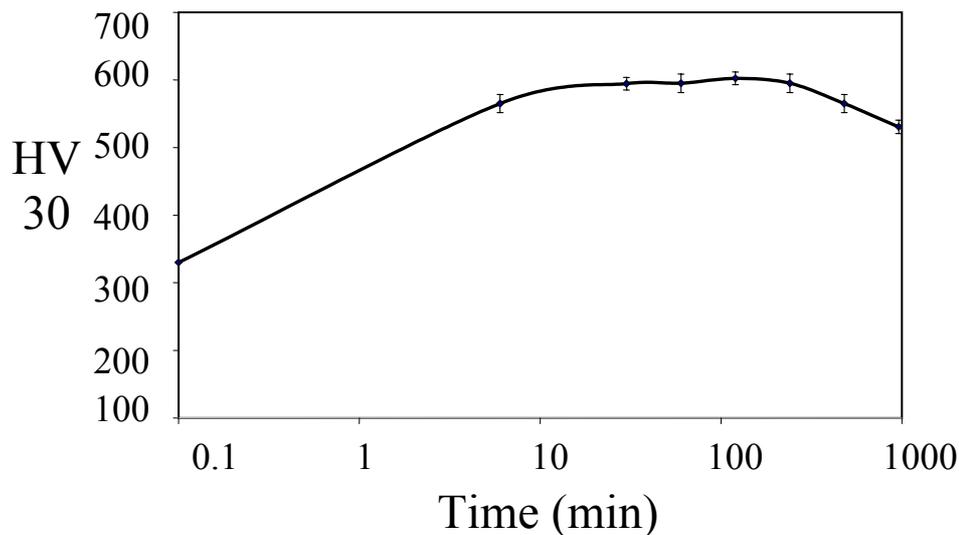


Figure 1) Changes in the hardness of the alloy versus isothermal aging time at 793 K.

Tensile properties of the specimens aged for 7.2 and 14.4 ks, corresponding to peak-aging and over-aging conditions, respectively, are given in Table 2. An ultimate tensile strength of 1795 MPa and total elongation of 3% have been obtained in the peak-aged specimen while

Table 2) Tensile properties of the alloy after aging for 7.2 and 14.4 ks at 793 K

Aging time (ks)	YS (MPa)	UTS (MPa)	EL %	RA %
7.2		1795	3	12
14.4		1675	5	14

longer aging time has resulted in lower strength and higher ductility. Heo and Lee [10] reported ultimate tensile strength and total elongation of Fe-9Ni-5Mn-5Mo-1.5Ti-3Cr (wt. %) alloy aged for 7.2 ks at 793 K as 1721 MPa and 10.2%, respectively. Therefore, it is found out that increasing of Cr content from 3 up to 4 wt. % increases strength and decreases ductility of Fe-9Ni-5Mn-5Mo-1.5Ti (wt. %) alloy.

Table 3. Typical quantitative chemical composition of a grain boundary precipitates

Fe	Ni	Mn	Mo	Cr	Ti
Bal.	6.8	4.7	14.7	3.5	4.2

Figure 2 (a) shows a SEM micrograph showing intergranular fracture of the alloy aged for 7.2 ks at 793 K. Higher magnification view shows ductile dimpled intergranular fracture mechanism of the specimen as illustrated in Fig. 2(b). Second phase precipitates and dimples formed at these precipitates are observed in Fig. 2 (c). EDS spectrum indicating chemical composition of the second phase precipitates is shown in Fig. 2 (d).

Table 3 gives quantitative chemical composition of the second phase precipitates indicating higher Mo and Ti concentration than nominal composition of the alloy. These precipitates are mainly Mo-enriched which suggests them as  $Fe_2(Mo)$  laves phase while to a less extent, Ti-enrichment of these precipitates was also found. Therefore, second phase precipitates at grain boundaries of this alloy is proposed to be  $Fe_2(Mo, Ti)$  Laves phase as proposed by Asayama et al [13] in Fe-Ni-Ti-Cr and Heo and Lee [10] in Fe-Ni-Mn-Mo-Ti-Cr alloys.

Figure 3 (a) shows a SEM micrograph showing crack propagation along prior austenite grain boundaries in the specimen aged for 7.2 ks. Higher magnification view in Fig. 3 (b)

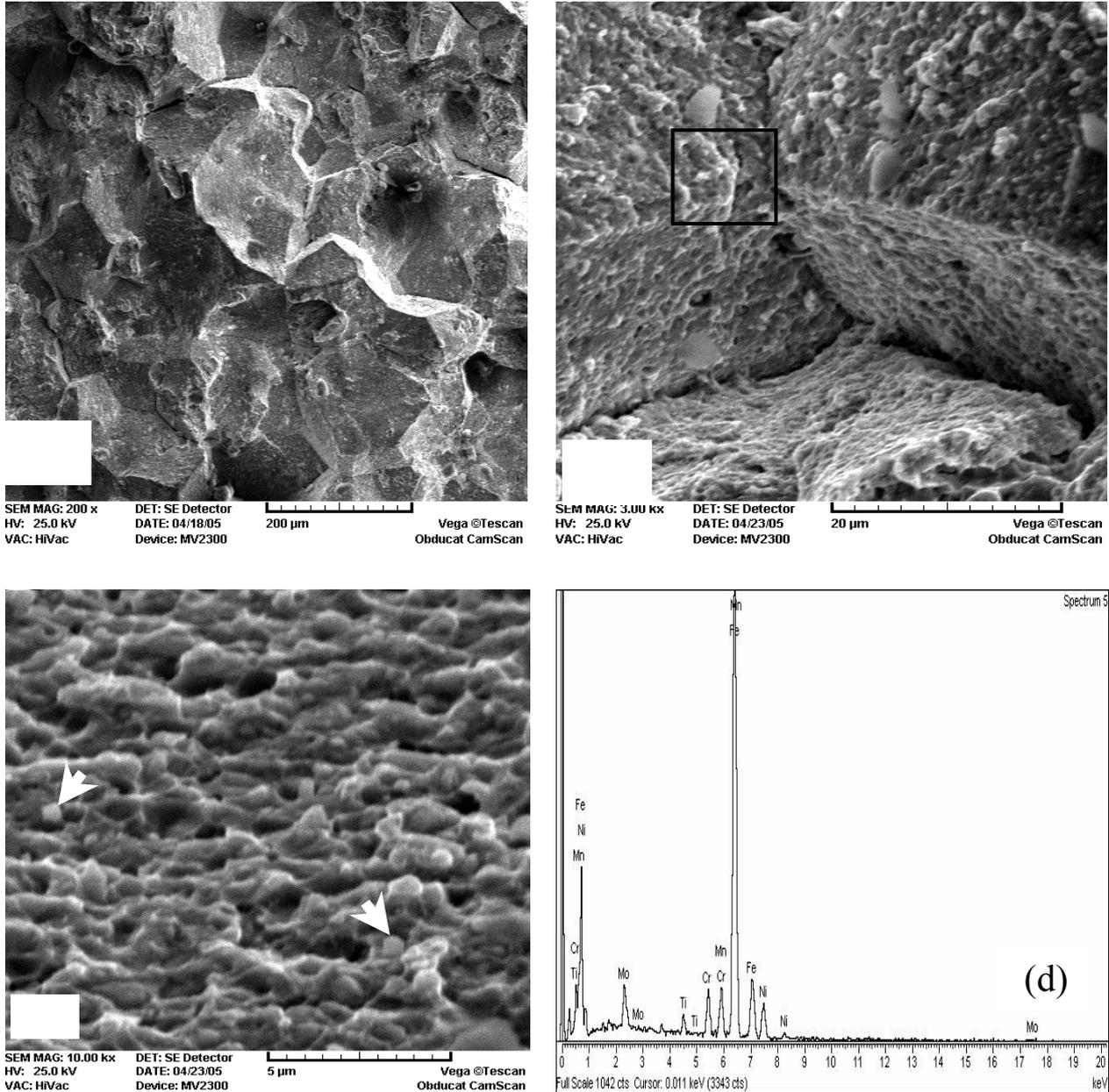


Figure 2. (a) SEM micrograph showing intergranular fracture of the alloy aged for 7.2 ks at 793 K; (b) higher magnification view showing ductile dimpled intergranular fracture mechanism; (c) showing second phase precipitates at dimples formed at grain boundaries; (d)EDS spectrum indicating chemical composition of second phase precipitates shown by arrows.

illustrates second phase precipitates in the crack propagation path. Void nucleation at precipitate-matrix interface is shown in Fig. 3 (c) indicating the responsibility of these precipitates in intergranular failure of the alloy. Superimposed red spectrum on Fig. 3 (c) indicates Mo distribution scanned along line (A-A) showing higher Mo concentration of the precipitate.

It has been found out that  $\text{Fe}_2\text{Mo}$  Laves phase precipitates at longer aging times and higher aging temperatures [11, 13]. Furthermore, partial substitution of Mn and Ti in this phase have been reported to yield  $(\text{Fe, Mn})_2\text{Mo}$  [10] and  $\text{Fe}_2(\text{Mo, Ti})$  [13] type precipitates. Heo and Lee [10] have proposed that  $(\text{Fe, Mn})_2\text{Mo}$  and  $\text{Ni}_3\text{Ti}$  precipitates act as sinks of Mn and Ti atoms, respectively. The ductility reservation in Fe-9Ni-5Mn-5Mo (wt. %) and Fe-9Ni-5Mn-5Mo-1.5Ti (wt. %) alloys at later stages of aging has been attributed to precipitation of  $(\text{Fe, Mn})_2\text{Mo}$  and  $\text{Ni}_3\text{Ti}$ , respectively [10, 11]. Heo [11] and Heo and Lee [11] had proposed segregation of Mn and Ti atoms at grain boundaries as the source of grain boundary failure in the alloys, and consequently, desegregation of these elements from grain boundaries was assumed to take place by precipitation of  $(\text{Fe, Mn})_2\text{Mo}$  and  $\text{Ni}_3\text{Ti}$ .

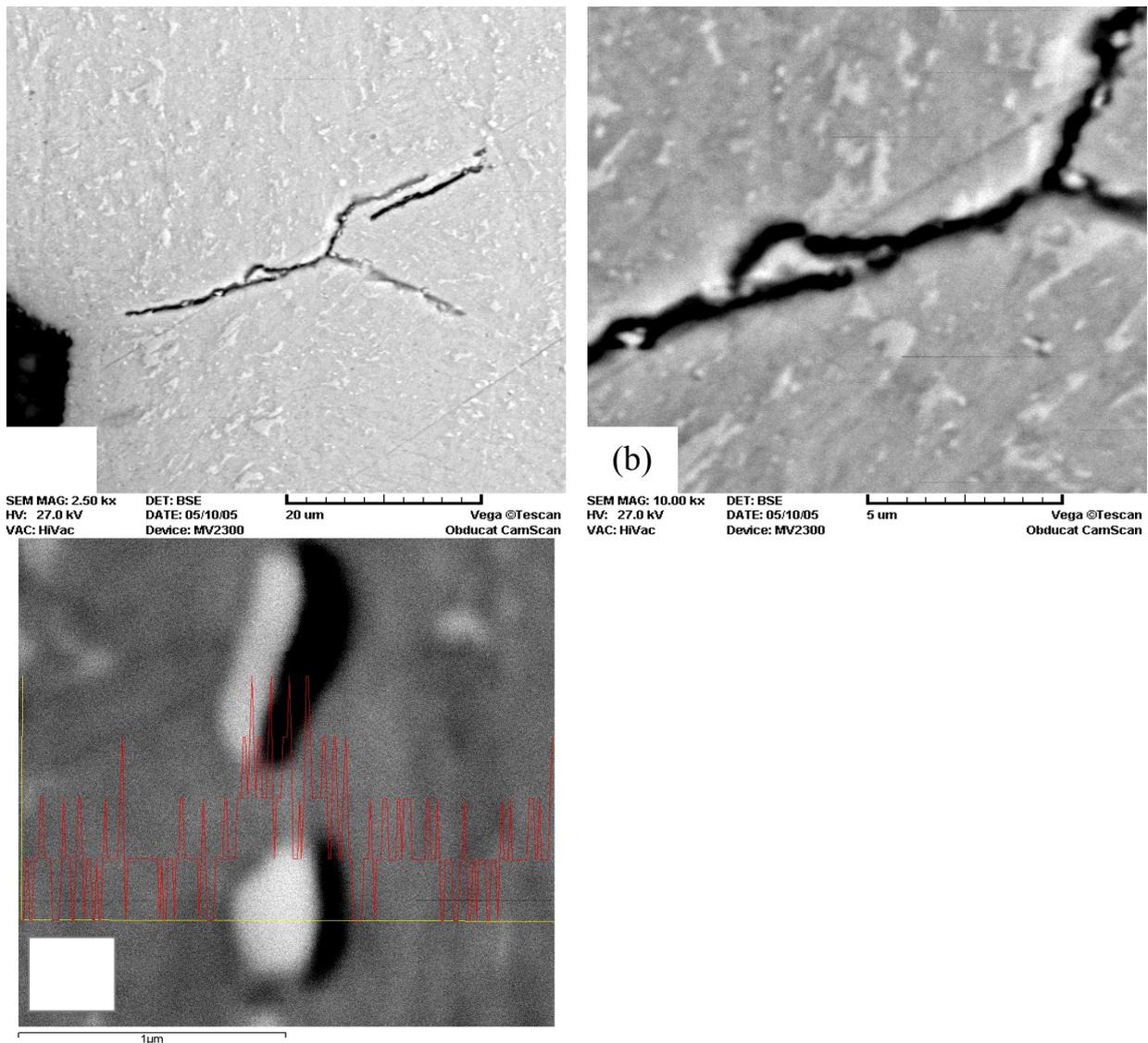


Figure 3. (a) SEM micrograph showing crack propagation along prior austenite grain boundaries; (b) higher magnification view illustrating second phase precipitates in crack

propagation path; (c) showing void nucleation at precipitate-matrix interface. Superimposed red spectrum indicates Mo distribution scanned along line A-A.

Segregation of Mn atoms at grain boundaries and its responsibility on intergranular failure of Fe-Ni-Mn maraging alloys has been questioned recently. The source of intergranular failure in these alloys has been attributed to grain boundary precipitation [4-6]. Therefore, precipitation of (Fe, Mn)<sub>2</sub>(Mo, Ti) type precipitates seems to affect precipitation of f.c.t.  $\theta$ -NiMn and Ni<sub>3</sub>Ti intermetallics at grain boundaries in Fe-Ni-Mn-Mo-Ti maraging alloys. It has also been reported that Cr addition augments precipitation of Fe<sub>2</sub>Mo Laves phase in Fe-Ni-Mn-Mo-Ti alloys [10]. Consequently, aging at high temperature (793 K) and high Cr content seems to augment precipitation of (Fe, Mn)<sub>2</sub>(Mo, Ti) Laves phase in the present Fe-9Ni-5Mn-5Mo-1.5Ti-4Cr (wt. %) alloy.

### 3. SUMMERY

Fe-9Ni-5Mn-5Mo-1.5Ti-4Cr (wt. %) showed intergranular ductile dimpled fracture after aging for 7.2 ks at 793 K. Precipitation of a Mo-enriched phase was found at grain boundaries which are proposed as the source of intergranular failure of this alloy. High Cr content and high aging temperature were assumed to encourage grain boundary precipitation.

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