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Improvement in mechanical properties of C300 maraging steel by application of VAR process

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Abstract

The prime objective of this research was to improve the mechanical properties of C300 maraging steels originally cast in the vaccum induction melting (VIM) and AIM furnaces by application of vaccum arc remelting (VAR) process. For this purpose two sets of C300 maraging steel with different amounts of Ti were cast in two different types of furnaces. Three bars with 1, 1.5 and 2 wt% of Ti were produced in the argon induction melting (AIM) furnace and two bars with 0.65 and 1 wt% Ti in the VIM furnace. Then all of the bars were subjected to VAR process in order to study the effects of this process on the reduction of N and O gases and inclusions, hence improvement in the mechanical properties. The results show that the total reduction of N and O gases in the bars cast in the AIM furnace was up to 40%, the amounts of inclusions irrespective of their kind reduced up to 30% while ductility and impact energy increased up to 40%. However, these parameters in the bars cast in the VIM furnace changed as follows: total gas reduction decreased by 12%, ductility and impact energy increased by 30% and 47%, respectively. So this research provides a very informative data base for those who are interested in studying the effect of VAR process on the mechanical properties of this kind of cast steel.

Keywords: Vacuum arc remelting (VAR); C300 maraging steel; Inclusions; Gas reduction; Ti effect; Argon induction melting (AIM); Vacuum induction melting (VIM)

1. Introduction

Maraging steels with high strength and toughness in addition to good ductility are said [1] to be suitable materials for various applications up to a temperature of 500 °C. The amounts of carbon and other harmful elements in these steels are low. Therefore, due to their low C content, their martensitic structure has lower hardness and strength relative to some other martensitic steels.

However, when these steels are subjected to aging treatment a large number of very small particles in nanoscale will form within their grains, which causes a substantial improvement in their hardness and strength [1]. The types of precipitates form due to aging are reported [1] to be Ni_3Ti, Fe_2Mo and NiMn.

C300 maraging steel used in this research had yield strength of 300 ksi (2069 MPa) .The reported nominal compositions and mechanical properties of this steel are presented in Tables 1 and 2 [2].

Nowadays vacuum arc remelting (VAR) process is used for production of high-quality alloys with uniform microstructure and high mechanical properties such as strength and toughness [3]. This process is said [3] to produce directional structure due to its metallic water cooled mould.

The arc used in the VAR furnace can break up inclusions into small parts and also under high vacuum it can decompose inclusions chemically and release some of their ingredient gases [4]. Table 3 shows the most important reactions that occur during degasification process in vacuum [4].

2. Experimental work

As indicated earlier two bars with 0.65 and 1 wt% Ti were cast in the vacuum induction melting (VIM) furnace and three bars having 1, 1.5 and 2 wt% Ti in the argon

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induction melting (AIM) furnace. The average chemical composition of each bar was established by quantimetry technique before subjecting them to VAR process. The mean chemical compositions of the bars before and after VAR application are shown in Table 4. The measured errors for all of these elements were within the range of 0.10–0.35 of the mean composition. The specification of the VAR furnace and the details of melting conditions used are given in Table 5. Tensile and charpy impact tests were performed according to standards ASTM E8 and ASTM A370.

3. Results

The effect of VAR on the mechanical properties of the three bars cast in the AIM furnace is presented in the form of graphs in Fig. 1(a–f) and the effect of this process on various mechanical properties of the sample with 0.65 wt% Ti in Fig. 2(a–d).

Typical inclusion distribution, size and shape of the sample having 1 wt% Ti before and after VAR application are presented in Figs. 3 and 4. These figures indicate that

Table 1
Nominal composition of C300 maraging steel [2]

Elements	Ni	Mo	Co	Ti	Al	C	Fe
wt%	18	5.0	9.0	0.7	0.1	<0.03	Rem.

Table 2
Reported mechanical properties of C300 maraging steel [2]

Mechanical properties	UTS (MPa)	YS (MPa)	Elongation (%)	RA (%)	Fracture toughness ($MPa\,m^{1/2}$)
	2050	2000	7	40	80

Table 3
Equilibrium degasification reaction in vacuum [4]

Sl. no.	Reaction	Equilibrium relation	Unit of h	K vs. T relation	Values of h at 1600 °C and 1 mmHg
1	$[H]=\frac{1}{2}H_2(g)$	$[h_H]=K_H\cdot p_{H_2}^{1/2}$	ppm	$\log K_H=-\frac{1905}{T}+2.409$	0.77
2	$[N]=\frac{1}{2}N_2(g)$	$[h_N]=K_N\cdot p_{H_2}^{1/2}$	ppm	$\log K_N=-\frac{518}{T}+2.937$	14.1
3	$[C]+[O]=CO(g)$	$[h_C][h_O]=K_{CO}\cdot p_{CO}$	wt%	$\log K_{CO}=\left(-\frac{1160}{T}\right)-2.00$	4.7×10^{-4a}
			ppm	$\log K_{CO}=\left(-\frac{1160}{T}\right)-6.00$	0.47^{a}

Note: 1 mmHg = 1 Torr = 1.315×10^{-3} atm.
[a]At $h_C=0.05$ wt%, i.e. 500 ppm.

Table 4
Melting conditions and mean compositions of the five bars used

Average weight percent of Ti	Initial process	Secondary process	Mean weight percent of element											
			Ni		Ti		Mo		Co		C		S	
			After VAR	Before VAR	After VAR	Before VAR	After VAR	Before VAR	After VAR	Before VAR	After VAR	Before VAR	After VAR	Before VAR
1	AIM	VAR	17.50	18.27	1.01	1.06	4.20	4.40	9.20	9.35	0.009	0.011	0.010	0.012
1.5	AIM	VAR	17.62	18.36	1.42	1.48	4.20	4.41	9.22	9.39	0.012	0.014	0.010	0.012
2	AIM	VAR	17.32	18.15	1.94	1.96	4.18	4.38	9.30	9.41	0.009	0.011	0.010	0.012
0.65	VIM	VAR	16.98	18.01	0.61	0.65	4.10	4.13	8.01	8.45	0.001	0.001	0.008	0.010
1	VIM	VAR	16.45	17.03	0.93	0.97	4.05	4.19	8.75	8.86	0.001	0.001	0.009	0.010

Table 5
The details of VAR furnace and casting condition used

VAR furnace model	Power used (kW)	Electrode material	Mould material	Mould capacity (g)	Vacuum level (Pa)	Arc temperature (°C)	Argon pressure (Pa)
ALD LK 6.45	600	Tungsten	Copper	400	$3\pm1\times10^{9}$	2500 ± 20	$1.3\pm0.1\times10^{5}$

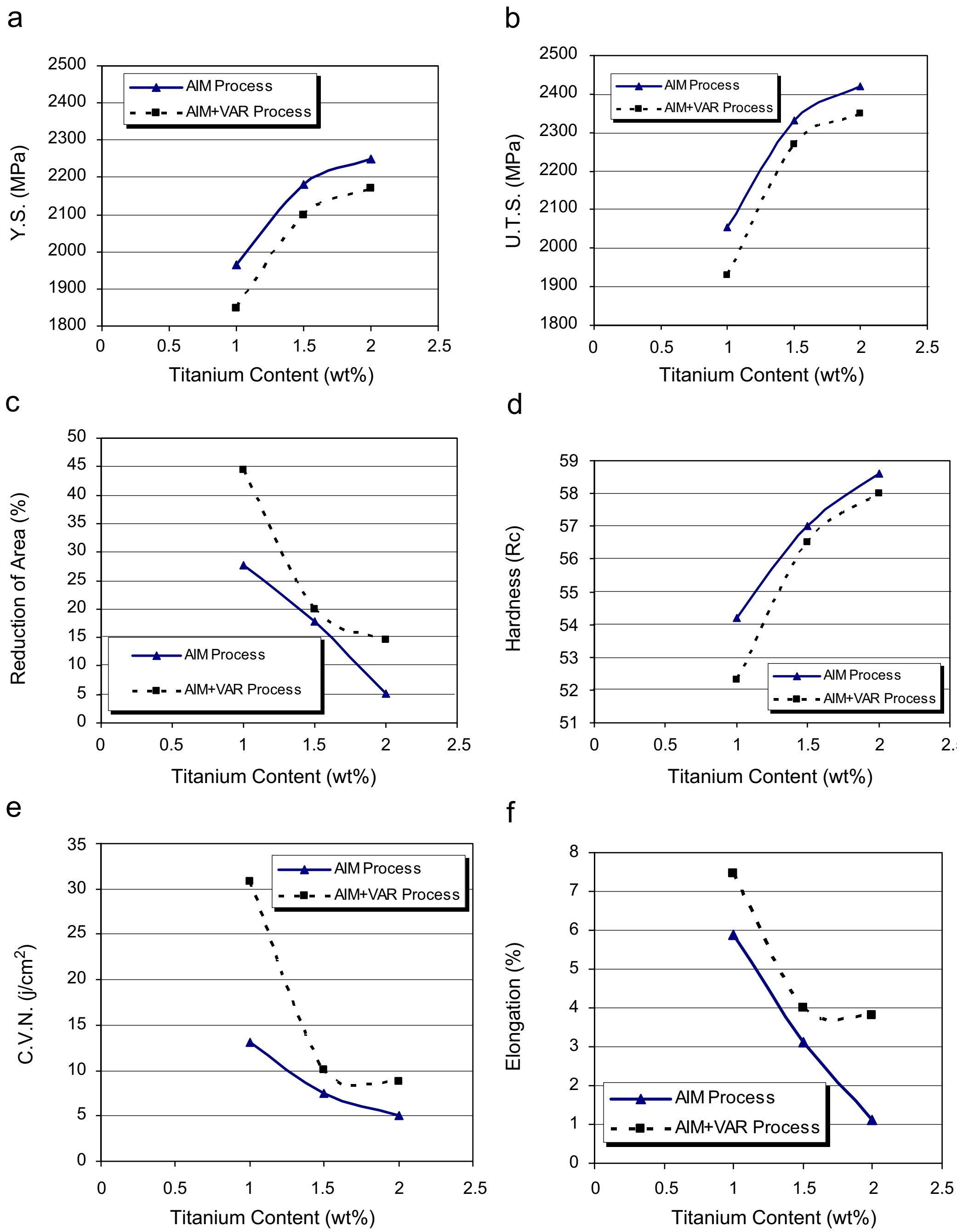

Fig. 1. The effect of VAR on strength, flexibility, hardness and impact energy of C300 maraging steels with 1, 1.5 and 2 wt% Ti produced by AIM.

the use of VAR process not only substantially decreased the amount of inclusions, but also modified their distribution and decreased their sizes.

The percentage changes in various mechanical properties of the samples before and after application of VAR are shown in Table 6. This table indicates the amount of reduction (−) or increase (+) in a property after the related bar was subjected to this process.

Table 6 also shows that the average reduction of yield stress, UTS and hardness are 4.73%, 3.86% and 2.4%, respectively, while the amounts of increase in impact energy, elongation and reduction of area are 41%, 38% and 37%, respectively, when the bars cast in the AIM furnace are subjected to VAR process.

Fig. 5 compares the flow curves of the samples having 1 wt% Ti produced in different furnaces. This figure indicates a slight upward shift of the flow curve of the sample produced in the AIM furnace relative to the one produced in the VIM furnace.

Comparison of the yield strength, the tensile strength, the ductility and the impact energy of the samples having 1 wt% Ti, but cast originally in different furnaces, is shown

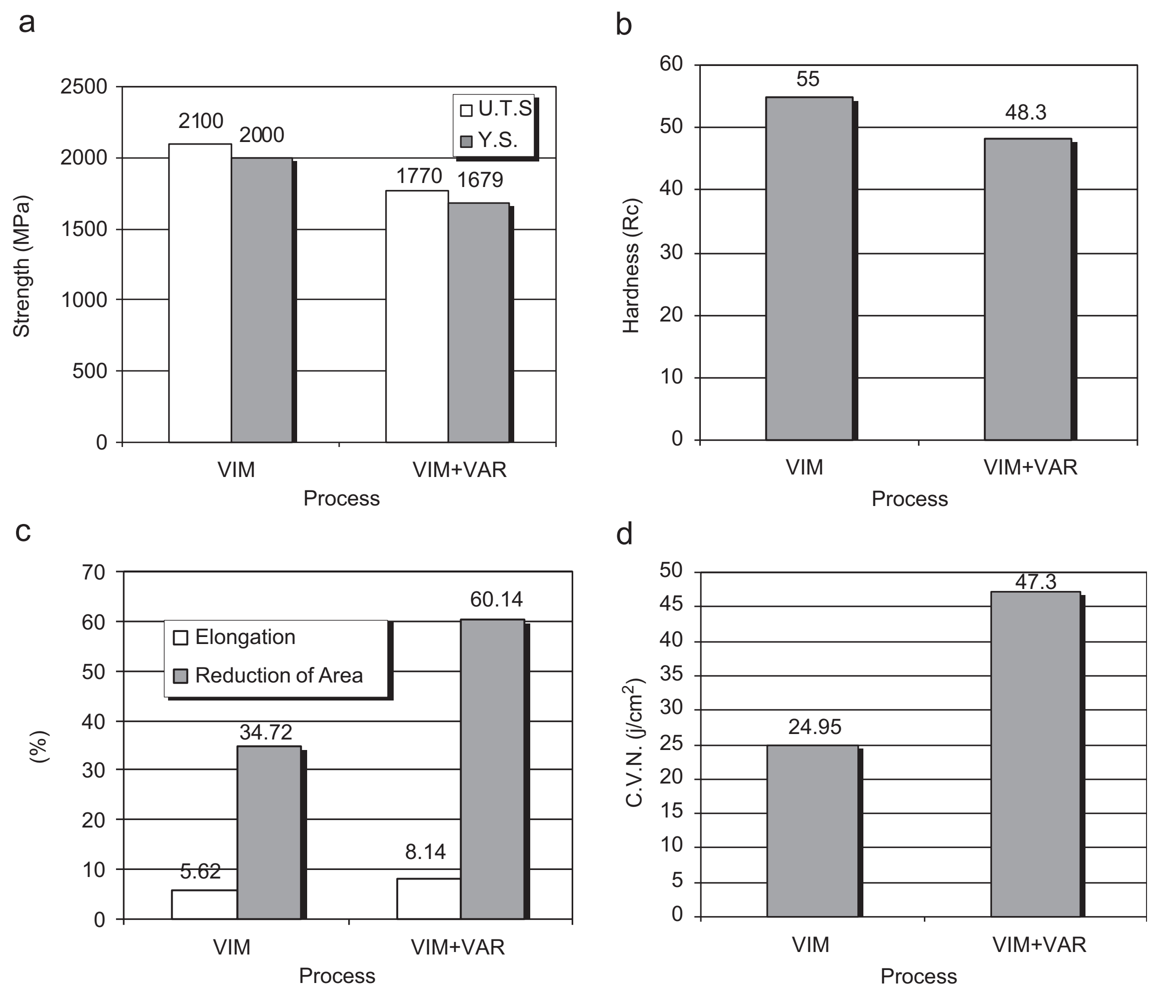

Fig. 2. The effect of VAR on strength, hardness, flexibility and impact energy of C300 maraging steels with 0.65 wt% Ti produced by VIM.

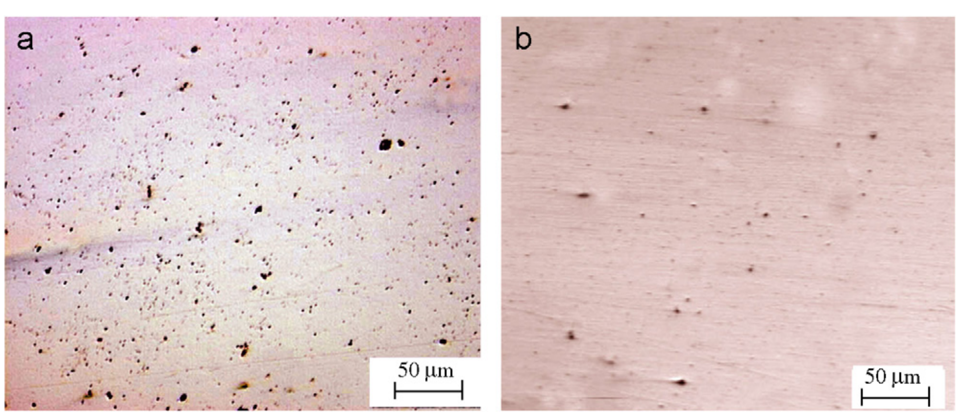

Fig. 3. Typical effect of VAR on inclusions (amount, size and distribution) of C300 maraging steel with 1 wt% Ti: (a) cast in AIM furnace, (b) same as (a) + VAR.

in Fig. 6(a–d). These bar charts show that, while strength and hardness of the sample produced in the AIM furnace decreased by 4% and 4.3%, respectively, relative to the one produced originally in the VIM furnace, its impact energy and ductility increased by 29% and 1%, respectively. Looking at these results one may say that the originally casting process did not affect seriously the strength, hardness and ductility of the bars.

Fig. 7 shows the effect of VAR in reduction of inclusions in the samples produced originally in the AIM furnace.

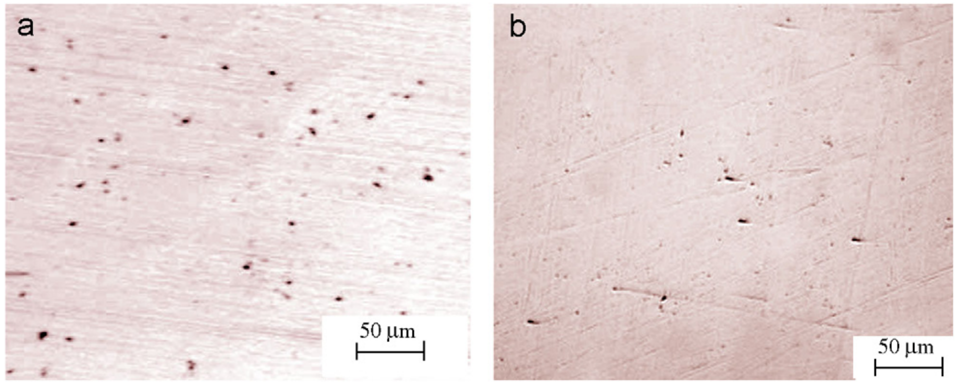

Fig. 4. Typical effect of VAR on inclusions (amount, size and distribution) of C300 maraging steel with 1 wt% Ti: (a) cast in VIM furnace, (b) same as (a) + VAR.

Table 6
The effect of VAR on the increase (+) or the reduction (−) of various mechanical properties of the steel bars with 1, 1.5 and 2 wt% Ti

Amount of Ti (wt%)	The average percentage changes in various mechanical properties of the bars after being subjected to VAR process: (−) reduction, (+) increase					
	UTS	YS	Elongation	CVN	Hardness	RA
1	−6	−5.8	+21	+57	−3	+37
1.5	−2.7	−3.6	+22	+25	−0.8	+10
2	−2.9	−4.8	+71	+42	−1	+64
Average of the changes	−3.86	−4.73	+38	+41	−2.4	+37

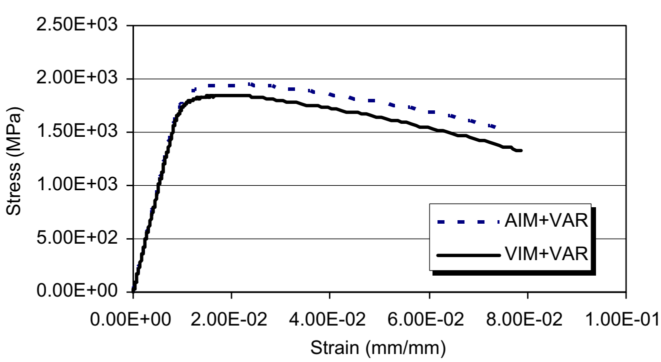

Fig. 5. Comparison of the steel flow curves having 1 wt% Ti, but produced by different methods.

The effect of VAR process on the total amounts of N and O gas reduction is presented in the form of bar charts in Figs. 8 and 9, and the percentage reduction of the total N and O gases is presented in Table 7.

On the basis of the above data, one can see the effect of VAR on the samples originally produced by the AIM furnace which caused a reduction of minimum 17% of gases in the sample having 1 wt% Ti and a maximum 39% in the sample with 1.5 wt% Ti. However, the amount of reduction of these gases due to the application of VAR process on the samples with 0.65 wt% Ti produced originally by the VIM furnaces was 12%.

4. Discussion

Large inclusions within the bars were broken to smaller ones and distributed with more homogeneity when they remelted by arc in vacuum. Parts of the inclusions were possibly decomposed chemically due to high temperature of the arc and relatively suitable vacuum used. In addition, this process caused some of the other elements such as Ti to be wasted. Therefore, reduction of these elements and gases caused the formation of fewer inclusions. On the other hand, breaking thermally some of the particles, particularly the large inclusions, increased the number of particles available within the matrix. This caused an increase in the strength and hardness of the matrix due to the increasing role of higher number of particles as barrier to dislocation movement.

It is reported [7,8] that the ductility of the maraging steels strongly depends on the morphology and the amounts of inclusions. It has also been said [7,8] that VAR process modifies inclusion characteristics such as morphology and size, so that this process can improve the ductility and the toughness of this type of steels. Therefore, considering the above argument and the obtained results in this research one may conclude that, due to VAR process used on the samples cast in the AIM furnace, the shapes and the sizes of the inclusions, particularly the large one, were modified, so that these parameters affected the mechanical properties indicated in the Results section.

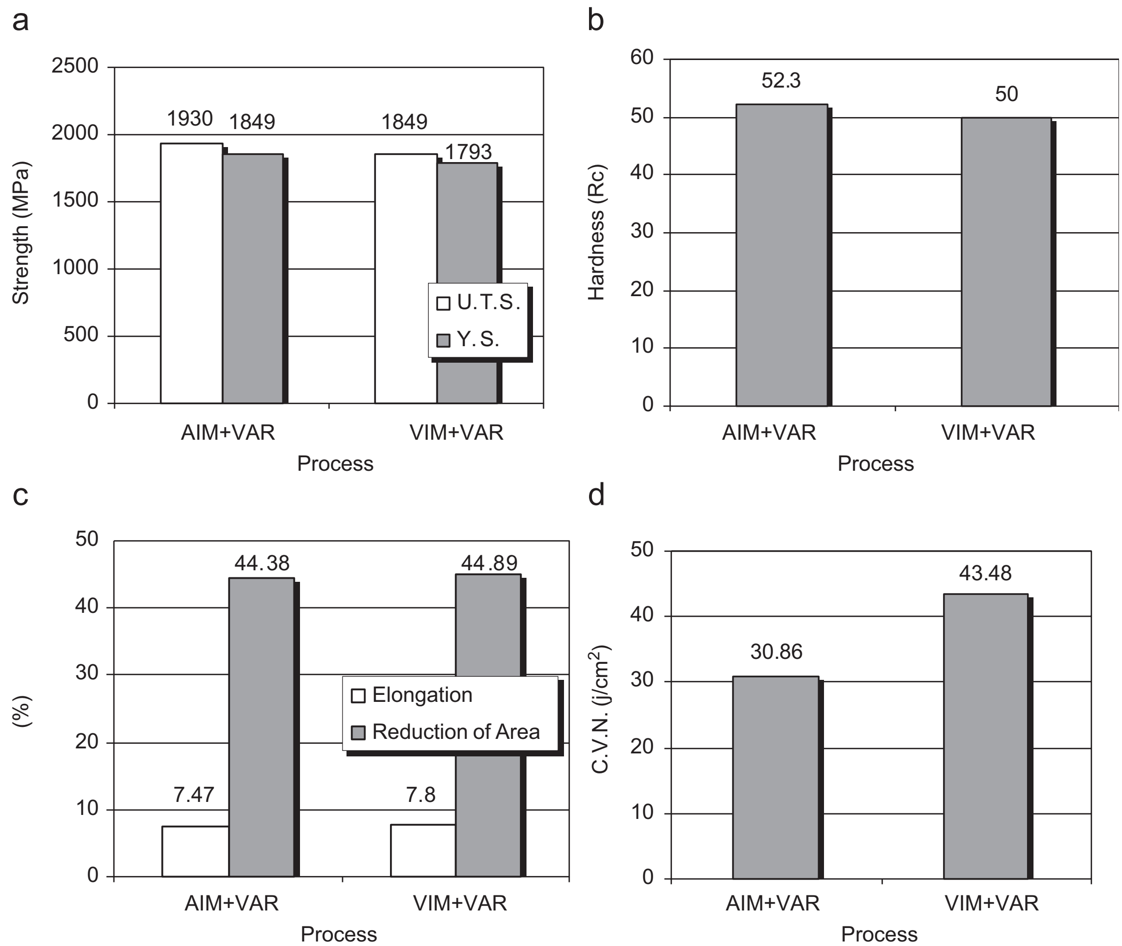

Fig. 6. Comparison of various mechanical properties of the samples with 1 wt% Ti cast originally in different furnaces.

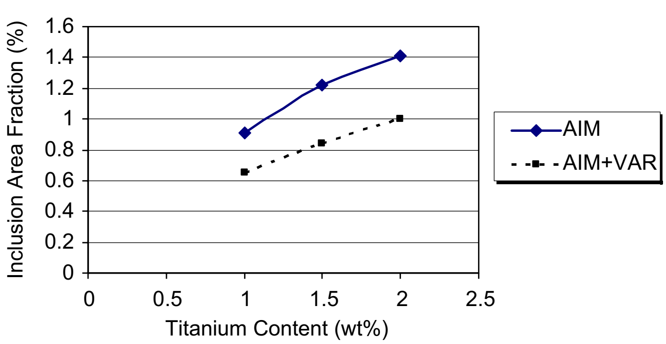

Fig. 7. The effect of VAR on the reduction of inclusions in C300 steel produced by AIM process.

One type of the most reported precipitate forms in this type of maraging steel is Ni_3Ti whose amount depends on the Ti content [8–10]. These precipitates formed in maraging C300 steel under investigation during aging at 500 °C for 3 h, so that they increased strength and hardness substantially. However, the rate of increase in strength and hardness up to 1.5 wt% Ti was much more than those having 2 wt% Ti. This might be an indication of lower rate of formation of this type of precipitate when the Ti content exceeds 1.5 wt%. In other words, when the amount of Ti exceeds 1.5 wt%, the extra Ti together with other harmful elements such as O, N and S seems to segregate within the dendrite arms and create an environment suitable for formation of more inclusions. Fig. 7 shows that by increasing Ti content of the bars the amount of inclusions substantially increased while at the same time the rates of increasing strength and hardness decreased, which justifies the above argument.

When the melt had lower amount of Ti, all or most of it probably remained in the form of solution in the produced bars, but when its amount increased, some part of it, as indicated above, segregated within the interdendritic areas and formed inclusions during solidification.

During aging of C300 maraging steel, most of the solvent Ni and Ti atoms combined to form Ni_3Ti, as a result of which Ni content of the matrix decreased substantially. This in turn caused the rate of formation of these precipitates to gradually decrease at higher Ti content, but the overall amount of inclusions increased. So in all the increasing rates of strength and hardness decreased. Therefore, from the above argument one may conclude

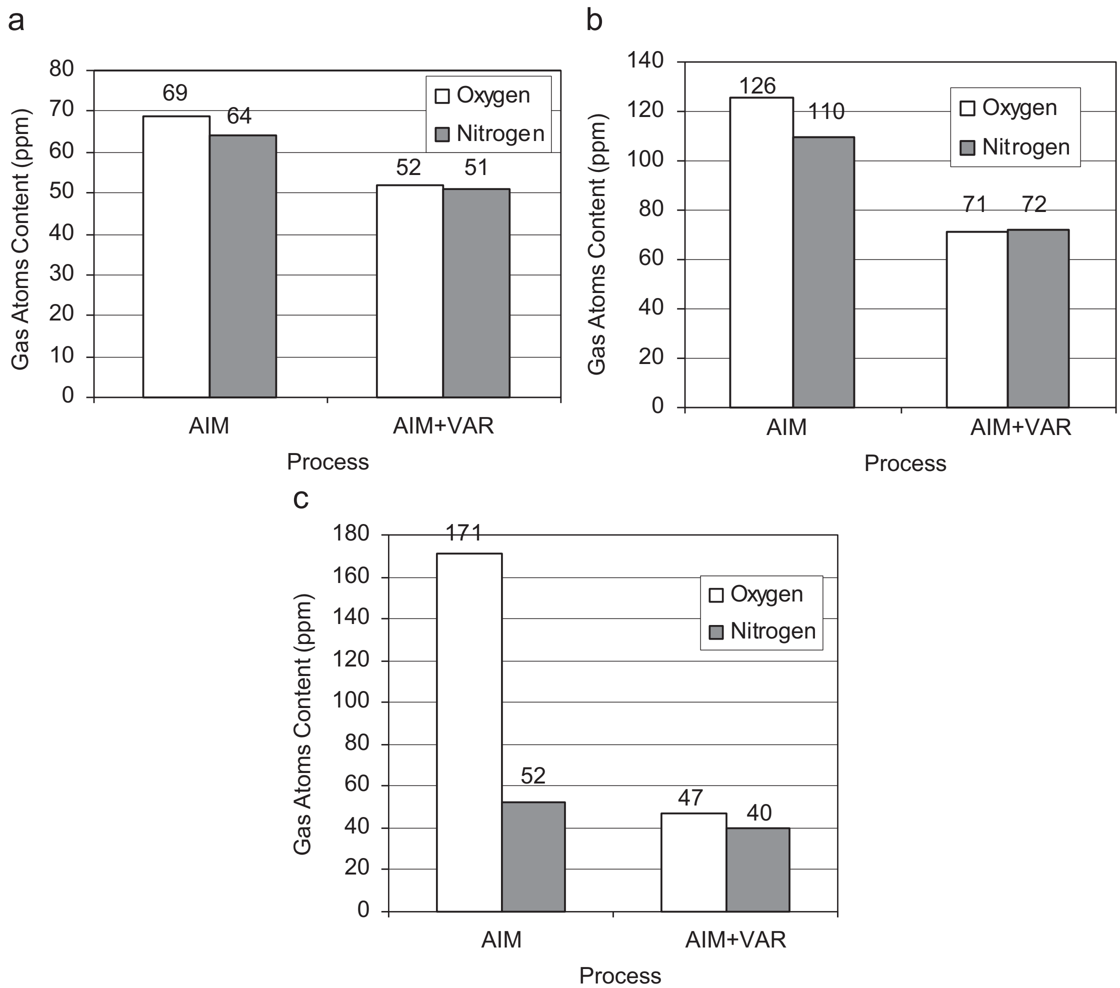

Fig. 8. The effect of VAR on the reduction of the total N and O gases in the samples cast originally in the AIM furnace and having different Ti content: (a) 1 wt% Ti, (b) 1.5 wt% Ti, (c) 2 wt% Ti.

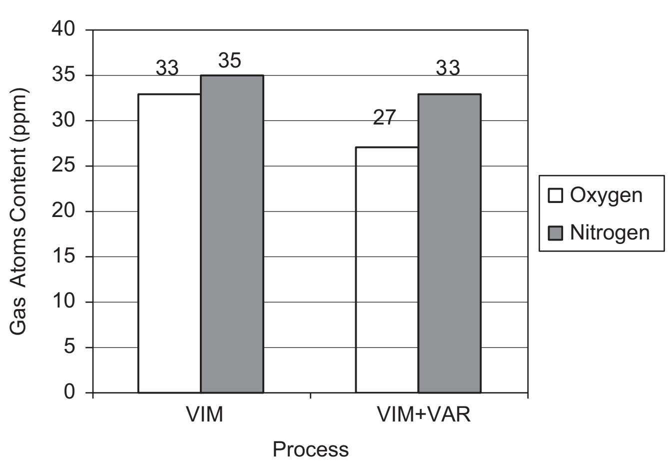

Fig. 9. The effect of VAR on the reduction of the total N and O gases in the samples produced in the VIM furnace and having 0.65 wt% Ti.

that, since up to 1.5 wt% Ti most of the solute Ni atoms were consumed for formation of Ni_3Ti precipitates, the rate of formation of the matrix precipitates gradually decreased. This in turn caused the rate of increasing strength and hardness to decrease.

Table 7
Percentage of the total N and O gas reduction due to the application of VAR process

Ti content (wt%)	Total N and O reduction by VAR process (%)
1	17 ± 2
1.5	39 ± 3
2	34 ± 3

AIM and VIM processes have an essential difference which each other and that is the pressure level. In the VIM furnace the pressure was very low while in the AIM furnace the pressure on the surface of the melt was high (i.e. $1.3 \pm 0.1 \times 10^5$ Pa) due to pressurized argon gas. Therefore, in the VIM furnace, the pressure helped the solvent gases and gases due to inclusion decomposition leave the melt much easier than when the AIM furnace was used. Therefore, one expects more inclusions in the bar produced in the AIM furnace than those in the VIM furnace. This can be observed in the typical images presented in Figs. 3 and 4 from the samples with 1 wt% of Ti.

The application of VAR process on the bars produced originally differently had nearly the same effect on the modification of the inclusion sizes, shapes and their amounts. This process decreased the yield and the ultimate tensile stresses but caused an improvement in the ductility and the toughness of the steel produced either in the AIM or the VIM furnaces. Since the impact energies obtained were at room temperature and not at fracture appearance transition temperature (FATT) of the alloy and also due to the fact that charpy impact test gives random numbers for any high-strength material, one can not be sure about the amount of high energies obtained in this research. However, all one can say is that the impact energies in the samples cast in the VIM furnace increased more relatively to those cast in the AIM furnace.

5. Conclusions

1. The effect of VAR on the bars produced in the AIM furnace improved their flexibility by about 38% while the hardness and the strength of the bars were slightly reduced.
2. The effect of VAR on the bars produced in the VIM furnace improved their ductility and the impact energy by 30% and 47%, respectively, while this process did not affect the hardness and the strength of the bars noticeably.
3. The mechanical properties of the bars produced in AIM + VAR process were similar to those produced by VIM + VAR process.
4. VAR process reduced the amount of atomic gases in the bars produced in the AIM furnace by 40% and the amount of inclusions by 30%.
5. The effect of VAR on the bar cast in the VIM furnace caused a reduction in atomic gases by 12%.

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