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Chemical Composition Optimization for Austenitic Steels of the Fe-Mn-Al-C System

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Alloys of the FeMnAlC system have been developed for different uses, from cryogenic temperatures up to 673 K, with specific composition recommended for each specific application. More recently, the possibility of adopting alloys of this system for structural purposes has attracted considerable attention. However, the absence of systematic criteria in the design of such compositions imposes severe restrictions on practical uses of these alloys. In this paper, we define composition limits in order to obtain an optimum microstructural state, characterized by the absence of embrittling components, and more restricted limits to obtain acceptable properties for structural applications, based on minimum values for ultimate tensile strength and impact toughness.

Keywords austenitic steels, FeMnAlC alloys, mechanical properties

1. Introduction

A reasonable number of results concerning the effects of alloying elements on microstructure and properties of steels of the FeMnAlC system are already available in the literature.[1–10] In these papers, different chemical compositions are proposed as attempts to solve specific practical problems, in some cases, leading to compositions patented in various countries.[7,8,11] However, although they may satisfy very localized demands, the lack of systematic criteria in the design of such compositions almost always results in very restricted possibilities for applications of such alloys. In general, they have either insufficient strength or low fracture toughness, preventing them from being used, for instance, in structural components.

It is well known that the presence of carbon and manganese stabilizes the austenitic structure of the system under consideration.[10] The minimum content of these elements is limited by the single-phase condition. The combined minimum content of carbon and aluminum is restricted by the requirement for a sufficient strength in the aged state, while the maximum content is determined by an admissible low level of ductility and impact toughness. At the same time, the maximum content of manganese is limited by the appearance of grain boundary β-Mn, which is responsible for severe embrittlement of the alloy.[1,10,12] The aim of the present study is the determination of the best combination of composition ranges for the basic alloying elements to produce an alloy of this system for use in structural applications.

The limits for such composition ranges were defined after consideration of microstructural and mechanical properties. From the microstructural point of view, the criterion is based on the absence of δ-ferrite in the starting structure, and, in the course of further thermal processing, on the prevention of coarse grain-boundary precipitation and on the prevention of a decomposition reaction that leads to the appearance of β-Mn. From the mechanical properties point of view, the criterion is based on the best combination of mechanical strength ($UTS > 1100$ MPa) and impact toughness ($K_{CU} > 50$ J/cm^2).

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2. Experimental Procedures

Different melts with Al content between 3 and 10% were prepared with C and Mn limited to 0.85 to 1.0% and 28 to 30%, respectively. The effects of carbon content, between 0.3 and 1.2%, were analyzed in melts with 9% Al and 28 to 30% Mn. Melts with different combinations of C and Al content were also analyzed. The Mn was varied between 24 and 34%, with invariable Al (9%) and C (0.9%) content. Different experimental compositions were chosen based on available information concerning the effects of C content on phase composition at the Fe-rich corner of the ternary Fe-Mn-Al phase diagram,[10,13,14] the basic requirement being the provision of a fully austenitic structure for each composition. A total of 31 different compositions were prepared.

Test melts were prepared in a 100 kg induction furnace and poured off into 20 kg cylindrical ingot-electrodes containing different amounts of the elements under investigation. These ingot-electrodes were subjected to repeated melting and refining in an electric-slag remelting furnace. The ingots thus obtained were homogenized at 1150 °C for 6 to 8 h and subsequently shaped as rods with circular (12 mm diameter) and square (14 × 14 mm) cross sections. Tensile samples taken from the circular rods and U-notch impact specimens (1 mm notch radius) taken from the square rods were heated to 1050 °C and then quenched into water at room temperature. Aging was performed at 550 °C for 16 h.[10]

Metallographic specimens were etched with a 4 to 7% solution of nitric acid in ethanol. The content of δ-ferrite was determined by metallographic and x-ray structure analysis. The microstructural state and mechanical properties of metallurgical semifinished products were also analyzed in this study.

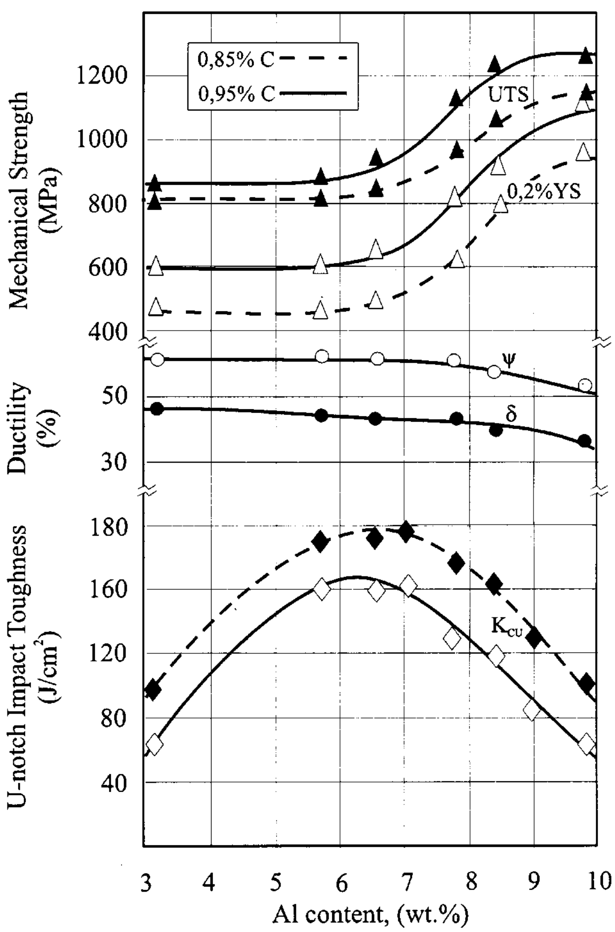


Fig. 1 Effect of Al content on mechanical properties. Thermal processing: water quench from 1150 °C and aging at 550 °C for 16 h

Fig. 2 κ-phase precipitation in steel with 4.6 wt.% Al, after aging at 600 °C during 16 h

3. Results and Discussion

3.1 Effects of Aluminum Content

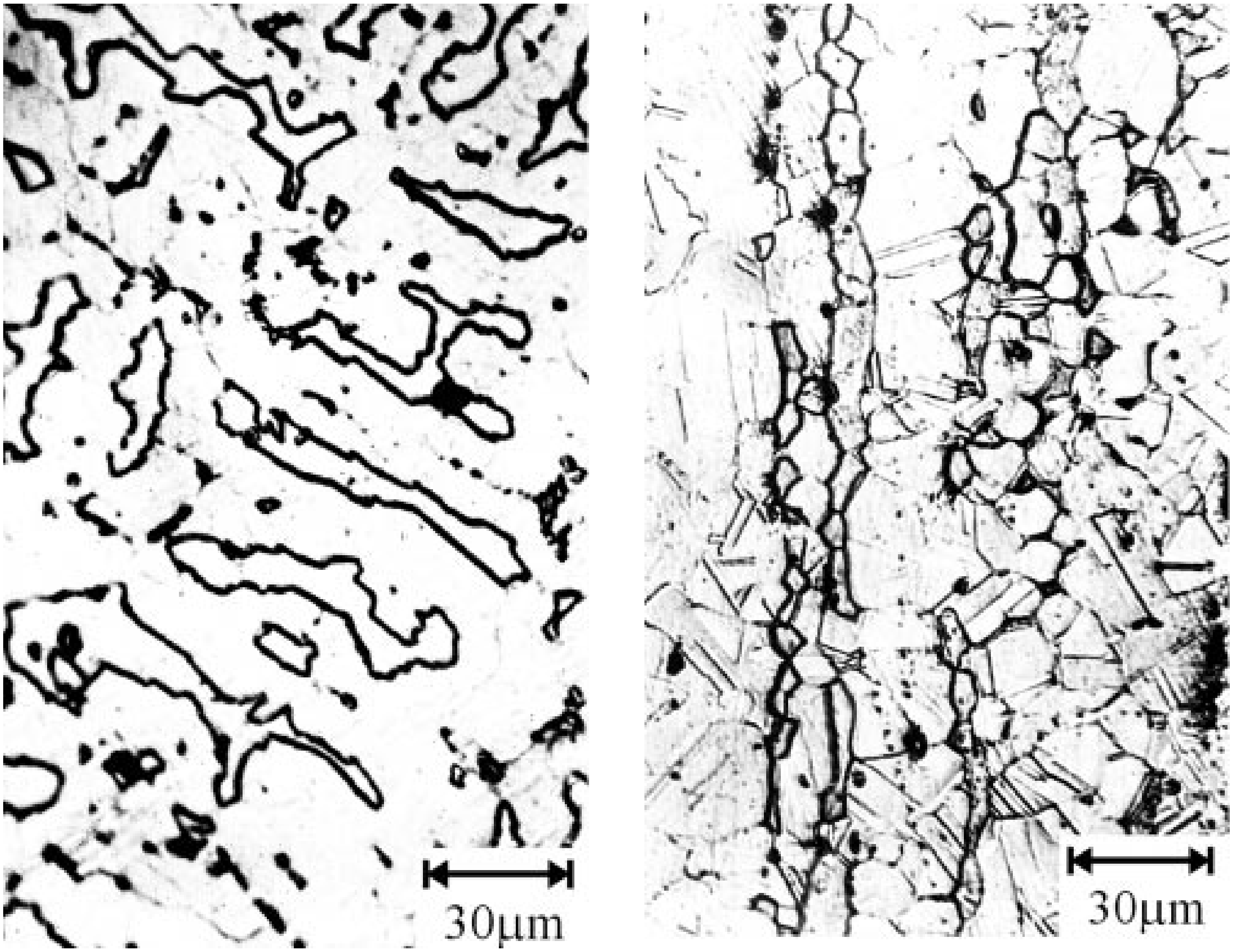
Aluminum forms a substitutional solid solution with Fe, and, due to the difference in atomic radii, somewhat distorts the steel crystal lattice. Therefore, the presence of aluminum slightly increases the steel yield stress.[6,9,11,15–19]

It was established that considerable hardening is obtained by aging at 550 °C when the aluminum content exceeds 7% (Fig. 1). According to Huang *et al.*,[20] precipitation of κ-phase particles within the matrix at 650 °C occurs when the aluminum content is higher than 6.2%. As it follows from Fig. 1, the onset of hardening at 550 °C corresponds approximately to this same Al content. For lower aluminum contents, however, the homogeneous nucleation does not occur. With a low supersaturation degree, high temperatures are needed to provide long-range diffusion of the Al atoms, and, in this case, carbides in the form of individual discrete particles are precipitated inside grains as a result of the eutectoid reaction. This reaction is typical of phase transformations occurring in accordance with the nucleation and growth mechanism for a new phase.[21]

The carbon content significantly affects the value of the aluminum critical concentration, which is acceptably lower, the higher the carbon concentration in solid solution. In the case of low aluminum content, the carbide phase precipitates during aging as a network along grain boundaries (Fig. 2), which is highly detrimental to impact toughness. Within the field of homogeneous precipitation, with increasing aluminum content (beyond 7%), both ductility and impact toughness decrease (Fig. 1), due to an increasing volume fraction of the hardening phase particles.

In case aluminum content exceeds 10%, δ-ferrite appears in the steel microstructure (Fig. 3). The presence of δ-ferrite decreases the technological plasticity of such alloys and enhances mechanical properties anisotropy.

With up to 12% δ-ferrite in the cast steel, subsequent hot working within the range 1150 to 1170 °C is accompanied by the δ-ferrite dissolution. This statement is in good agreement with the data of Krivonogov *et al.*,[12] and so it can be established that the temperature of 1150 °C is the recommended temperature for δ-ferrite dissolution.



(a) (b)

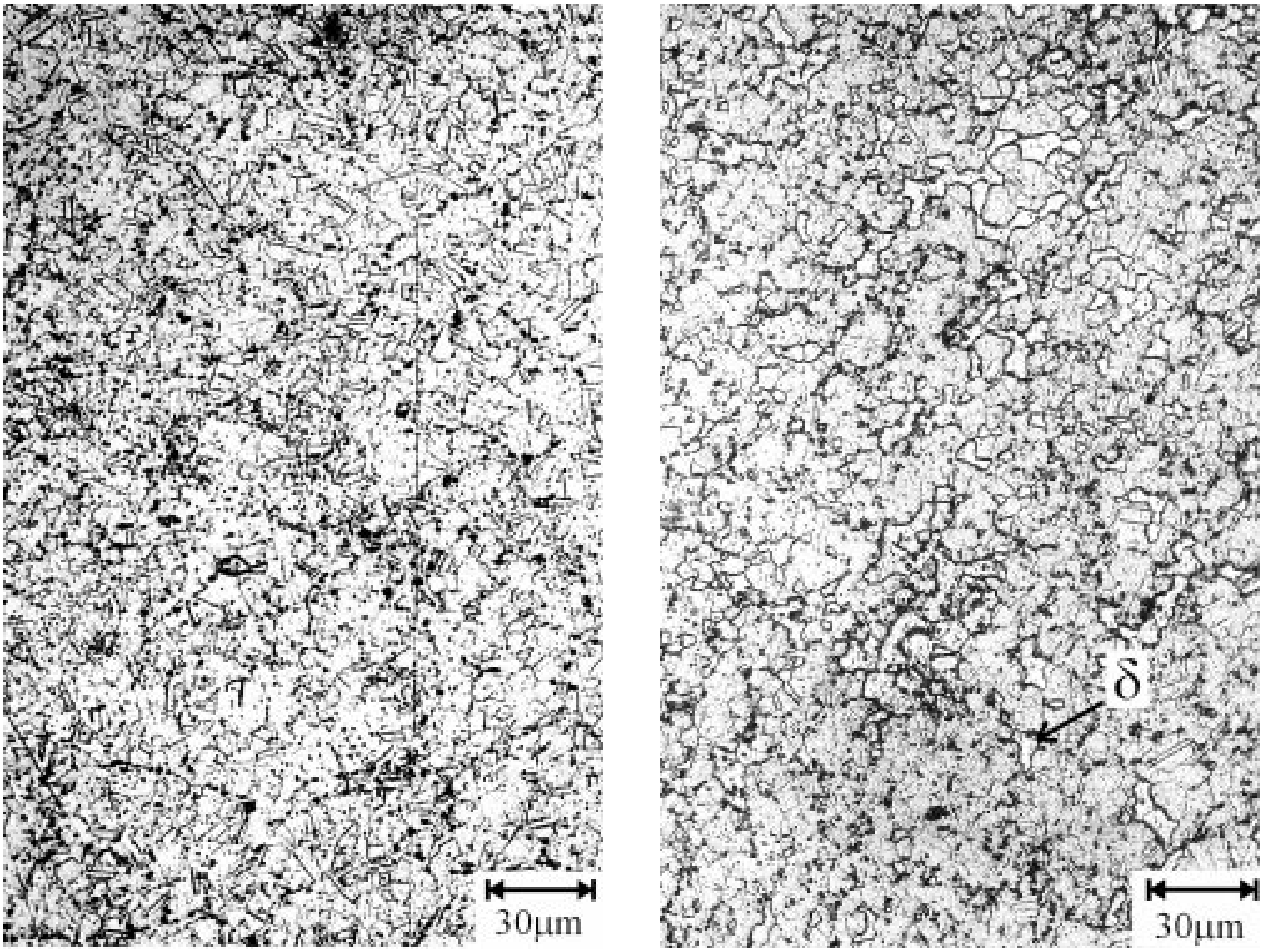
Fig. 3 δ-ferrite in steel with 10.5 wt.% Al: (**a**) as cast and (**b**) after deformation

The presence of δ-ferrite in the ingots seems to be related to the melting process and to the Al content. In the case of the aluminum content exceeding 9.5% in open air melting, the amount of δ-ferrite (mainly in the central upper zone) considerably increases with the ingot weight due to development of liquation.

With the use of refining processes such as electroslag and plasma-arc remelting, when the volume (depending on the size of the liquid bath) of the solidifying metal is small, the occurrence of liquation can be considerably reduced. In the central part of ingots with a square cross section (415×415 mm) and a mass of 2.2 metric tonnes, which are obtained by electroslag melting, after subsequent rolling (with production of rods 20 mm in diameter or a square cross section up to 105×105 mm) has been completed, δ-ferrite is absent in the steel structure for aluminum contents under 9.7%. The presence of this amount of Al may result in semifinished products of large cross sections in which the δ-ferrite content is about 5%. For aluminum content lower than 9.5%, δ-ferrite is absent in hot-worked semifinished products. However, if the hot-working temperature exceeds 1170 °C (the solidus temperature of Fe-29Mn-9Al-0.9C steel is about 1320 °C), an additional amount of δ-ferrite can be formed in the structure.

Another possibility for controlling the occurrence of structural inhomogeneities caused by liquation (as the formation of δ-ferrite), other than by controlling the thermomechanical processing, is by high rate solidification, when the development of zonal and dendrite liquation is suppressed. Jet spraying of liquid metal in argon atmosphere results in small spherical particles (less than 500 μm in diameter) cooled at a very high rate, and δ-ferrite in the subsequent worked steel was not found even up to 12% aluminum content (carbon and manganese contents, respectively, are 0.9 and 29%). With 14% Al, δ-ferrite may reach a volume fraction around 10% (Fig. 4).

The existence of δ-ferrite in the steel structure leads to an excess carbon concentration in the remaining solid solution, which is higher than the average carbon content in the steel. This fact results in intensifying processes of precipitation of an excess (hardening) phase during aging treatments.



(a) **(b)**

Fig. 4 Granulated and pressed (at 1150 °C) steel: quenching from 1100 °C. Al content: (**a**) 9.8% and (**b**) 14%

3.2 Effects of Carbon Content

The presence of carbon itself ensures a significant increase in strength due to interstitial solid solution hardening: For each 0.1% of carbon, the yield stress increases by 30 to 40 MPa.[18,19]

Aging this steel within the temperature range 400 to 850 °C allows the precipitation of κ-phase particles with magnetic properties.[12] The saturation magnetization of samples measured after aging for 16 and 100 h at different temperatures presents qualitative information on the intensity of the aging process (Fig. 5). Thus, it was established that carbon, being the most diffusion-mobile element in steels, is a leading component at the onset of the aging process.

For the same aluminum content, the value of $4\pi J_s$ increases only up to a certain carbon concentration. To raise this value, it is necessary to increase the amount of aluminum in steel. Thus, the extent of the aging process depends on the aluminum content.

A high carbon concentration (1 to 1.3%) causing noticeable solid-solution hardening (Fig. 6) can be used when this steel is applied in the cast state or for producing machinery components by powder metallurgy methods. In the latter case, the

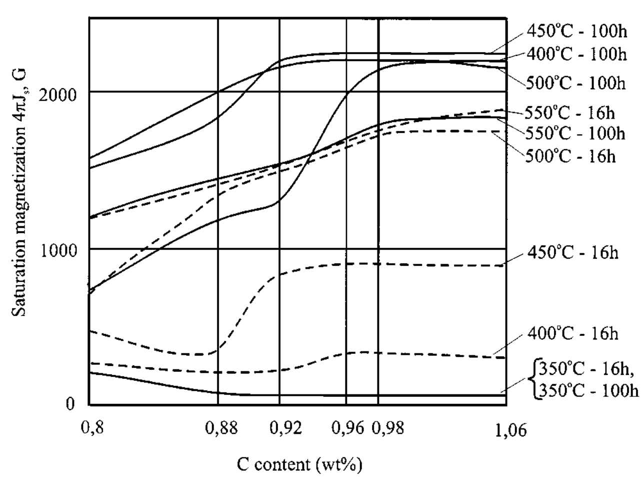


Fig. 5 Effect of carbon on the process of austenite aging. Al 9%, Mn 30%

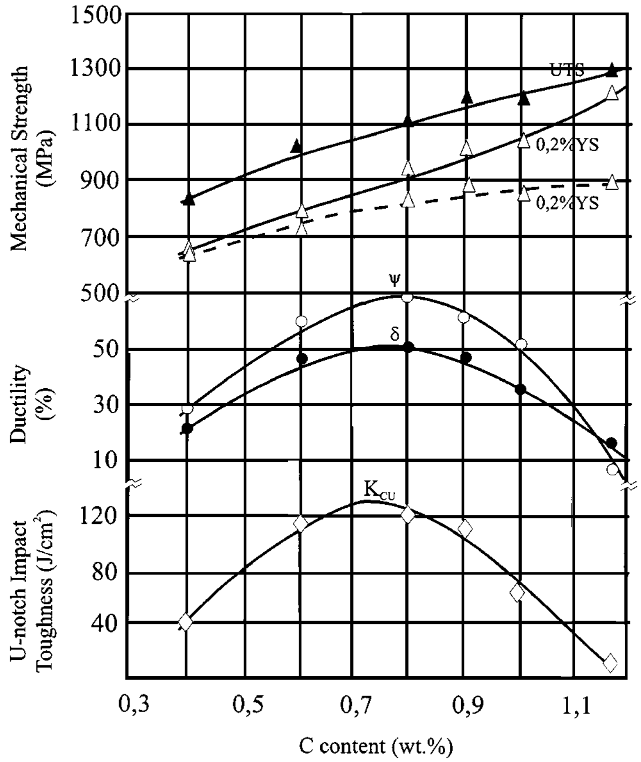


Fig. 6 Effect of carbon on mechanical properties. Al 9%, Mn 30%. Quenching from 1050 °C in water (dashed curves) and quenching from 1050 °C in water + aging at 550 °C during 16 h (solid curves)

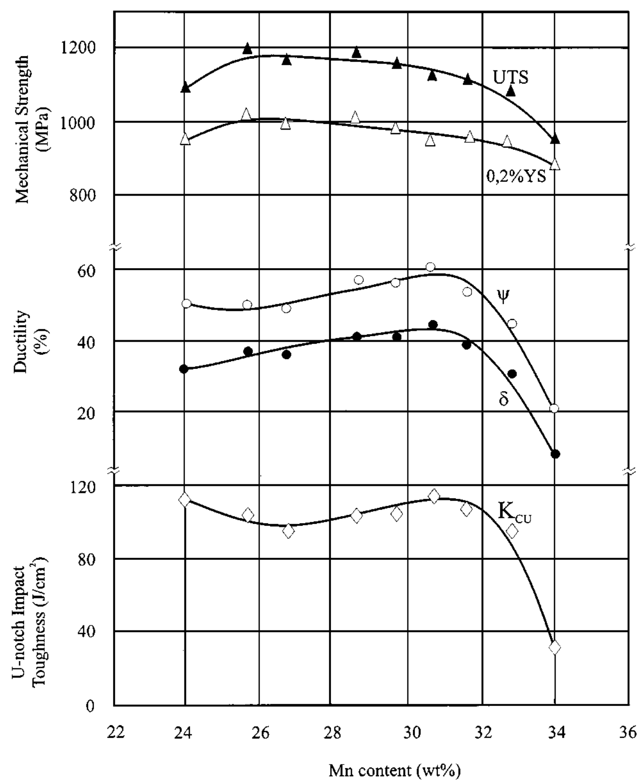


Fig. 7 Effect of manganese on mechanical properties. Al 9%, C 0.9%. Water quenched from 1050 °C and aged at 550 °C for 16 h

component is used in the quenched state or with subsequent cold working, as a rule, in small cross sections. In the aged (550 °C, 16 h) state, carbon concentrations exceeding 1% lead to the appearance of boundary carbide precipitations, and U-notch impact toughness decreases at least 40 J/cm^2 (Fig. 6). For carbon concentrations lower than 0.7%, δ-ferrite appears in the steel structure. In this case, the saturation magnetization in the as-quenched condition is higher than 200 G, whereas without δ-ferrite, this value is lower than 90 G.

3.3 Effects of Manganese Content

The influence of Mn is shown in Fig. 7. Manganese, forming an almost perfect substitutional solid solution with iron, virtually does not affect solid-state hardening. The solubility of aluminum and carbon in the steel γ-solid solution increases with the concentration of manganese. By virtue of this fact, the amount of κ-phase that precipitates during aging decreases.

For C and Al contents of, respectively, 0.9 and 9%, the manganese concentration must be no less than 26%. An Mn concentration less than 25% allows the appearance of δ-ferrite, whereas a concentration exceeding 31 to 32% Mn will give origin to β-Mn precipitation after long-time aging at 550 °C, causing extreme brittleness. This is in good agreement with previous results shown by Kayak.[10]

3.4 Optimization of the Steel Composition

The experimental results discussed above can be used to define the best alloy composition to obtain, after solution treating at 1050 °C followed by 16 h aging at 550 °C,[10] a steel with the combination of tensile strength higher than 1100 MPa and impact toughness above 50 J/cm^2, to be used in structural components.

We assumed the contents of alloying elements, namely, manganese, aluminum, and carbon, to be independent variables. The mechanical properties *UTS* and K_{CU} were considered as response functions. It was also assumed that the dependence of both *UTS* and K_{CU} are functions of the steel composition, which can be expressed by a second-order polynomial. Spatial figures limited by surfaces of equal-content levels for the properties under investigation were plotted. The analysis of variations of mechanical properties as functions of the alloying element contents allowed us to conclude that the *UTS* level $\geq$ 1100 MPa at $K_{CU} \geq 50$ J/cm^2 can be attained for melts with carbon content of 0.84 to 0.99% at the concentrations of other elements of 8.8 to 9.7% for aluminum and 28.5 to 30.5% for manganese.

However, taking into account liquation processes, particularly in the case of heavy ingots, which are intended for practical use in industry, it is reasonable to imply narrowed limits, namely, 9 to 9.5% for aluminum and 0.9 to 0.95% for carbon. The calculated limits of 28.5 to 30.5% for manganese can be preserved.

4. Conclusions

In steels of the system Fe-Mn-Al-C, optimum microstructural states, characterized by the absence of δ-ferrite, grain boundary carbide precipitates, and β-manganese, are attained for the following contents:

- $6.2\% < Al < 9.7\%$,
- $0.7\% < C < 1\%$, and
- $25 < Mn < 31\%$.

Solidification of the steel in small volumes with suppression of liquation processes makes it possible to avoid the appearance of δ-ferrite in the steel structure provided the aluminum content does not exceed 12% (for 0.9% C and 29% Mn).

Alloys of this system can be processed by aging to obtain a combination of $UTS > 1100$ MPa and U-notch impact toughness > 50 J/cm^2, which is an appropriate material to be used in the manufacture of mechanical components for structural purposes. This combination of properties is possible provided that the alloying elements are present in the following limits:

- aluminum from 9% to 9.5%,
- carbon from 0.9 to 0.95%, and
- manganese from 28.5 to 30.5%.

Acknowledgments

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