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.\textsuperscript{[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.\textsuperscript{[7±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.\textsuperscript{[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 $\beta$-Mn, which is responsible for severe embrittlement of the alloy.\textsuperscript{[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 $\delta$-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 $\beta$-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 ($K_{IC} > 50$ J/cm$^2$).

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.\textsuperscript{[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.\textsuperscript{[10]}

Metallographic specimens were etched with a 4 to 7% solution of nitric acid in ethanol. The content of $\delta$-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.
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 \( \kappa \)-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%, \( \delta \)-ferrite appears in the steel microstructure (Fig. 3). The presence of \( \delta \)-ferrite decreases the technological plasticity of such alloys and enhances mechanical properties anisotropy.

With up to 12% \( \delta \)-ferrite in the cast steel, subsequent hot working within the range 1150 to 1170 °C is accompanied by the \( \delta \)-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 \( \delta \)-ferrite dissolution.