

Influence of Microstructure on Mechanical Properties of Martensitic Stainless Steel Welds

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Abstract: The mechanical properties of welds in martensitic stainless steels are critically dependent upon the microstructure developed in the weld metal and heat affected zone. Hence it is essential to understand the transformations that take place during the welding cycle.

The purpose of the present paper is to present an overview of the phase transformations which take place in the weld metal or heat affected zones of martensitic stainless steels and their influence on mechanical properties of the welds.

Keywords: Martensitic stainless steel; mechanical properties, delta ferrite; retained austenite

I. Introduction:

Fusion welding involves localized heating, melting and cooling with the thermal cycle experienced varying over a wide range depending on the thickness of the material being weld and the welding process employed. In practice, all the metals and alloys which experience welding display some metallurgical change between the base metal and weld and HAZ region and hence the joint properties of these regions will differ significantly from those of the base metal.

Metallurgical transformation will take place during both heating and cooling, however for weld metal it is only the cooling cycle that is of concern. The metallurgical changes during welding may be mainly of two types, the first one is the major phase changes that occur and secondly the involvement of second phase particles either dissolution on heating or precipitation on cooling.

Because the properties of welds in steels are critically dependent upon the microstructure developed in the weld metal and heat affected zone, it is essential to understand the transformations that take place during the welding cycle.

The purpose of the present paper is to present an overview of the phase transformations which may take place in the weld metal or heat affected zones of martensitic stainless steels and their influence on mechanical properties of the welds.

II. Phase Transformations

Phase transformations take place during the original solidification process of the weld metal, and solid state transformations may occur in both the weld metal and heat affected zone. The predominant phase transformation in the martensitic stainless steel welds is the austenite-to-martensite transformation that occurs in the fusion zone and regions of the HAZ that have been heated into the austenite phase field.

2.1 Fusion Zone

The fusion zone of martensitic stainless steel with a nominal 11 to 14 wt% Cr and 0.1 to 0.25 wt% C solidify as delta ferrite. Segregation of C and other alloying elements during solidification can in some cases result in the formation of austenite, or a mixture of ferrite and austenite, at the end of solidification. As the weld metal cools in the solid state, the δ -ferrite transforms into fully austenite structure below about 1100°C. The austenite will transform to martensite upon further cooling. This transformation is represented by the following sequence.

Transformation path 1: fully martensitic microstructure

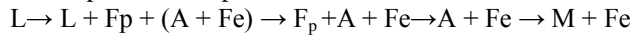
$L \rightarrow L + F_p \rightarrow F_p + A \rightarrow A \rightarrow \text{martensite}$

Where, F_p is primary ferrite, and A is austenite.

However complete transformation to austenite will be influenced by

- i. Segregation during solidification resulting in the formation of ferrite, which remains stable during cooling and remain at dendritic axes [1]. On the other hand, some of the ferrite stabilizers are also rejected into the liquid during solidification, so that the inter dendritic regions also can become ferrite, with some of the ferrite remaining at room temperature [2]. The amount of ferrite will depend on the ratio of ferrite to austenite promoting elements and the solidification conditions. This transformation is represented by the following sequence.

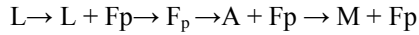
Transformation path 2: Two phase martensite + eutectic ferrite microstructure



Where, Fe is eutectic ferrite.

- ii. The transformation of δ -ferrite to austenite during cooling is completed if the cooling rate is lower. However, cooling rate being higher at elevated temperatures; some non-equilibrium δ -ferrite can remain [1]. This transformation is represented by the following sequence.

Transformation path 3: Two phase martensite + primary ferrite microstructure



Depending upon cooling rate some carbide precipitation may also occur on cooling to room temperature [3]. These carbides are normally of the type $M_{23}C_6$ or M_7C_3 where M is predominantly chromium and Fe. The M_7C_3 carbides are usually restricted to the high carbon alloys (greater than 0.3 wt %C).

The probability of the presence of untransformed austenite increases, when the content of alloying elements increase and in some cases it may require to cool the weld below room temperature, to obtain fully transformed structure.

2.2 Heat Affected Zone:

In the as-welded condition, depending upon the maximum temperature attained and the duration of the welding cycle, the heat affected zone of martensitic stainless steel welds can exhibit a number of distinct micro structural regions. A macrograph of an autogenously weld in a 12Cr-1Mo stainless steel is shown in Fig. 1 [4]. The various micro structural regions of this alloy are:

Region 1: It is a region which is adjacent to the fusion boundary. The microstructure at elevated temperature consists of austenite, but some ferrite may be present at the austenite grain boundaries. Upon cooling to room temperature, the austenite transforms to martensite and some of the ferrite remains in the microstructure. The fraction of ferrite in the HAZ increases with increased welding heat input, since a longer time at high temperatures allows diffusion to make the transformation to ferrite more complete, while the reverse reaction on cooling is very sluggish [5]. In fact the high temperature ferrite remains stable to room temperature, possibly because the formation of alloy carbides at the ferrite-austenite interface immobilizes the interface [6]. The amount of ferrite that is present at room temperature will be a function of the amount that was present initially and the rate of dissolution of this ferrite as it cools through the austenite phase field. The presence of ferrite can promote local softening relative to the adjacent fusion zone and HAZ.

In region 2 of the HAZ, the microstructure will be fully austenitic at elevated temperature. The temperatures in this region of the HAZ are sufficiently high resulting in base metal carbide dissolution and consequent grain growth. Upon cooling, this region will be fully martensitic. Because all or most of the carbon will have gone back into solution in the austenite, the peak HAZ hardness will generally occur in this region.

Region 3 of the HAZ is also heated into the austenite phase field during welding, but because the temperature is lower than in region 2, carbide dissolution will be incomplete and austenite grain growth will not be so pronounced. This reduction in grain growth is due to both the lower temperature experienced and the pinning effect of the undissolved base metal carbides. Failure to dissolve the carbides results in a lower austenite carbon concentration and a subsequent reduction in the hardness of the martensite that forms upon cooling.

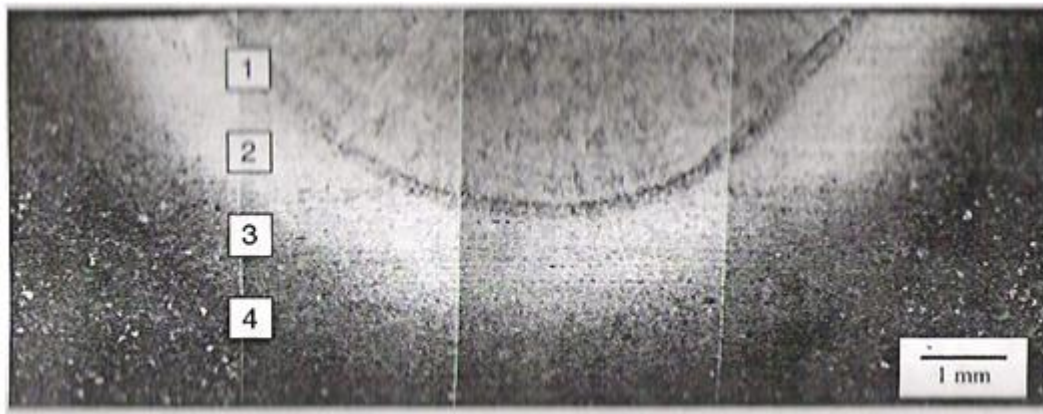


Fig. 1. Macrograph of an autogenous GTA weld in a 12Cr-1Mo stainless steel showing distinct regions in the HAZ [Lippold, 1984]

In region 4, little or no transformation to austenite occurs. Within this temperature regime [800 to 950°C] carbide coarsening can occur, resulting in some local softening relative to the base metal.

If alloys with higher carbon content are considered, the two-phase austenite + ferrite region will shrink and eventually disappear. This will result in elimination of the softened region at the fusion boundary, since untempered martensite will extend all the way to the fusion boundary. An alloy of 0.4 wt% C, for example, will have no ferrite in the HAZ near the fusion boundary. At lower carbon contents, considerable ferrite may form in the HAZ near the fusion boundary, resulting in more pronounced softening.

III. Influence of Phases on Mechanical Properties

3.1 Martensite

Martensite is the desired predominant phase in martensitic stainless steels. Its presence is a consequence of the diffusion less transformation of austenite during cooling to room temperature.

Martensitic transformation in these steels is athermal i.e., the amount of martensite formed depends only on the under cooling below the Ms temperature and not on the time at temperature. This behavior is expressed in the Koistinen and Marburger equation [7]

$$V_m = \exp(-0.011 * (M_s - T_q))$$

Where V_m is the fraction of martensite and T_q is the quenching temperature below M_s .

Depending upon carbon content, the martensite in these steels present in various forms i.e., lath martensite, plate martensite or a combination of lath and plate martensite. In alloys containing less than about 0.6 wt% C, the martensite forms as laths which are aligned parallel to one another. The schematic illustration of the microstructural features of lath martensite is shown in Fig. 2[8] and the optical structure is shown in Fig. 3.

Plate martensite structure is normally present in high carbon steels and in alloys with low M_s temperature [9-13]. The structure is shown in Fig. 4 [14]. Medium carbon steels may contain a mixture of lath and plate martensite so that their structure is unusually complicated, as shown in Fig.5[14]. The relative amounts of plate martensite increase when elements such as nickel are added that lower the M_s temperature [14].

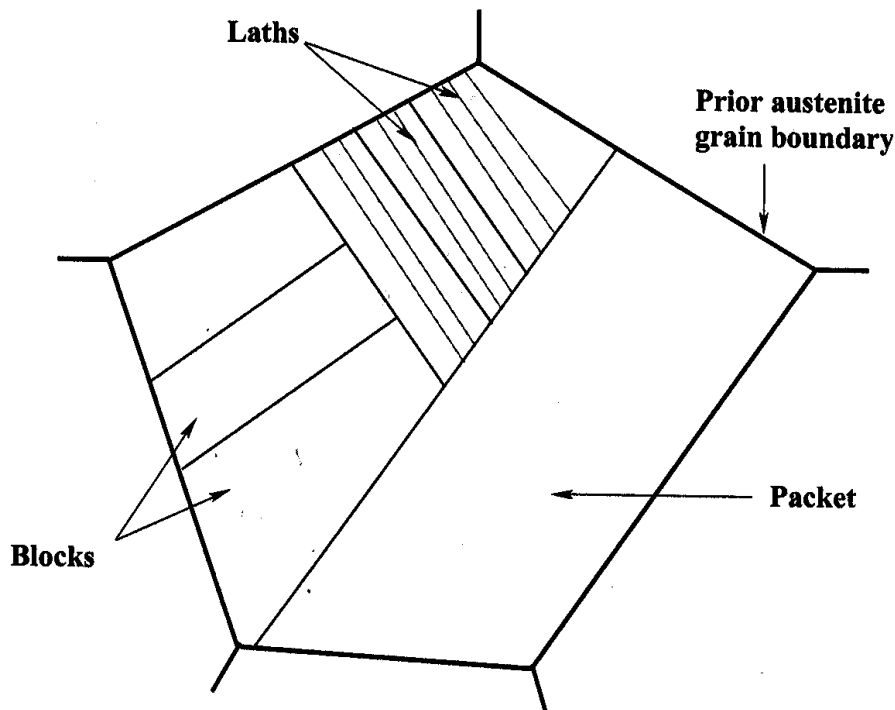


Fig. 2 Schematic illustration of the microstructural features of lath martensite [Maki. et al., 1980]

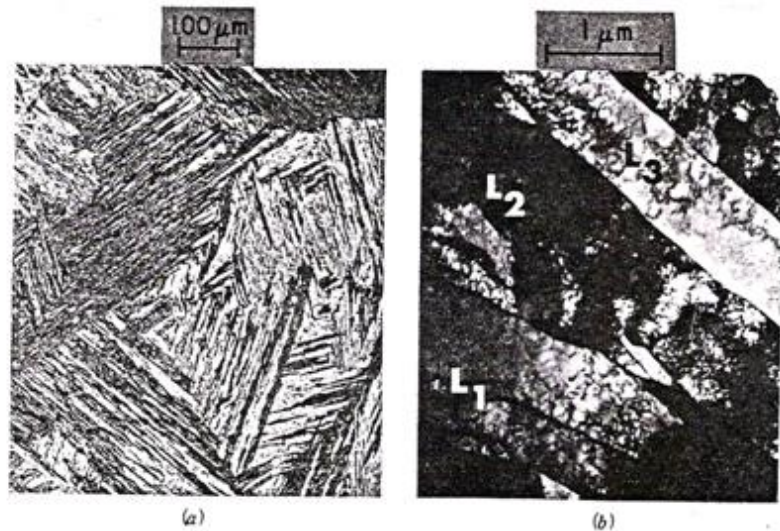


Fig. 3. Structure of lath martensite in 0.02% Mn steel. [Speich, G. R, et al., 1972] (a) Light micrograph. (b) electron transmission micrograph {L1,L2, L3 represents separate laths; the laths are separated by high-angle boundaries but each lath may contain many low -angle dislocation cells.

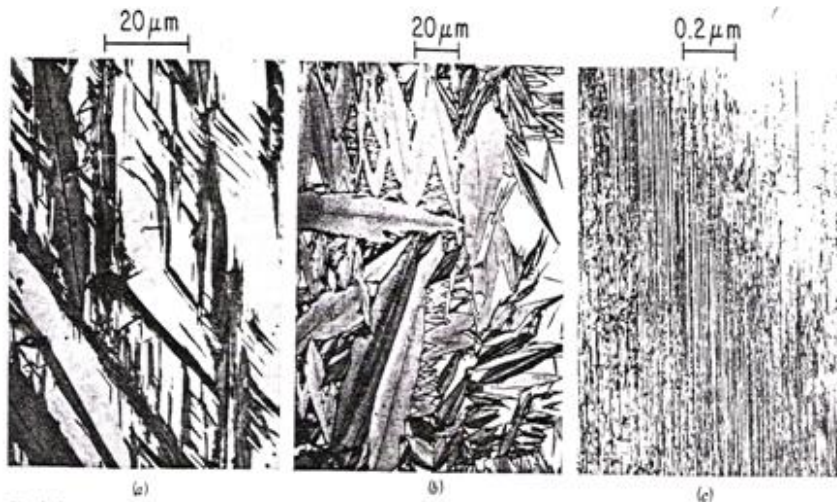


Fig. 4: Structure of plate martensite: (a) 1.2 %C steel, light micrograph; (b) Fe-30%Ni alloy, light micrograph; (c) Fe-30%Ni alloy, electron transmission micrograph. [Speich, et al., 1972]

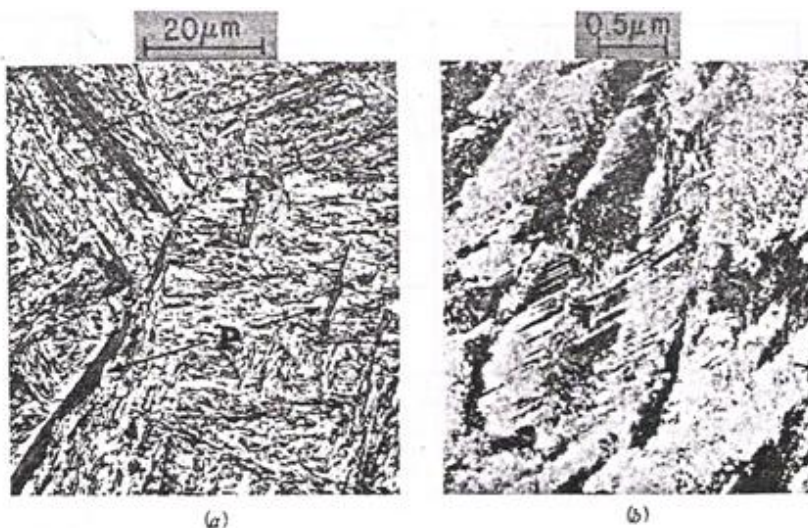


Fig. 5: Mixed lath and plate martensite structure in 0.57%C steel; (a) light micrograph (b) electron transmission micrograph (plate martensite labeled P; twinned substructure labeled T) [Speich, et al., 1972]

3.2 Retained Austenite

Depending upon the temperature at which the welding operation finishes and the precautions taken to avoid cracking, the weld can consist of martensite or a mixture of martensite and untransformed austenite. The probability of the presence of untransformed austenite increases, when the content of alloying elements increases and in some cases it may require to cool the weld below room temperature, to obtain fully transformed structure. Particularly, higher carbon grades are likely to retain large amounts of untransformed austenite in the as quenched structure, frequently as much as 30 % by volume. The Ms temperature is the primary factor affecting the level of retained austenite in martensitic stainless steel welds, and numerous empirical equations have been proposed to model the effect of a given element on the Ms temperature [14]. If an alloy element lowers the Ms temperature, retained austenite levels are increased within the steel, and vice versa [9].

Large increase in fracture and impact toughness in structural steels has been attributed to the presence of stable, retained austenite [15-18]. It has been shown that retained austenite decreases the yield strength in tension for heat treated low alloy steel [19].

The increased amount of retained austenite have been reported [20] to impart higher impact toughness when the steel is tempered at low temperatures, but the yield strength is lowered when the retained austenite is present in stainless steels of type AISI 431 [21-23]

3.3 δ -Ferrite

The amount of δ - ferrite retained is a function of both temperature and time, and is dependent upon the initial homogeneity of the steel and the extent to which equilibrium conditions are approached [24]. The presence of ferrite may be detrimental [25]. Studies have shown that small amounts of ferrite significantly improve the toughness of these steels at room temperature but ferrite presence in excess of 10 % can result in an approximate 50 % reduction in impact toughness [1, 26]. Its presence also decreases the tensile and fatigue strength [27]. Presence of significant amounts of delta ferrite results in low transverse strength and ductility, and also lower corrosion resistance [21, 28]. Hence it is not desirable for the welds to contain too much delta ferrite, both in the form of intra and inter dendritic form, since it doesn't harden during heat treatment.

3.4 Carbides

Depending upon cooling rate some carbide precipitation may also occur on cooling to room temperature [3]. These carbides are normally of the type $M_{23}C_6$ or M_7C_3 where M is predominantly chromium and Fe. The M_7C_3 carbides are usually restricted to the high carbon alloys (greater than 0.3 wt %C). The microstructure consisting of undissolved carbides is deleterious to toughness, particularly if the carbide phase is present as a network at the original austenite grain boundaries, or at inter lath boundaries [21, 29].

IV. Conclusions:

This paper presented an overview of the phase transformations which may take place in the weld metal or heat affected zones of martensitic stainless steels and their influence on mechanical properties of the welds. Depending upon the maximum temperature attained and the duration of the welding cycle, the various phases present in weld and HAZ of martensitic stainless steels include martensite, retained austenite, delta-ferrite and carbides. The influence of these phases on mechanical properties has been discussed.

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