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Review Article

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Effect of Metallurgical Fundamentals and Welding Processes on Joining of Dissimilar Steels

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ABSTRACT

The dissimilar materials welding is characterized by several metallurgical characteristics which do not arise in similar materials welding. Service life of mixed joint strongly depends on manufacturing and operating conditions. In this study, welding of different materials will be investigated in a way that up-hill diffusion processes, hot cracking, dilution percentage, thermal characteristics of the material and welding procedure. Micro analyses of different material's welding and metallurgical problems will be examined. The result of this study will allow us to explain potential joining mechanism for dissimilar steels.

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Introduction

When designing piping systems for various industrial facilities, materials which satisfy optimal performance are preferred. The general design condition in this type of application is durability, corrosion resistance and mechanical property. In addition to materials' property, productivity, economy and sustainability are considered during design a process. Stainless steel is generally used for corrosion resistance, and carbon steel is used for structural application. Carbon steels are not good candidates for corrosive environment. Joint of dissimilar metals are inevitable if piping system composed of different steel types based on design criteria and environmental condition. The joints are generally manufactured by welding. Either arc welding process or friction welding processes are used in welding pipes. Compared to the weld between same materials, the dissimilar metal weld of carbon and stainless steels can cause weld defects and corrosion due to difference in stress, diffusion of carbon and other elements, and weld imperfections. Optimization of welding conditions and preferring proper filler materials based on the metallurgical fundamentals are important to prevent weld defects and corrosion for sound welds in dissimilar steels [1].

The weld metal composition generally alters through the weld, especially in multilayer welding. So, an elemental composition gradient is formed in multipass welding. Inhomogeneous dilution and composition gradient affect solidification condition. This is important for hot cracking.

Factors which is responsible from failure of dissimilar steels' welding:

- Limited solubility of two steels and brittle phase formation
- Wide range between melting temperature of the steels
- Differences in thermal expansion coefficient
- Differences in thermal conductivity

Diffusional activities between parent metals and weld metals occur at elevated temperatures. This leads to modification in microstructure. It is possible when austenitic stainless steel-based consumables are used. Chromium has a greater affinity to carbon than iron. Therefore, carbon atoms can diffuse from parent material to weld metal at above 425 °C.

Using suitable filler material is another important criterion to obtain enough physical and mechanical properties. Consumables must be compatible with parent materials, and they must be capable of being added with a minimum amount of dilution. There is a special diagram which is used to predict the microstructure of the weld metal and select possible filler metal when welding a dissimilar steel [2]. The diagram is called the Schaeffler diagram. But they are beyond the scope of this research.

Metallurgical Fundamentals

Carbon Diffusion

Atomic diffusion will always occur to decrease Gibbs free energy of the system during welding. Consider butt welding of two blocks of the same A-B solid solution together and hold at elevated temperature allow diffusion to occur. Gibbs free energy of the system given in Figure 2. G_1 is Gibbs free energy of B rich side and G_2 is Gibbs free energy of a rich side. G_3 is the initial Gibbs free energy of the system. If conditions like high enough temperature and time are satisfied system tend to allow diffusion. Final Gibbs free energy of the homogenous alloy after welding (G_4) is lower than initial energy (G_3). This case is an explanation of alloying elements tends to diffuse [3].

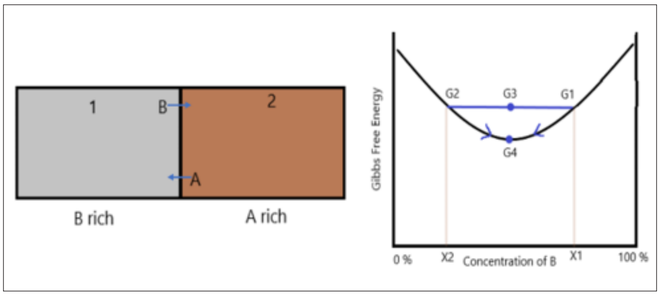

Figure 1: Free Energy Diagram for 'Downhill' Diffusion

Consider now a homogeneous solid solution of composition x made up of components A and B metals whose free energy diagram is as illustrated in Figure 2. G_3 is the initial Gibbs free energy. However, a. reduction in free energy in this case is achieved by the development of A-rich and B-rich regions. Therefore, overall free energy of the system decreases to G_4.A system is achieved to lower its free energy by increasing concentration gradient via diffusion. This phenomenon is called uphill diffusion. In This case atomic movement occurs from lower to higher concentration [3].

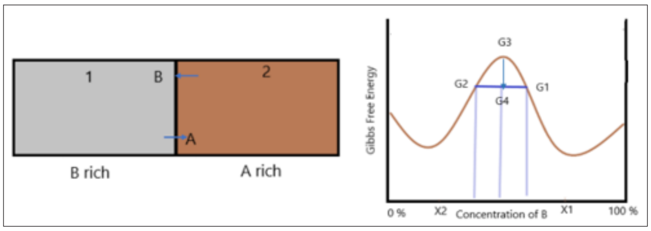

Figure 2: Free Energy Diagram for 'Uphill' Diffusion

Steels of equal or same carbon concentration but different substitution solute content like Cr and Ni, the chemical potential of carbon on each side may be different. This is related to the difference of substitution atoms' concentration. So, carbon atoms may migrate to lower concentration side via uphill diffusion. Finally, uphill diffusion causes nonhomogeneous atomic distribution in the weld [4].

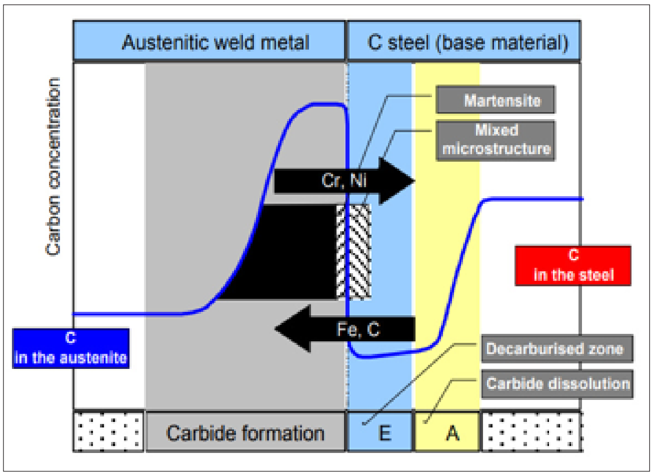

Figure 3: Model of Diffusion Process in Austenitic Stainless Steel and Carbon Steel Welding [5]

With increasing Ni content in the high alloyed steels or weld metal, the diffusion process is decelerated and accumulated short distance away from fusion line. Thus, the elements are concentrated in a narrow in austenitic weld metal (Figure 5). The results of uphill diffusion are a decarburized zone in ferritic material, and formation of wide martensite and carbide borders in the austenitic or high alloy steel. The formation of martensitic border lead to cold cracking and may cause detachment of welded joint [5].

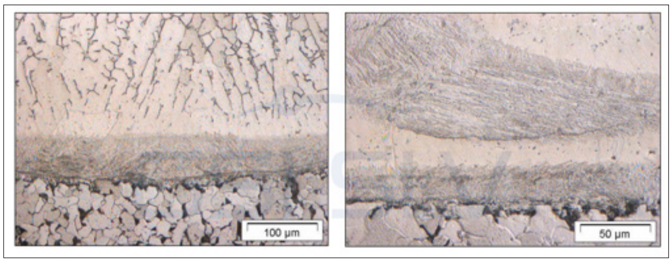

Figure 4: Martensitic border between the Ferritic-Pearlitic base metal and austenitic weld metal [5]

According to Figure 3, not only carbon but also the iron and the alloying elements try to compensate for the joining zone. But this compensation is nearly impossible in fusion welding methods like metal active gas welding. Carbon diffusion is an interstitial diffusion, and alloying element's diffusion occurs according to substitutional diffusion rules. Generally, more energy and time is needed for substitutional diffusion. Therefore, carbon movement is dominated [5].

Hot Cracking

Hot cracking is the formation of liquid phase along grain boundaries or to another place in the weld metal structure. The cracking during welding can be associated with the effect of tensile stresses on a not well-developed dendritic network in the weld metal and/or heat affected zone. The use of fully austenitic or nickel-based welding filler materials may lead to hot cracks in the weld metal, in joining zone and main metals. Hot cracking in stainless steel welds is caused by low-melting eutectics containing impurities such as S, P and alloy elements such as Ti, Nb. Solidification cracking is observed as a macro cracking, occurring at the junctions of dendrites. It can be detected by visual and liquid penetrant testing. Micro cracks in the interdendritic region may be observed at high magnifications. The increase in cracking that occurs when the solidification range is widened by the formation of low-melting eutectics with impurity element [6].

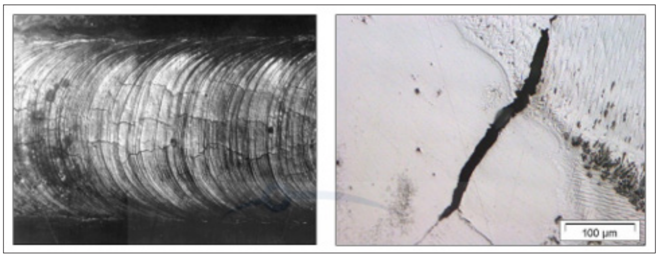

Figure 5: Hot cracks in fully austenitic weld metal cladding and welded joint between austenitic stainless steel and Nickel-based Alloy [5]

Liquidation cracks may arise in the heat affected zone (HAZ), and a coarse-grained microstructure in HAZ is very risky in terms of hot cracking. The higher alloyed base material should be exhibiting the smallest possible grain size before welding to decrease the danger of hot cracking [5]. The heat input in welding affects hot cracking behavior in welding as well. When energy density increases, hot crack susceptibility decreases. For example, energy density is higher for electron and laser beam welding compared to arc welding. On the other hand, in arc welding, welding passing strategy affects hot cracking. Instead of waving and single pass, linear multi pass more beneficial for preventing hot cracking [6].

Another solution to mitigate hot cracking is to eliminate the alloy from the weld metal during welding, particularly if there is an alloy present in the structure that can precipitate a phase with a low melting temperature. Phosphorus and sulfur are the primary elements responsible for this issue. Utilizing filler wire containing manganese during the welding process facilitates the binding of phosphorus and sulfur as manganese phosphide and manganese sulfide, consequently removing them from the weld metal [7].

Formation of Intermetallic Phases

If such materials e.g. ferritic, bainitic, martensitic steels or creep resistant pressure vessel steels like X10CrMoVNb9-1 are welded with stainless steel in mixed joints, higher alloy base material side may degenerate metallurgical. This is related to intermetallic phases which are precipitated at certain temperature range during cooling or stress relieving and tempering heat treatment. Hard and brittle sigma phase (σ), chi phase (χ) may be given as example for intermetallic phases. Materials which exhibit chromium contents over 10 % are at risk of intermetallic phases:

- Ferritic stainless steels
- Metastable austenitic stainless steels with ferrite proportion
- Austenitic-ferritic stainless steels (duplex steels)
- Nickel alloys with Ni contents under 40 %

Primarily precipitated ferrite (δ ferrite) has a tendency of embrittlement since Cr concentration is higher than mean alloying concentration. Ferrite formers such as Si and Mo accelerate the embrittlement process. On the other hand, delta ferrite proportion under 10 % may be uncritical during welding or heat treatment, above 12 % delta ferrite may lead to embrittlement phenomena. In the case of multipass welds and high heat input, cracks may form because of the welding heat and cooling process. The Ni element counteracts embrittlement thanks to its austenite forming effect.

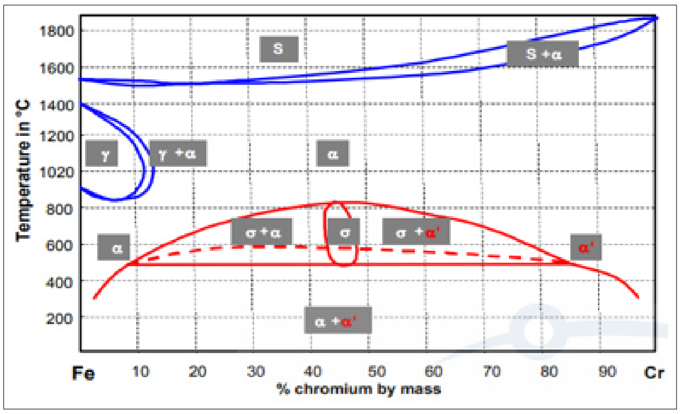

Figure 6: Binary Iron-Chromium Sytem and α' and σ Phases [5]

Ferritic phase proportion in stainless steel part of dissimilar weld has tendency to 475 °C embrittlement as well. This effect may arise in ferritic stainless steels or duplex stainless steels due to σ precipitation. Especially, weld metal which contains delta (δ) ferrite has inclination to the embrittlement phenomena. In addition, Chromium content up to 12 % and technically irrelevant annealing times in the range of 105 hours may lead to embrittlement. σ phase precipitate more with higher Cr content. Austenitic cast steel with 25 % delta ferrite ratio may already be brittle at 300 °C in long time operation [5].

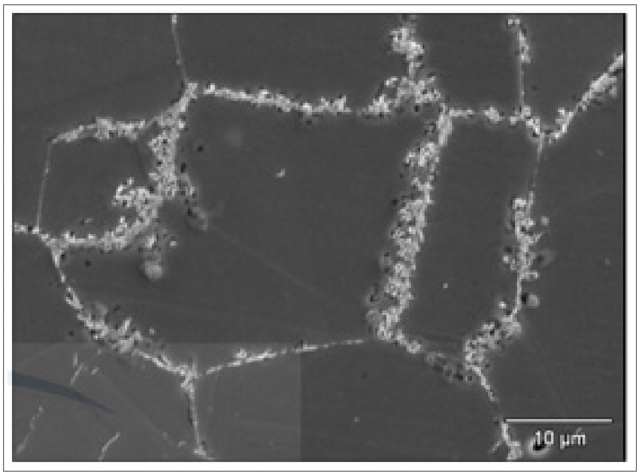

Figure 7: SEM image of σ phase precipitations (white) at the grain boundaries of a stainless steel [5]

There is another main problem in welding of low alloyed steel or carbon steel with stainless steel. Chromium in stainless steel and carbon in low alloyed steel make compound, and $Cr_{23}C_6$ precipitates are formed at 500-900 °C. This leads strength degradation of the welded joint, weld cracks and intergranular corrosion. This phenomenon is named grain boundary sensitization [1]. Chromium is the main alloying element to make stainless steel corrosion resistant. Upon $Cr_{23}C_6$ formation Cr content in stainless steel part decrease. So, stainless steel loses its corrosion resistance property, and the intergranular corrosion starts.

There are several methods to prevent sensitization problems. The first one is fast cooling at 500-900 °C temperature range. Time is needed for precipitate formation. If the cooling rate is fast enough, the probability of precipitation decreases. The second method is related to carbon concentration in main metals. Carbon is needed for $Cr_{23}C_6$ phase formation. If main materials which contain low carbon may be choose in design, $Cr_{23}C_6$ may not be precipitate easily. The third method is using stabilizing elements such as Ti, Ta and Nb. These elements are more active than Cr in terms of making compounds with carbon. So, Cr composition in stainless steel part may conserve.Finally, solution heat treatment at elevated temperature may be applied for weld which contains $Cr_{23}C_6$ precipitates.

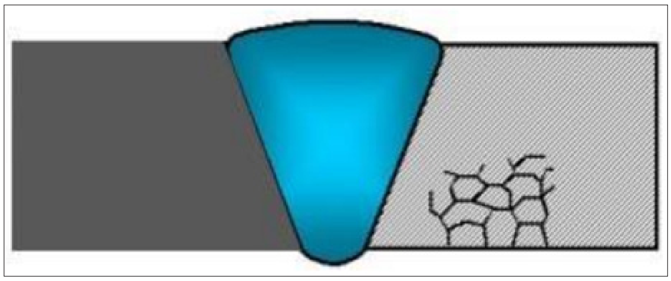

Figure 8: Schematic image of intergranular corrosion after $Cr_{23}C_6$ precipitation

Conclusion

In this paper study, carbon diffusion phenomena, hot cracking and formation of intermetallic phases are investigated. According to this review, decarburized zone in ferritic material, formation of wide martensite and carbide borders in the austenitic or high alloy steel are associated with uphill diffusion. Hot welding problem and responsible elements such as P, S and creation of low melting eutectic phase formation explained. Arc welding process and beam welding process are compared in terms of hot cracking susceptibility. So, laser beam welding is more applicable thanks to its higher energy density. Finally, formation of intermetallic phases such as α', sigma phase (σ), chi phase (χ) are explained. Precipitation of intermetallic phases are associated with suitable conditions which are elemental composition of steel and elapsed time at elevated temperature. In addition, sensitization problem in dissimilar materials welding and result is discussed in intermetallic phase's topic. Four methods to prevent $Cr_{23}C_6$ formation is discussed. As a result, precaution for preventing sensitization generally depends on controlling elemental composition of the weld and heat treatment strategy.

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