Some Metallurgical Problems in Welding

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The paper deals with various metallurgical problems associated with good welding in steel. Metallurgical background of defects like hot crack, hot tear, cold crack, weld metal and heat affected zone brittleness have been discussed from the point of view of weld metal and base metal compositions, impurities and deoxidation conditions. The role of oxygen, hydrogen and nitrogen and various inclusions, their distribution and morphology have been examined.

The quality of a weld is judged by the freedom from defects in the joint and satisfactory performance of the weldment in service. The most serious problems affecting good welding are rapid temperature variations in the base material causing various unbalanced and unstable changes in the solubility and precipitation of various alloying elements and impurities. The metallurgy of the deposited metal is influenced by a very large number of factors like condition of stress, rate of cooling, welding heat input, joint design, deoxidation and fluxing treatment arising out of various welding processes and types of electrodes used.

The complexity of the problem related to good welding being of such magnitude, an analytical approach to the fundamentals of metallurgical problems involved is necessary for the understanding of the conditions relating to good welding.

Good welding, as is well known, must satisfy the following conditions :

(1) Absence of weld metal and fusion boundary hot cracking or hot tearing.

(2) Absence of heat affected zone cold cracking and hot tearing.

(3) Toughness of the weld metal and heat affected zone to resist brittle fracture.

(4) Low susceptibility of the near heat affected zone to quench ageing and strain ageing.

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Each of these factors needs careful study to ascertain the conditions that lead to these defects and requirements to get a satisfactory weld. These are discussed below :

Hot Cracking and Hot Tearing

In a very large number of cases of structural failures, the origin of the failure can be traced to weld metal or heat affected zone cracking. Two main types of cracking namely hot and cold cracking are known to occur. The chief variety, namely hot cracking, is distinguished from cold cracking, in that the surface of the hot cracks generally has temper colour in contrast with the bright metallic surface of the cold cracks. Hot cracks generally occur during the solidification of the weld metal whereas cold cracks may occur even days or months after welding.

Another distinguishing feature is their metallurgical characteristics. Hot cracks are practically always intergranular and mostly they travel in the direction along the columnar grain growth in the weld. In carbon steels, hot crack generally passes through the ferrite network, whereas cold crack is almost invariably transgranular in nature.

Extensive investigations have been carried out to ascertain the conditions under which hot cracks in welds or near fusion boundaries, form and develop. These lead to the present day knowledge which can be summarised as follows :

During solidification of the weld metal, columnar grain grows in the direction of the heat gradient while remaining liquid becomes richer in impurities and alloying elements lowering the solidification temperature. If the compositions and freezing conditions are such that the already solidified metal exerts contractional stress on the last part of the metal which has not yet solidified fully, hot cracks in the weld metal will be found. A congenial condition for hot cracking is therefore, a metal composition which has a wide fusion range and the liquid should also be present over a relatively wide temperature interval in a distribution that will allow high stress to be built up between the grains[1].

This would explain the reason for the deleterious effect of sulphur and phosphorus in weld metal. It is well known that sulphur in steel forms a low melting eutectic that segregates in the micro-structure and provides a path of low rupture strength. Two particular compounds of sulphur in steel have low melting points. These are FeS and NiS which remain molten long after the surrounding metal has solidified and penetrate in the interdendritic space of solidified weld metal. This problem has long been recognized and it has also been known that sulphur forms compounds with manganese and chromium which are more favourable from the point of view that these compounds have a much higher melting point, 1620°C for MnS, compared to 1180°C for FeS and 920°C for NiS. Further unlike FeS, MnS does not dissolve in molten steel to extend the freezing range[2]. To tie up one part of sulphur, 1.71 parts of manganese are required. In weld metal, however, 5 to 50 parts are used for low alloy steel. This high level is desirable to prevent formation of a Fe, Mn, S complex which also enhances hot cracking susceptibility.

There are other elements, as well, which form low melting compounds, with many constituent elements of steel like Mn, Cu and Ni. These also segregate on cooling and finally exist as inter-crystalline liquid films even after all metal crystals have formed. The problem is particularly important in higher carbon weld metals in which the relative effect of sulphur and phosphorous is much greater than at lower carbon levels. Silicon appears to aid sulphur in hot cracking influences; so if sulphur is very low, silicon content need not be restricted to a very low level.

Hot cracking due to presence of low melting eutectic is not restricted to the weld metal only but is also found in the HAZ of the base metal in another form known as hot tearing. In the base metal HAZ area adjacent to weld metal, which reaches the temperature range of the solidus, the sulphide inclusions may form eutectic liquid or semi-liquid non-metallic film at the grain boundary, reducing the fracture toughness at the area. Manganese sulphide inclusion forms such films in prior austenite grain boundaries above 1300°C[3]. The imposed stress then may cause microcracking at that area as, under such conditions, very small thermal stresses can separate the grains.

The other possibility of hot crack formation is through intergranular breakdown taking place at a temperature below solidus point when the weld is a single phase solid solution with little microchemical heterogenity but well defined physical heterogenity, that is, with local accumulation of crystal lattice defect.[4] Under these conditions, the brittle failure in welds is primarily due to accumulation of lattice defects and therefore akin to other forms of intergranular breakdowns taking place at high temperatures in solid state, for instance, during creep.

Another metallurgical parameter of interest in relation to propensity to hot cracking is grain size of both weld metal and parent metal. As grain size increases, the amount of grain boundary per unit volume decreases and consequently the impurities which segregate to grain boundaries will be present with greater concentration in grain boundaries. Hence coarse grained weld metal or base metal are likely to display greater susceptibility to hot cracking.

Apart from the effect of metallurgical micro constituents in steel in influencing hot cracking, other metallurgical factors influencing the toughness of the weld metal and the HAZ need analysis for the purpose of control. Large columnar grains are known to possess little toughness. Microstructure depends on cooling condition [7]for a specific composition. Composition is an equally important factor. Further, nature and distribution of impurities influence the toughness to a great extent, and depend on chemical reaction taking place in the molten metal (as determined by nature of electrode coating and shielding). These will be discussed again later in[7]the text.

Cold Cracking

Cold cracking occurs at fairly low temperatures and are characterised by clean untinted fracture surface. These cracks are in general intragranular. In contrast to hot cracking, cold cracking may not form immediately after welding but might be delayed for hours and even weeks and months after the welding operation. Though the main cause for cold cracking can be attributed to a single reason—the presence of hydrogen—usually a combination of conditions creates a situation under which the metal in the particular area fails. Other pertinent conditions lending support to hydrogen are considered to be hardening and production of metallurgical transformational structures which are inherently brittle and imposition of residual stresses arising out of fabrication.

The susceptibility of the structure to cold cracking would depend on its susceptibility to hydrogen embrittlement. If the microstructure developed in the heat affected zone provides a crack susceptible matrix over which an additional factor like effect of hydrogen can operate, the result will be destructive. Since martensite is such a structure which has got low ductility and is crack susceptible, such microstructure promotes cold cracking. It has also been found that when twinned martensite is present, the result is still worse.[5] In structures which contain bainite colonies, the behaviour is intermediate between plain martensite and twinned martensite structure. Formation of twinned martensite structure is again depending on the carbon content and the amount of alloying element present. As the carbon content goes up, the martensite formed increases in hardness and decreases in ductility. Therefore, improved strength and weldability should be obtained by reducing the carbon level and obtaining strength by other means. Over and above the hardening of the heat affected zone, the weld metal may also transform to martensite depending on the cooling rate and weld metal composition.

The cracking propensity of the hardened structures does not, however, always correlate well with their hardness and ductility. Some work carried out show that different metallurgical microstructures vary in their sensitivity to hydrogen embrittlement and this factor over-shadows the influence of hardness and ductility upon cracking tendency. From the point of view of hydrogen sensitivity, it has been found that ferrite and pearlite structure is least sensitive, next comes bainite structure then martensitic and finally martensite with internal twinning.[6] Tempered martensite, however, is superior to bainite of similar composition.

It is generally true that the hydrogen level is generally higher in the weld metal than in the heat affected zone. However, it is not known what are the various levels of hydrogen acceptable in the heat affected zones of various susceptible microstructures without cracking.

Other constituents found in steel seem to have also effect on the hydrogen sensitivity for cracking of heat affected zone. It has been found that steel with extremely low sulphur can be exceptionally sensitive to hydrogen induced heat affected zone cracking and an inverse relationship between sulphur content and flaking tendency has been established for basic open-hearth steel[7]. For such steel, it has also been reported that hydrogen content of even less than 2 ml. per hundred gram of metal makes it sensitive to flaking. The possible cause for this might be found in the following explanation. The fact that sulphur is the most potent void producer of the commonly occurring impurities has to be taken into account. Sulphur combines with manganese in stoichiometric ratio of 1.71 : 1 manganese/sulphur. From it, it can be calculated that .01% of sulphur produces manganese sulphide inclusions of the order of .053% by volume. As the coefficient of expansion of manganese sulphide is greater than that of iron matrix[8], in cooling from high temperature, shrinkage cavities can form between MnS/metal interface. This is in contrast to the behaviour of oxides and silicates which have lower coefficient of expansion, than steel. The voids produced in the manganese sulphide/metal interface can hold some amount of the hydrogen in the metal ; in addition, manganese sulphide occludes also some quantity of hydrogen. As such, extremely low content of sulphur in the steel therefore results in low occlusion capacity for hydrogen. The balance of the hydrogen content contributes towards cracking. These explain why extremely low sulphur content of a steel makes it more susceptible to hydrogen cracking.

Fracture Toughness

Another problem involved with steel welding is the control of the toughness of the weld metal and the heat affected zone. Factors which affect the toughness of steel are well-known and the same factors are involved in affecting the toughness of the weld metal as well. Columnar grains, bigger grain size, large amount of non-metallic inclusions and their adverse distribution, formation of low melting films around the grains all affect toughness of the weld metal as well as the heat affected zone. If weld metal is not properly deoxidised the deoxidation product may produce a film along the grain boundaries and also produce extensive porosity. The ideal state of deoxidation would produce globular non-metallic particles distributing throughout the grains and under such conditions the presence of non-metallics or oxides does not affect the toughness to a great extent.

On the other hand, if oxides and sulphides are not fully absorbed by the deoxidation products and appear as films of grain boundaries, their effect on fracture toughness is serious.

Experimental work has provided some correlation between constituents of deoxidation products and their capacity to absorb sulphur. It was found for CO_2 welding of mild steel that good fracture toughness resulted when the weld metal was deoxidised with manganese and silicon. In such a case, a large amount of manganese silicate is formed which can scavenge off sulphur. But when the weld metal is deoxidized with manganese, silicon and aluminium, there were hot cracks in the weld metal and non-metallic segregates rich in sulphur. Among the three deoxidants, aluminium takes up the oxygen in preference to manganese and silicon and composite spherical inclusions of Al_2O_3, MnO and SiO_2 which are rich in alumina result. Capacity of these inclusions to scavenge the sulphur has been found to be much less, about 1/10th of that of manganese silicate.[9] As a result, sulphur induced hot cracks result in such welds.

Effect of Gases

Depending on the condition of deoxidation of steel, oxygen may be bound up as oxides of iron, silicon and aluminium. Oxygen is not harmful as iron oxide and does not spread between grain interfaces but tends to form globular shapes. Further, iron oxide having a certain solubility for iron sulphide tends to reduce cracking caused by sulphur. If, however, oxygen in form of iron oxide interacts with a third element (e.g. Si) to form a phase or compound which has a much reduced solubility for the harmful element, it is rendered ineffective. (Pronounced effect of silicon on hot cracking of weld metal during solidification can therefore be explained in terms of upsetting oxygen balance and thereby allowing formation of films like sulphides). Though manganese, like silicon, is also a deoxidizer, it is less potent than silicon. It also tends to form $(MnFe)_S$ which has a higher melting point and lower spreadability between iron grains (larger dihedral angle) than FeS. Hence manganese does not render oxygen level in steel less effective in reducing hot cracking as silicon does. It therefore appears that it is not the oxygen content itself which is important but the quantity, manner and distribution in which oxides exist. Thus deoxidation practice plays an important role in hot cracking.

Nitrogen in weld metal or the base metal has much greater influence. High nitrogen content results in the incidence of fissures and cracking in weld deposits. Weld deposits with nitrogen level of the order of .007% or less is known to produce no fissure cracks with even high hydrogen content[10]. Susceptibility to porosity of the weld metal also increases with increasing nitrogen content. The nitrogen plays a very deleterious role in the base material at a zone close to the HAZ. It has been found that at the zone slightly away from the heat affected zone which attains a temperature of about 700°C during welding of steel, hardening and lack of ductility occurs. The maximum brittleness of this region is attributed to quench ageing and not to microstructural changes. Since it is attributed to nitrogen it is unlikely to occur in killed and aluminium treated steel. Further at greater distances from the weld, there are evidences of plastic deformation which may lead to strain ageing embrittlement, if the steel is subjected to it. This again, is considered to be caused by the presence of nitrogen. Even killed steels are also subject to this embrittlement under these conditions. Both these above effects are known to be removed by heating at 600 to 650°C.

Effect of hydrogen has already been discussed in detail.

Effect of Inclusions

The role of impurities and inclusions in controlling the quality of weld have been discussed already, as they affect both hot and cold cracking, toughness and fatigue of the joint. Composition, size, shape and distribution of inclusions are important in this respect.

Silicates present in the form of stringers promote lamellar tearing in silicon killed steels. Manganese silicates in dense formation have been found to produce fissuring of hot tear type. Refractory aluminous silicates are considered to promote porosity acting as nucleation sites for gassification.[11] Alumina, when it is directly absorbed in welding pool also promotes lamination. Composite aluminous manganese silicates, by virtue of their decreased capacity to absorb sulphur promote hot crack.

The role of sulphide inclusions has already been dealt in detail.

Finally, since type and morphology of non-metallic inclusions in the weld metal depend on the reactions taking place in the weld pool during solidification, which in turn depend on the physico chemical parameters of different welding processes, any generalisation as regards the effect of steel cleanness on good welding has to be taken in a restricted sense.

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The Institute has received the following publications

Welding in the World (International Institute of Welding)	Vol. 9 1/2 1971 3/4 1971 5/6 1971
Welding Journal (American Welding Society)	January, 1971 February, 1971 March, 1971
Soudage et Techniques Connexes (in French) (Publications De La Soudure Autogene, Paris)	January-Feb. 1971 March-April, 1971
Australian Welding Journal (Australian Welding Institute)	May-June 1971
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Journal of The Association of Engineers India	October-Dec. 1970 January-March, 1971
Boiler Plant & You (BHEL High Pressure Boiler Plant, Tiruchirapalli-14)	July, 1971
Revista Soldadura (In Spanish) (Argentinian Institute of Welding)	Feb.-March 1971