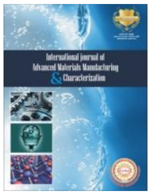

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Literature Review on Analysis of Sensitization and Corrosion of Ferritic Stainless Steel (FSS) by Different Welding Processes

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ABSTRACT

This paper deals with the review of different literature. The review focuses light on analysis of sensitization and corrosion by the different authors for controlling sensitization and corrosion in ferritic stainless steel by using different welding processes. Besides the problem of low ductility and poor toughness of ferritic stainless steel, welds due to the microstructures characteristics of the weld section as a result of weld heat input rate and heat transfer rate factor , susceptibility to intergranular corrosion caused by the depletion of the chromium content of the weld matrix particularly in the HAZ is a major concern limiting the full deployment of the material in certain engineering application regardless its attractive economics combined with moderate strength and excellent corrosion characteristics of AISI 409 M. Ferritic stainless steel during welding (TIG,MIG, and SMAW) have been investigated. Its sensitization and corrosion can be evaluated by chemical exposure of the weld cross section. Then the characteristics of sensitization and corrosion can be analyzed using scanned electron microscope. This review concluded that variation in heat input resulted in significant changes in the mechanical properties of the weld which results on the sensitization and corrosion.

Introduction

Ferritic Stainless steel:

Ferritic stainless steel are iron chromium alloys with body centered cubic crystal structure having chromium content usually in the range of 11-30 wt%. These steel exhibit good ductility, formability and moderately better yield strength to those of the austenitic grade, but the high temperature strength is somewhat poor. Ferritic stainless steel is a candidate material in less serve corrosion atmosphere for chemical processing equipments, furnace parts, storage vessels, railway wagons and household appliances. However, despite these economic and metallurgical attributes, ferritic stainless steels are less used in engineering application. This is because fusion welding of ferritic stainless steel particularly the first generation group AISI 430 is associated with many problems. These problems are grain coarsening in both fusion zone and HAZ coupled with formation of grain boundary martensite in the weld, and these result in lower ductility and toughness in the weldment. Other than these one of the problems is susceptibility to intergranular corrosion caused by the chromium content of the weld matrix.

Sensitization:

The property of stainless steel particularly the ferritic grade is comprised when thermally treated in the range greater than 900^{o}C, and as such it becomes readily prone to corrosive attack. This characterization is generally referred as sensitization. Thus, sensitization is describe as the susceptibility of Fe-Cr-C steel to intergranular corrosion when the chromium content of the surrounding matrix becomes depleted beyond the concentration necessary to maintain passivity of the steel. The depletion of the chromium content is indicated by the

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precipitation of chromium carbides on the grain boundaries as $M_{23}C_6$ or M_7C_3, producing a continuous depleted zone which is more susceptible to corrosion attack. Because of high sensitization temperature range the weld decay in ferritic stainless steel occurs close to weld metal, rather than at a distance away in case austenitic stainless steel. Furthermore lowering the carbon content is not very effective in preventing the weld decay in ferritic stainless steel. In fusion welding, this situation is approximated in the heat affected zone (HAZ). Therefore sensitization is essentially a HAZ phenomenon. in fusion welding and has been reported as a major cause of stress corrosion failure in most fusion-welded proprietary alloys.

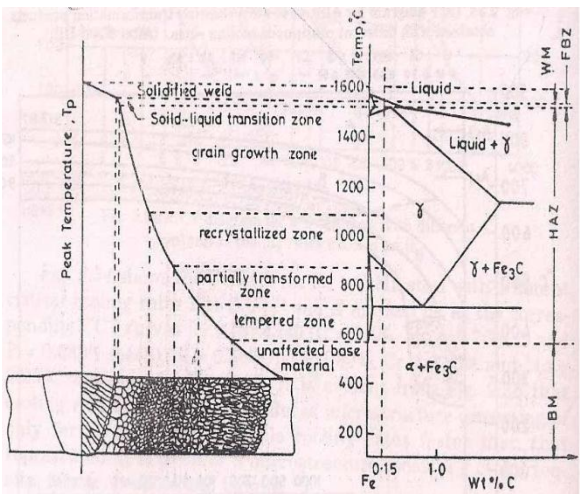


Fig: Different welding zone

Corrosion:

It is a chemical reaction of the metal with the environment to form oxide, nitride, carbonate, sulphate or other stable compound. It is the tendency of the metal to return to its most stable thermodynamic state that with the most negative free energy of formation. Corrosion can be broadly classified into two main types i) where the metal dissolve chemically ii) where the metal dissolution is electrically driven. Factors influencing the corrosion are as follows: weldment design, Fabrication technique, Welding practice, Welding sequence, oxide film and scale, weld slag and spatter, improper choice of filler metal etc. [29]

Fusion welding:

In Fusion welding, heat is provided by an electric arc struck between a carbon or metal electrode (connected to one terminal of a power supply) and metal to be welded (which is connected to the other terminal). Fusion welding used are i) Shielded Metal Arc Welding (SMAW), ii) GTAW (Gas Tungsten Arc Welding), iii) Gas Metal Arc Welding (GMAW) .This welding is used as, in all cases, the weldzone is protected from the atmosphere by a gas, slag or vacuum, which is absolutely necessary to achieve and preserve optimum corrosion resistance and mechanical properties in the joint. [27]

Literature Review

Ferritic stainless steels are designed to transform partially to austenite on cooling, passing through the dual-phase (austenite +ferrite) phase field on the Fe-Cr equilibrium phase diagram. This partial solid-state phase transformation of ferrite to austenite during cooling improves the weldability and as welded toughness of these steel by restricting heat affected zone grain growth. The alloys are supplied in the fully annealed and desensitized condition. During annealing (normally at temperature between 700^{o} and 750^{o}C), any austenite formed on cooling through the dual-phase region transforms completely to ferrite. Due to its low solubility in ferrite, the majority of the carbon precipitates as chromium rich carbides or carbonitrides during annealing, but any chromium depleted zones formed in the ferrite are healed through rapid chromium back diffusion from the grain interiors.

M.O.H. Amuda [1] investigated the effects by producing the welds on a 1.5mm thick plate of 16 wt% Cr FSS conforming to AISI 430 commercial grade , using TIG torch in argon environment at a heat flux between 1008W to 1584W and speed between 2.5mm/s and 3.5mm/s and concluded that:

i) The width of the sensitization zone increases with increasing the heat input. The depth of the sensitization zone in the thickness direction is insignificant and it is generally within one half of a millimetre.

ii) The use of heat input greater than 432J/mm increases the development of sensitized regions. This level of heat input corresponds to heat fluxes in the range 1008-1296W and welding speed between 3mm/s and 3.5mm/s. Under this condition the average cooling time is about 10s.

Du Toit M [2] investigated the susceptibility of 12% chromium type 1.4003 ferritic stainless steel to heat affected zone sensitization and intergranular stress corrosion cracking and concluded that sensitization may lead to intergranular pitting and stress corrosion cracking within the heat -affected zone on exposure to a corrosive environment. Four distinct modes were identified:

Mode 1: Sensitization of martensite within the heat-affected zone of the welds deposited on incorrectly annealed parent metal with a dual-phase ferrite-martensite microstructure.

Mode 2: Sensitization of martensite when multiple welds are deposited in such a way that the heat-affected zone of the 2nd pass overlaps the heat-affected zone of the 1st pass.

Mode 3: Sensitization of d-ferrite within the high temperature heat-affected zone during rapid cooling after welding at very low heat input levels.

Mode 4: Sensitization of austenite within the high temperature heat-affected zone during very slow cooling after welding at excessively high heat input levels.

Also he concluded that Titanium-stabilized grades of 1.4003 are generally not susceptible to Mode 1, Mode 2or Mode 4 sensitization, but may be susceptible to Mode 3 sensitization if the austenite potential is low.

M.L.Greeef [3] investigated the susceptibility of 11-12% chromium type EN 1.4003 ferritic stainless steel to sensitization during continuous cooling after welding at low heat input levels. It concluded that sensitization of type En 1.4003 ferritic stainless steel during continuous cooling after welding is possible if low heat input levels are used. Welding at low heat inputs can suppress the transformation of ferrite to austenite as the heat affected zone cools through the (austenite+ferrite) dual phase region during welding. This results in largely ferritic high-temperature heat affected zones. With an increase in heat input, the cooling rate after welding is reduced, and more austenite forms in the high-temperature heat affected zones. Sensitization is prevented by the presence of enough austenite to eliminate continuous ferrite-ferrite grain boundaries.

Bipin Kumar Srivastav,S.P. Tewari [4]studied the effect of arc welding parameters on quality of welds and concluded that several process control parameters in SAW influence bead geometry, microstructure as well as weld chemistry .Their combined effect is reflected on the mechanical properties of the weld in terms of the weld quality as well as joint performance . The selection of the suitable process parameters are the primary means by which acceptable heat affected zone properties ,optimized bead geometry and minimum residual stresses are created. The mechanical properties of the weld are influenced by the composition of the base metal and to a large extent by the weld bead geometry and shape relationship as well. It observed that with increase in electrode stick out, hardness of the weldment increases, yield strength and impact value decreases, ultimate tensile strength of the joint initially decreases but thereafter increases provided welding current and voltage arc kept at a constant level. The function of the flux ingredients such as Cao, Mgo, CaF2 and Al_2O_3 in submerged arc welding studied and concluded that among the flux ingredients, MgO appears to be important on its own in influencing the mechanical properties.

M.O.H.Amuda and S.Mridha [5] studied and analyzed the sensitization problem in ferritic stainless steel welds as well as remediation techniques. Several mechanisms have been explored to explain the dynamics of sensitization, but the chromium depletion has been only one proved experimentally. Sensitization is controlled using different initiatives ranging from control of interstitial elements (C+N) to level usually less than 0.03 wt % through ensuring higher austenite potential and use of dual stabilization involving principally Titanium and Niobium to the control of weld heat input within the range 0.5-1.5kJ/mm.

E. Bayraktar, D.Kalpan [6] analyzed the characterisation of base metal and welded parts by hardness, Erichsen and impact tensile tests (ITT) of Ferritic Stainless steel based on the TIG and observed that the transition temperature and deep drawability can be used for evaluating of the welding conditions and also of the material characteristics.

C.J.Van Niekerk, M.Toit [7] tested two plates of 2 and 4 mm for sensitization characteristics of AISI 409 titanium stabilized ferritic stainless steel during low heat input welding and concluded that for a plate thickness of 2mm, sensitization occurs for heat input of 0.1 to above 0.25 kJ/mm, and for 4mm plate thickness in the 0.2 to 0.9 kJ/mm heat input range. Due to faster cooling rate of thicker sections the 4mm s5teel experienced sensitization over a much larger heat input range than the 2mm steel. TiN is stable at temperature below 1500oC, therefore there is a decrease in the availability of Ti to form TiC and increased $M_{23}C_6$ precipitation.

K.Shamugam, A.K. Lakshminarayan and V. Balasubramania [8]studied the effect of filler metals such as austenitic stainless steel, ferritc stainless steel and duplex stainless steel on tensile and impact properties of the ferritic stainless steel conforming to AISI 409M grade and concluded that the joints fabricated by duplex stainless steel filler metal showed higher tensile strength and hardness compared to the joints fabricated by austenitic and FSS filler metals. Joints fabricated by austenitic stainless steel filler metals exhibited higher ductility and impact toughness compared with the joints fabricated by ferritic stainless steel filler metals.

E. Bayraktar, D. Katundi [9]conducted testing on a special crash test device in different temperature and the simulated crash test were performed at a constant speed of 5.52m/s and concluded that according to the testing temperature, fracture mode varies. At a low temperature, brittle fracture occurs while at a high temperature ductile fracture occurs.

Eslam Ranjbamode [10]studied the microstructural characteristics of tungsten inert gas (TIG) welded AISI 409 ferritic stainless steel and effect of the welding parameters on grain size local mis-orientation and low angle grain boundaries was investigated. It concluded that the welding plastic strain is an increasing factor for local misorientation and low angle grain boundaries. It shows that the final state of strain is the result of the competition between welding plastic strains and stress relieving from recrystallization.

hmed Khalid Hussain [11**]** studied the influence of welding speed on tensile strength on welded joints in GTAW process of aluminium alloys. Experiments were conducted on specimen of single V butt joint having different bevel angles and bevel heights. The experimental results show that depth of penetration of weld bead decreases with increase in a bevel height. The tensile strength increased with lower weld speed and decreasing heat input rate. It was also found that bevel angle of the weld joint has profound effect on the tensile strength.

E.TABAN [12] investigated the microstructural and toughness properties and mechanical properties of the gas metal arc welded 6 mm thick modified X2CrNi12 SS with two different heat input and concluded that the grain size has dominant effect on impact toughness. Grain coarsening has no adverse influence either on tensile properties or on a bend properties but the heat affected zone impact toughness for sub-zero temperature generally decreases and this depends on the amount of grain coarsened microstructure and eventual precipitates present.

J. Rawlings [13] investigate the effect of service temperature on the mechanical properties of several ferritic P/M stainless steel grades including 410L.409 Cb and concluded that the elevated temperature tensile properties of these ferritic P/M alloys were excellent and in most cases actually exceeded results published for wrought materials.

Reza Atefi [14] tested different chemical composition in order to highlight the influence of stabilizing elements on microstructure as the existing filler wires leads to oxidation problem and / or thermal fatigue strength that drastically reduces assembly lifetime and revealed the major influence of titanium on the grain refinement in the molten zone. A minimum Ti content 0.45 wt% in filler wire is required to be efficient as a grain refiner.

Yunan Prawoto [15] evaluated the corrosion rates and pitting morphology of the selected duplex stainless steel and found that decreasing pH increases the corrosion rate. Similarly, increasing temperature increases corrosion rates this can be achieved well using different solutions with different temperature and periods of immersion.

M.O.H Amuda and S. Mridha [16] reports the microstructural features of FSS welds produced under different heat input rates along with the governing parameters of welding like travel speed, welding current and material properties and investigated that irrespective of the welding condition, the primary solidification structure changed from a predominentely ferritic structure to a matrix interspersed with increasing fraction of inter dendritic martensite in the weld metal grain boundary martensite in the heat affected zone. This implies that below the critical welding current value, the mechanical properties of ferritic steel weld might be influenced by both welding current and speed.

M. Aksoy [17] studied the influence of strong carbide forming elements such as Mo,Ti,V,Nb and homogenization on the adhesive wear resistance on the ferritic stainless steel (18 wt.% Cr). The wear behaviour of the homogenized and unhomogenized samples was investigated in a block-on-ring apparatus under the loads of 40, 60, and 80 N respectively and the best result has been found that from the samples containing V and Mo. In addition the samples which consist of $M_{23}C_6$ carbides in their microstructure without carbide forming elements, gave good wear resistance under the load of 40N.

V. Balasubramanian [18] investigated the effect of welding processes such as shielded metal arc welding, gas metal arc welding and gas tungsten arc welding on tensile and impact properties of the ferritic stainless steel conforming to AISI 409M grade on a rolled plates of 4 mm thickness which was used as the base material for preparing single pass butt welded joints and concluded that gas tungsten arc welded joints of ferritic stainless steel have superior tensile and impact properties compared with shielded metal arc and gas metal arc welded joints and this is mainly due to the presence of finer grains in fusion zone and heat affected zone.

A.K. Lakshminarayan ,K. Shanmugam [19] evaluated the tensile and impact properties, microhardness , microstructure, and fracture surface morphology of continuous current gas tungsten arc welding (CCGTAW), pulsed current gas tungsten arc welding (PCGTAW), and plasma arc welding (PAW) joints and investigated that the PAW joints of fss steel shows superior tensile and impact properties when compared with CCGTAW and PCGTAW joints and this is mainly due to lower heat input, finer fusion zone grain diameter, and higher fusion zone hardness.

D.C.Oliver [20] investigates the relative exterior corrosion resistance of three alloys- two ferritic stainless steel (AISI Types 409 and 441) and an aluminized mild steel; concluded that the De-icingsalts have a clearly detrimental effect on corrosion resistance and stated that primary external corrosion mechanism causingfailure at the cold end of the exhaust system in the presence of de-icing salts is pitting. The higher chromium type 441 alloy was far more resistant than type 409.

K. Shamugam [21] evaluated the effect of filler metals such as austenitic stainless steel, ferritic stainless steel and duplex stainless steel on fatigue crack growth behaviour of the gas tungsten arc welded ferritic stainless steel joints and found that the fatigue crack initiation behaviour, fatigue crack propagation behaviour and fatigue life of ferritic stainless steel joints fabricated using duplex stainless steel filler metal are superior compared to the joints fabricated using austenitic stainless steel and ferritic stainless steel filler metals.

Emel Taban [22] investigated the hybrid (plasma + gas tungsten arc) welding properties of 12 mm thick modified 12% Cr ferritic stainless steel complying with EN 1.4003 and UNS S41003 steels with a carbon content of 0.01% to improve the weldability and concluded that i) Sound joints of modified 12 Cr ferritic stainless steel could be obtained by means of hybrid welding since tensile and bend testing exhibited satisfactorily results. ii) In microstructural examination, some grain coarsening was determined mainly at the HTHAZ and fused metal at the root weld metal produced by plasma arc welding without filler metal. iii) Coarse ferrite grains do not have any adverse effect on tensile nor on bend properties but they lead to relatively low impact toughness only for sub-zero temperature depending on the amount of grain coarsened microstructures.

A.M.Mayer [23] discuss the possibility the diffusion from the weld metal can increase the carbon or nitrogen content of the heat affected zone consequently stabilize grain boundary austenite and concluded that ferrite grain growth in the heat-affected zones of welds in 3CR12 has a detrimental effect on impact properties of the welded joint. Ferrite grain growth can be inhibited by increasing the amount of grain boundary austenite in the heat-affected zone at high temperatures. Increasing carbon or nitrogen contents in the heat-affected zone should act to stabilize grain boundary austenite. Consequently, a decrease in ferrite grain growth should be observed in the heat affected zone of 3CR12 welds. A decrease in the ferrite grain size occurs in the heat-affected zones of welds in 3CR12 if the carbon or nitrogen content of the weld metal is increased.

Martin Nicholas, Van Warmelo [24] investigated the subject of sensitization in unstabilized ferritic /martenistic dual phase 11-14% Cr steel in some detail after a number of failures in service due to accelerated corrosion and concluded that sensitization could occur due to a number of different mechanisms which were dependant on the heat treatment, no of thermal cycles and phases present in the material. All the detected modes of sensitization could be prevented by stabilisation with titanium or niobium and suitable design of the material composition to produce a suitably high ferrite factor.

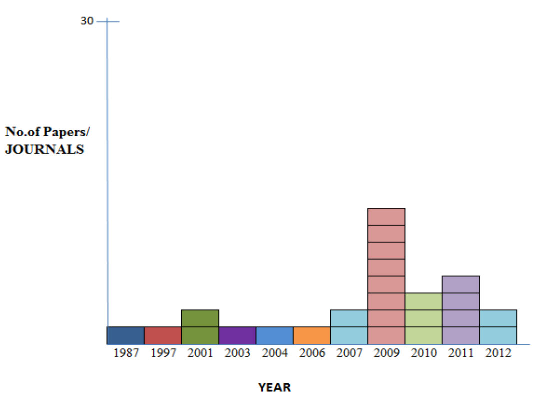
Hiroshi Area [25] studied the carbide precipitation and susceptibility to intergranular corrosion in ferritic stainless steel. The carbide precipitation at the grain boundaries was calculated by using the local equilibrium model and conclusions made that the cause of corrosion depends on whether the austenitic phase is created or not in the steel at the time of welding.

J. Pekkarinen [26] focused to determine empirically, which microstructural changes occur in ferritic and duplex stainless steel when heat input is controlled by welding parameters. They concluded that microstructure of ferritic stainless steel grade 1.4003 is fully martensitic in all welding parameters combination used. Hardness of martensite structure is dependent on heat input, increasing heat input decreasing the hardness. In duplex stainless steels microstructure is very much dependent on cooling rate. Ferrite content is decreasing with increasing heat input and the microstructure is however dependant also on composition and therefore the suitable welding parameters must be adjusted for each steel grade separately.

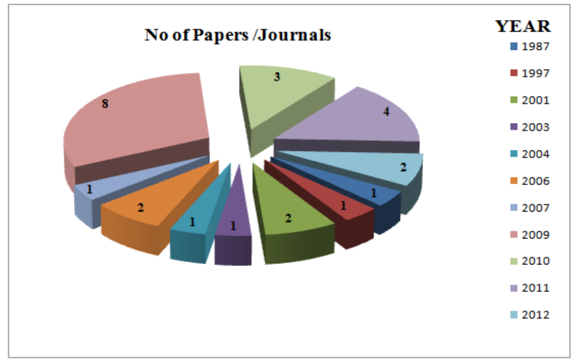
Conclusions

- Excessive welding speed can exacerbate sensitization during low heat input welding.
- Welding conditions that promotes the formation of martensite in the HAZ can be ideal for the prevention of sensitization.
- Sensitization can be controlled using i) Control of interstitial elements ;ii) Control of ferrite factor ;iii) With the use of stabilisation techniques ; iv) Control of weld heat input and cooling rate.
- Corrosion can be minimize by several methods such as i) Material and welding consumable selection, ii) Surface preparation; iii) Welding design ; iv)Welding practice v)Passivation treatment.
- Variation in heat input resulted in significant changes in the mechanical properties of the weld.
- Gas tungsten arc welded joints of ferritic stainless steel have superior tensile and impact properties compared with shielded metal arc and gas metal arc welded joints.

Analysis Of Literature Review



Graph: Numbers of papers/journals published in a year



Pie Chart: Number of papers/ journals published in year.

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