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A review on critical aspects of 316ln austenitic stainless steel weldability

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Abstract: Austenitic stainless steels are widely used for different applications in chemical, petrochemical, fertilizer, food processing and nuclear industries. These steels posses good weldability but suffer from the problems like sensitization leading to inter-granular corrosion, hot cracking or micro fissuring and stress corrosion cracking. Nitrogen alloyed austenitic stainless steels designated as 316LN contain low carbon due to which the risk of sensitization can be reduced. These steels are alloyed with nitrogen to compensate for the loss of strength due to decreased carbon content. Welding process like Tungsten Arc welding (TIG), Activated Tungsten Arc welding (A-TIG) and Multi Pass Tungsten Arc welding (MP-TIG) have been used for the fabrication of industrial components. This paper addresses the laser welding aspects, which may be of considerable interest because it offers several advantages over other welding processes.

Keywords: Austenitic Stainless Steel, Sensitization, Nitrogen, Laser Welding, Hot Cracking

1. Introduction

Laser Beam welding (LBW) process, shown in Fig 1, is a fusion joining process that produces coalescence of materials with the heat, obtained from a concentrated beam of coherent, monochromatic light impinging on the joint to be welded.

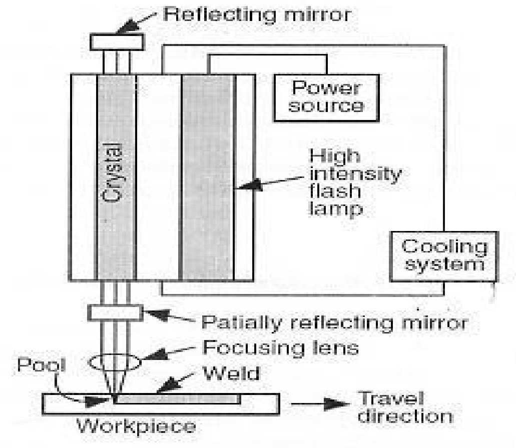


Figure 1. *Laser Beam Welding (LBW) process(1).*

In the LBW process, the laser beam is directed by flat optical elements, such as mirrors, and then focused to a small spot (for high power density) at the work piece using either reflective focusing elements or lenses.

LBW is a no contact process, and thus requires that no pressure be applied. Inert gas is generally employed, as shielding, to prevent oxidation of the molten puddle and filler metal may occasionally be used.

The laser predominantly being used for industrial material processing and welding tasks are the 1.0 µm YAG laser and the 10.6µm CO_2 laser, with the active element most commonly employed in these two varieties of lasers being the Neodymium (Nd) ion and the CO_2 molecule respectively.

The LBW process is enlisted, along with Electron Beam Welding. (EBW), In the high-power welding processes. LBW incorporates its unique characteristics to provide heat input, close to the minimum required, to fuse the weld metal; thus, metallurgical effects in the heat affected zone are reduced and heat-induced work piece distortion is minimized. In addition, single pass laser procedures have been qualified in materials of up to 32 mm thick, thus reducing the time to weld thick sections and the need for filler wire to be eliminated. Laser beams are readily focused, aligned and directed by optical elements. Thus the laser can be located at a convenient distance from the work piece and redirected around tooling and obstacles in the work piece. This permits welding in areas not easily accessible with other means of welding. In addition, the laser can be readily mechanized for automated, high-speed welding, including numerical and computer control.

LBW as a process has some limitations. Joints must be accurately positioned under the beam and at a controlled position with respect to the beam focal point. The process demands accuracy mostly in thick section, due to the fact that the weld penetration can easily miss the joint. Thus, weld penetrations of much greater than 19 mm are not considered to be practical production of LBW applications. Austenitic stainless steel can be readily welded by arc, laser beam, electron beam and friction welding processes,. The Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), Flux Cored Arc Welding (FCAW), and Gas Tungsten Arc Welding (GTAW) processes are the most commonly used, while plasma and submerged arc welding are also suitable joining methods. Sound welds can be produced by the use of SAW techniques, but certain restrictions may need to be placed on the process. Generally, the composition of the weld metal deposited, in this process, is more difficult to control than that produced with the other arc welding processes because of the effect of arc voltage variations on element pickup from fluxes and potentially high levels of dilution.

2. Welding Aspects of Austenitic Stainless Steel

2.1. A-TIG, MP-TIG Welding

A-TIG welding process would result in a significant increase in weld penetration in austenitic stainless steels and overcomes penetration variability as a result of chemical composition differences between heats of material. It would also result in reduced heat input reduction in distortion, reduction in cost, improved productivity and overall improved quality. Use of activated flux has also been found to improve the mechanical properties of the welds compared to conventional TIG welds.

The flux in the form of powders is made into a paste by mixing with acetone and the paste is applied on the surface to be welded by means of brush. The acetone evaporates within seconds leaving a layer of flux on the surface. The A-TIG process is suitable for any position welding. By employing A-TIG process, overall welding costs can be reduced upto 50%. These economics in fabrication costs can be achieved through. (a). Reduction in bevel preparation requirements. (b). Decease in number of weld passes. (c). Shortening of welding times. (d). Reduced consumption of welding filler wire. (e). Reduced distortion. Typical applications include pipes and tubes in nuclear industry, Fabrication of pressure vessels and tube to tube sheets in heat exchangers in the power and chemical industries, hydraulic cylinders and undercarriage legs in aerospace industry.

In general, the TIG welding process with and without filler metal are used to join this class of materials. However, the most constraints of TIG welding of stainless steel lie in the limited thickness of the material which can be welded in a single pass, poor tolerance to chemical composition of the deposited weld metal leading to the formation of undesirable phases and the low productivity of joining, In this process, weld penetration achievable in single pass welding of stainless steel (SS) is limited to 3mm when using argon as shielding gas. The penetration capability of the one in TIG welding can be significantly increased by application of a flux coating containing certain inorganic compounds on the joint surface prior to welding (2,3) . This enables to joint plates of higher thickness without introducing filler material to increase the productivity at low cost.

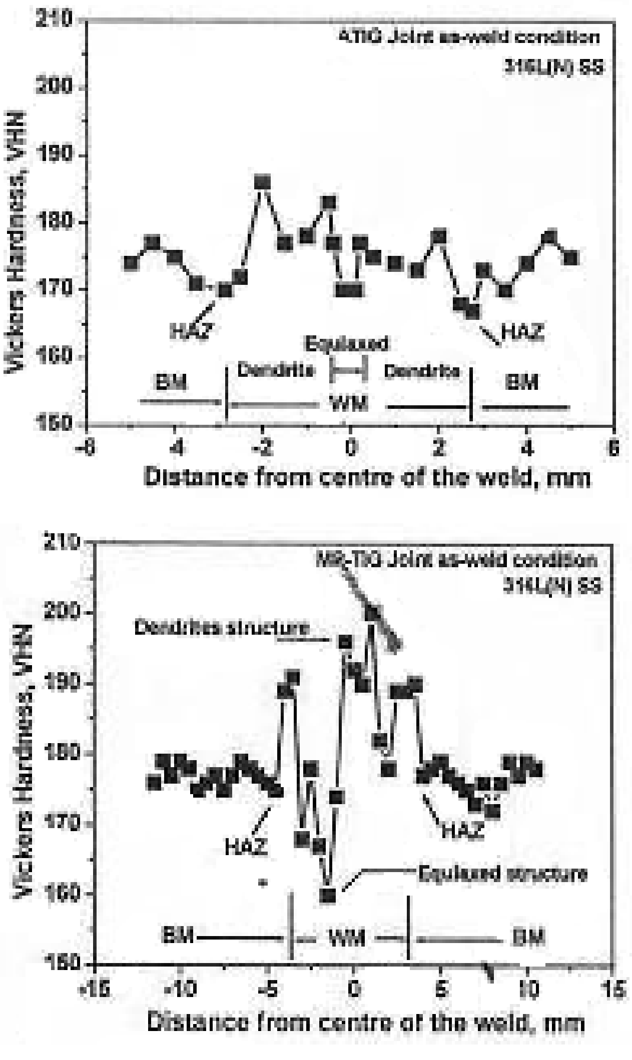
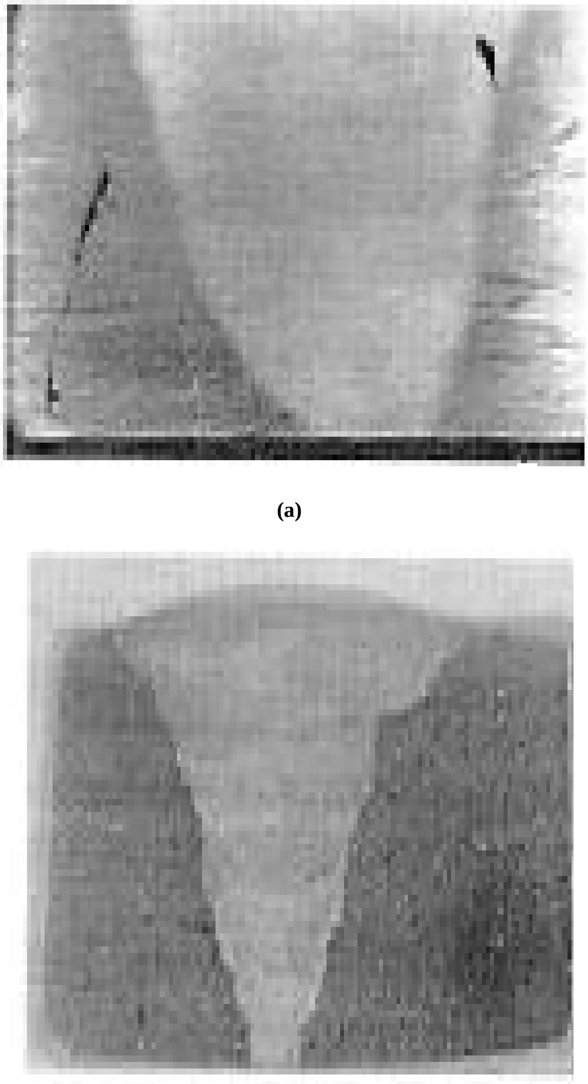


Figure 2. *Variation of hardness with distance from weld centre for (a) A-TIG and (b) MP-TIG joint.*

The variation of hardness with distance from weld centre for (a) A-TIG and (b) MP-TIG joint has been shown in Figure 2.0 It is seen from the above figure that the hardness variation was found to depend on microstructure. The equiaxed weld metal posses lower hardness than the dendritic weld metal.

This is due to the fact that the Coarse grain HAZ in the A-TIG joint displayed lower hardness than that in the MP-TIG joint. Relatively more uniform hardness was observed in the A-TIG Joint than in the MP-TIG Joint. A-TIG shows the weld-cross sections of the A-TIG ad multipass welds on 316LN stainless steel. A_TIG weld was made in singlepass while the multipass weld was made with 11 passes Fig 3.



(a)

(b)

Figure 3. *Cross section of the 316 LN stainless steel weld (12mm thick) produced by (a) A-TIG Welding (b) MP-TIG welding (11process).*

2.2. Creep Rupture Properties and Creep Damage

The variations of rupture life with applied stress for the base metal and the weld joints at 923K are shown in Fig.4

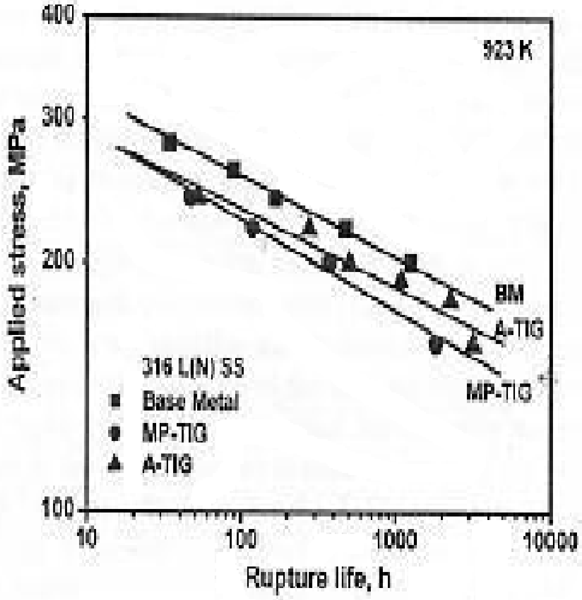


Figure 4. *variation of creep rupture life with stress for BM and A-TIG, MP-TIG weld joints.*

The variation obeyed a power low relation as observed in the relation between creep rate and applied stress. Both the weld joints possessed lower creep rupture life than the base metal Fig 5.

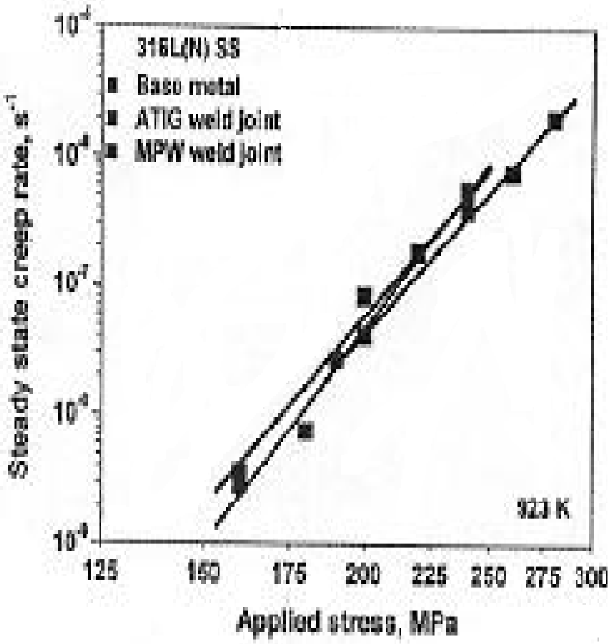


Figure 5. *Variation of steady state creep rate with applied stress at 923K.*

The A-TIG joint had higher rupture life than the MP-TIG joint. The difference in rupture strength between base metal and weld metal was found to increase with creep exposure in the case of MP-TIG joint; where as it decreased in the case of A-TIG joint. Both the weld joints had lower creep rupture ductility than the base metal and A-TIG joint had higher rupture ductility than the MP-TIG joint Fig 6.

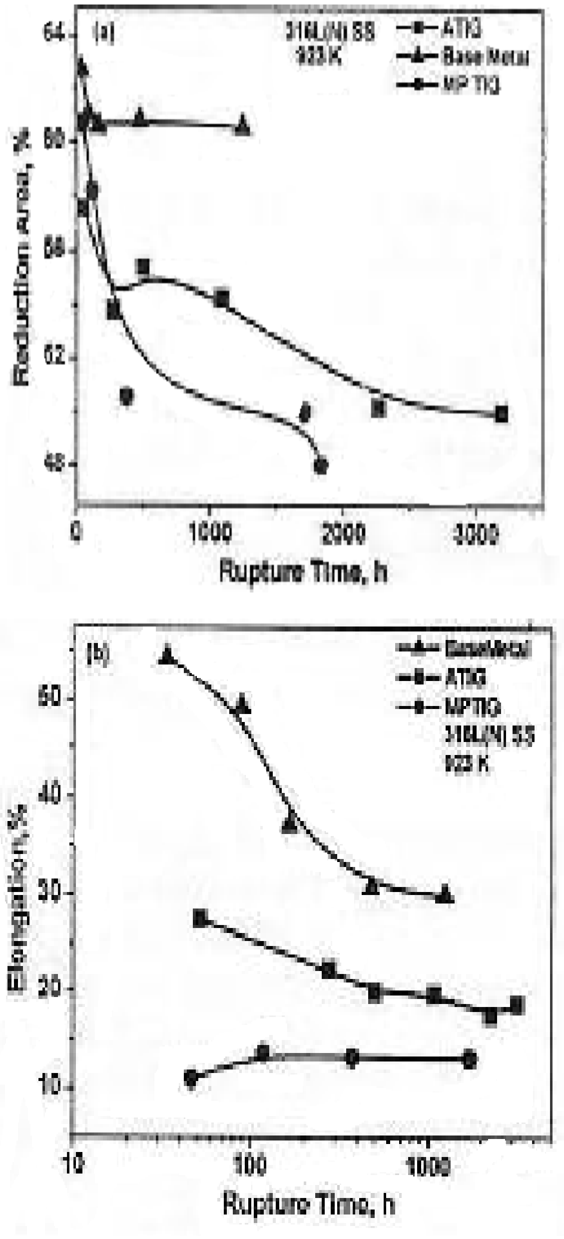


Figure 6. *Variation of (a) reduction in area (%) and (b) elongation (%) with rupture time for BM and weld joints.*

Austenitic stainless steels are generally easy to weld and do not normally require any pre heating and also post heating.

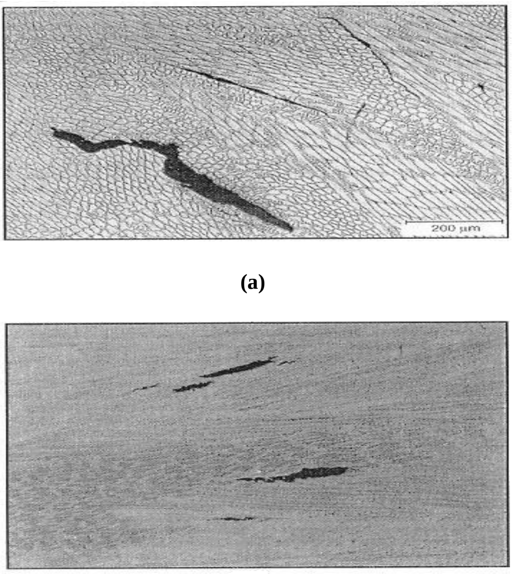
2.3. Laser Welding

Austenitic stainless steel, which is usually referred to as the 300 series is ideally suited to laser welding, Table 1.0, with the exception of grades 303 and 303Se which contain added sulphur and selenium: these elements, which aid free machining can produce hot cracking. Austenitic stainless steel has a thermal conductivity of one third of carbon steel and is a superior absorber of laser light. Consequently, slightly higher weld penetration depths can be achieved than with carbon steels for a given welding condition. Besides ease of welding, one of the reasons austenitic grades are ideally suited to laser welding is because the low heat input and high welding high speeds do not allow metallurgical damage to occur which can impair the corrosion resistance of the weld metal. If austenitic stainless steels are held for prolonged periods in the 450 to 870°C range, the chromium-rich carbides begin to precipitate at the grain boundaries and this reduces the corrosion resistance; a common occurrence when using high general heat input welding techniques. Another advantage of using a laser to weld austenitic stainless steels is the low weld distortion produced by the low general heat input and the laser weld shape. The austenitic grades have a 50% greater thermal expansion than carbon steels and coupled with a lower thermal conductivity are prone to unequal expansion and distortion when welded with high heat input arc welding techniques. Nevertheless partial penetration laser welds in thick section butt joints should be avoided because of possible weld solidification cracking, due to the unwelded portion of the joint resisting the high weld contraction stresses as the weld cools. Also the absence of oxygen or moisture entering the unwelded region of partial penetration butt joints during service. Can lead to crevice corrosion which penetrates the weld metal and causes subsequent weld failure. The austenitic stainless steels are considered the most weldable of the stainless steels. They are routinely joined by all fusion and resistance welding processes. Two important considerations for weld joints in these alloys are (1) avoidance of solidification cracking and (2) preservation of corrosion resistance of the weld and heat-affected zones. Type 316LN stainless steel often is welded autogenously. If filler metal must be used for welding Type 316LN, it is advisable to utilize the low carbon Types 316L or E318 filler metals. Contamination of the weld region with copper or zinc should be avoided, since these elements can form low melting point compounds which in turn can create weld cracking. 316LN stainless steel can be satisfactorily welded by shielded and resistance welding process. Oxyacetylene welding is not recommended, since carbon pickup in the weld may occur. Since austenitic welds do not harden on air cooling, the welds should have good toughness. When a filler metal is required, consider using a welding consumable with a matching analysis to Type 316LN or AWS E/ER 209. Both should provide welds with strength approaching that of the base metal. If high weld strength is not necessary, then consider AWS E/ER 316L. Post weld annealing is not required for most applications, but will provide optimum properties for severe service. Further aspects related to welding of 316LN are currently in progress, the results of which will be communicated during the course of time.

Table 1. *Composition of different grades of austenitic stainless steels.*

Specifications					
AISI	**C**	**Cr**	**Ni**	**Mo**	**Others**
304	0.06 max	17.5-19.0	9.0-11.0		
Typical	0.05	18.4	9.5		
304L	0.03 max	17.5-19.0	9.0-12.0		
Typical	0.02	18.4	9.3		
09	0.15 max	22.0-25.0	13.0-16.0		
Typical	0.06	23.0	14.3		
310	0.15 max	23.0-26.0	19.0-22.0		
Typical	0.10	25.0	20.0		
316	0.07 max	16.5-18.5	10.0-13.0	2.25-3.0	
Typical	0.055	17.0	11.9	2.5	
316L	0.03 max	16.5-18.5	11.0-14.0	2.25-3.0	
Typical	0.02	17.0	11.9	2.5	
347	0.08 max	17.9-19.0	9.0-12.0		Nb 10xC/ 1.00
Typical	0.06	18.5	10.0		0.75
321	0.08 max	17.0-19.0	9.0-12.0		Ti 5xC /0.7
Typical	0.05	17.6	9.4		0.4
316LN Typical	0.030	16.0-18.0	10.0-14.0	2.00-3.00	N 0.10-0.16 Mn 2.00 P 0.045 S 0.030 Si 0.75

2.4. Weld Solidification Cracking



(a)

(b)

Figure 7. *Weld solidification cracks in (a) fully austenitic weld metal (FN 0) (b) weld metal with FN 6 – FA solidification mode (8).*

Weld solidification cracking can be a formidable problem with the austenitic stainless steels. Cracking susceptibility is primarily a function of composition. Weld metals that solidify in the A mode and are fully austenitic tend to be the most susceptible, while those that solidify in the FA mode tend to be the most resistant to solidification cracking. High impurity levels, particularly sulfur and phosphorus, tend to increase the susceptibility in alloys that solidify in the A and AF mode [5,6,7]. However, the addition of other elements, such as niobium, has shown a tendency to increase the resistance to solidification cracking [4]. Examples of weld solidification cracking in alloys that solidify as primary austenite are presented in Fig.7.

Weld retrain conditions and weld shape also influence cracking susceptibility. High levels of heat input resulting in large weld beads or excessive travel speeds that promote teardrop-shaped weld pools are most problematic with respect to cracking. Concave bead shape and under filled craters a weld stops also promote solidification cracking. Weld solidification cracking is a strong function of composition, as shown by the schematic representation of cracking susceptibility versus Creq/Nieq (WRC-1992 equivalents) in Fig. 8

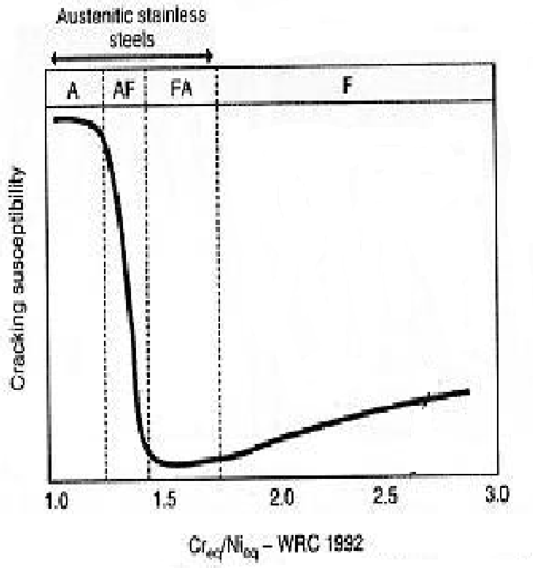


Figure 8. *Weld solidification cracking susceptibility as a function of composition.*

It can be seen, from the schematic figure, that the A and AF modes are the most susceptible to cracking that the FA and F modes, which show good resistance is solidification cracking. In fact, the F mode is more susceptible to cracking than FA, but superior to A and AF. Thus, composition can be used very effectively to control weld solidification cracking. The principal reason for the superiority of the FA mode in solidification cracking resistance is the existence of a two-phase austenite + ferrite mixture along SGBs at the end of solidification that resists wetting by liquid films and presents a tortuous boundary along which cracks must propagate [4,5,8,9]. Historically, a number of factors have been used to explain the beneficial effect of ferrite on solidification cracking resistance in austenitic stainless steels. However, some of those factors may have no significant or negligible influence on the resistance to solidification cracking.. Ferrite certainly has higher solubility for impurity elements such as sulfur and phosphorus, which restricts their partition to inter dendritic regions during primary ferrite solidification. The most important factors, however, are the nature of boundary wetting and the inherent boundary tortuosity that occurs when ferrite and austenite are both present at the end of solidification. In the FA mode, a ferrite- austenite boundary is present at the end of solidification that is both difficult for liquid films to wet and presents a very non-planar crack path. Thus, once a crack is initiated, it becomes very difficult for it to propagate along this boundary. On the other hand , both austenite-austenite (A mode) and ferrite-ferrite (F mode) boundaries are much straighter, since no secondary solidification product is present. This makes crack propagation much easier. In the AF mode, some ferrite is present along a relatively smooth A-A boundary resulting in some improvement over fully austenitic solidification. The effect of boundary tortuosity is presented in Fig.9

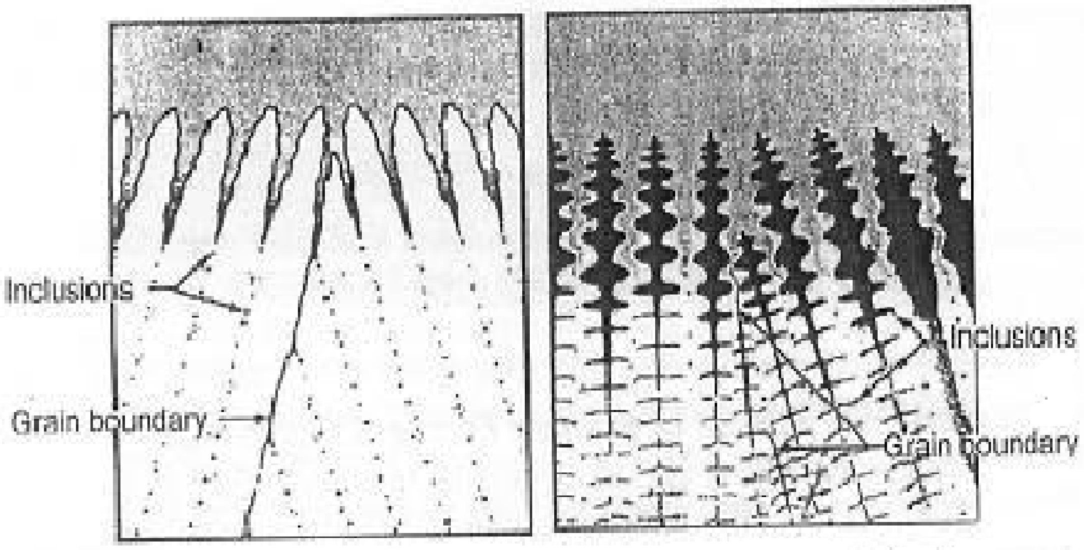


Figure 9. *Effect of solidification type on grain boundary tortuosity (a) A solidification (b) FA solidification with skeletal ferrite.*

Weld solidification cracks occur preferentially along solidification grain boundaries. Under type A solidification, this boundaries are very straight, contain no residual ferrite and offer very little resistance to crack propagation if a liquid films wets the boundary. By contrast, a Solidification Grain Boundary under type FA solidification contains a mixture of ferrite and austenite that mitigates liquid film wetting and complicates crack propagation, since the crack must follow a very non-planar austenite-ferrite interface.

2.5. Preventing Weld Solidification Cracking

Avoiding or minimizing weld solidification cracking in austenitic stainless steels is accomplished simply and most effectively by controlling the composition of base and filler metals. By assuring solidification as primary ferrite, the potential for cracking will be effectively eliminated. For most stainless steels this means that the composition should be controlled to achieve the FA solidification mode, resulting in the presence of FN 3-20 in the weld deposit. The use of constitution diagrams, such as WRC-1992, can be very help full in accomplishing the desire composition. In systems where the base and filler compositions preclude FA solidification, hence solidify as primary austenite, the potential for cracking will be much higher. The most effective way to avoid cracking in these welds is to reduce impurity content and / or minimize the weld restrain. High-purity fully austenitic weld metals can be quite resistant to weld cracking under conditions of moderated restrain. Convex bead shape and filled weld stops (craters) are also helpful. Depending on the application and / conditions, some care should be taken when prescribing a weld metal ferrite content. While the presence of ferrite levels in the range of FN 3 to 20 is almost certain to avoid solidification cracking , ferrite above FN 10 may in fact compromise mechanical properties if the weldment is to be stress-relieved of the structure put to service at either cryogenic temperatures or elevated temperatures. Service temperature in the range of 425 to 870°C can lead to embrittlement due to formation of alpha-prime (a’) or sigma (σ) phase, both of which form preferentially at the ferrite–austenite interface. For weld metals, with FN above 10, these phases can severely reduce toughness and ductility. High ferrite contents have also been shown to reduce elevated temperature stress-rupture properties. Hence, in the quest for appropriate base and filler metal, composition and moderate ferrite content is the aim to prevent solidification cracking.

3. Conclusions

The 316 Austenitic stainless steels can successfully be welded using processes such as A-TIG, MP-TIG friction welding, SAW, LBW and election beam welding. The (316LN) Austenitic stainless steel is a devel.

The welding of 316LN Austenitic stainless steels reduces considerably magnitude of residual stresses by A-TIG welding as compared to that of |M|P-TIG welding.

The 316LN Austenitic steel when subjected to laser welding, there will be problems like Gas evolution unless the welding parameters are optimized.

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