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Weldability of Steels and its Alloys under Different Conditions -A Review

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Abstract: Mechanical Properties like tensile strength, yield strength etc of various steel can be enhance by the welding process and different welding techniques are used in this study to evaluate the mechanical performance of steels. weldability of different steels are analyzed in this research paper. Two base metals (steels) are welded and analyzed for the, strengthening, hardness, microstructure etc. It was found that the shear strength of welding joints strongly depended on the welding current, welding time and kind of electrode used. As the weldability is affected by cracking therefore this paper review the basic concepts associated with hot cracking and other forms of elevated temperature cracking and describes some recent advances in the use of testing approaches to quantify susceptibility to these forms of cracking.

Keywords: Weldability, Steels, Mechanical Properties, cracking, test.

Introduction: Welding plays a significant role in the fabrication, erection and commissioning of plants and machinery for power, petroleum, chemical, steel and other industrial sectors. **Weldability**, is known as **joinability**,of a material refers to its ability to be welded. It is also refer as the capacity of a material to be welded under a specific set of fabrication and design conditions and to perform as expected during its service life. Generally speaking, weldability is considered very good for low-carbon steel (carbon level, < 0.15% by weight), good for mild steel (carbon level, 0.15 to 0.30%), fair for medium-carbon steel (carbon level, 0.30 to 0.50%), and questionable for high-carbon steel (carbon level, 0.50 to 1.00%). Because weldability normally decreases with increasing carbon content, special precautions such as preheating, controlling heat input, and post weld heat treating are normally required for steel with a carbon content reaching 0.30%. In addition to carbon content, the presence of other alloying elements will have an effect on weldability. In lieu of more accurate data, the table below **(Table 2)** can be used as a guide to determine the weldability of steel.weldability is often hard to define quantitatively, so most standards define it qualitatively. The term “weldability” has been used to describe a wide variety of characteristics when a material is subjected to welding. These include the physical and mechanical properties of the welded structure

1. Weldability

As mentioned earlier, depending on the heat input, the consumables used, restraint on the weld and the cooling rate, a weld failure which manifests as porosity, lack of fusion or cracking may occur. To understand these behaviors, it is essential to study the weldability of the materials. Weldability has been defined by the International Institute of Welding (IIW document no. IIW/IIS-22-59) as reference: 'A metallic material is considered to be weldable to a certain degree by a given process and for a given purpose when a continuous metallic connection can be obtained by welding using a suitable procedure so that the joints comply with the requirements specified both in regard to their local properties and their influence on the construction of which they form a part'. A number of weldability tests have been developed over the years to evaluate and quantify material weldability. Many of these test techniques have focused on the phenomenon known as “hot cracking”

This definition properly refers to both metallurgical and structural standpoint. Thus, any test to evaluate the weldability of a material should take into account all aspects of welding, the heating cycle, the cooling cycle, the stresses induced during solidification and fusion and also the structural variations. All these factors, individually or collectively, can cause cracking in the weldments. The weldment cracking is broadly classified into two categories: cracks which develop above the solidus of the metal are called 'super solidus cracks' and those that develop below the solidus temperature are called 'sub solidus cracks'. They are also commonly referred to as 'hot cracks' and 'cold cracks' depending on the temperature at which they develop. [18]

1.1 Weldability Assessment

The Weldability of any material/Steel Parts Depends on
1. Welding Properties of the Alloy--
Chemical Composition, Metallurgical Properties, Physical Properties
2. Design and Service Requirements--
Design, Loading Condition
3. Welding Conditions--
Preparation for Welding, Welding Operations, Post-Weld Treatments

2. Measurement of Weldability

No one is single test by which performance of welded structure can be accurately predict due to variables of restraint, fit up surface condition, service stress etc. even with these limitation weldability testing can provide useful clues as to the precautions such as preheat, joint design, appropriate selection, energy input and so forth which may be required for a reasonable degree of confidence in the resulting welded joint. There for weldability test are conducts to getting the quantitative measurement of weldability for a material or combination of materials.

2.1 Weldability Tests

Various tests are carried out to determine the weladability of materials such as theoretical test, simulated test, Visual examination, Component sampling test, Actual welding test.

2.2 Fabrication Weldability tests

These types of tests are used to determine the cracking tendency of welded joint .three types of cracking test are:-

Hot cracking test, Cold cracking test, related to cracks associated with specific fabrication conditions or structure

2.3 Service Weldability test

These types of tests are designs to determine the mechanical properties of welded joints in service. They are tensile test, Impact test, Bend test, Hardness test, Creep test, Fatigue test, Corrosion test [1]

3. Weldability of steels and alloys

Ure˜na. A., et al [2] studied Weldability of a 2205 duplex stainless steel by using plasma arc welding. For this purpose they determined the optimum welding conditions (welding intensity and travel speed) for butt joints of 2205 duplex stainless steel sheets using plasma-arc welding

(PAW). The influence of the welding parameter for each mode on the dimensions and shape of the welds and on their ferrite contents is investigated. The influence of the net input energy (H_{net}), defined as the proportion of heat input per unit of length reaching the work piece, on the penetration, shape and size of the welds was evaluated as indicated in Eq. (1).

$$H = \eta \frac{IE}{v}$$

And they conclude that Good operative weldability by PAW in 3mm thick sheet of a 2205 duplex stainless steel is achieved by welding with a net input energy in the range 2500–3200 J/cm, if the keyhole mode is used. This paper reports the determination of optimum welding conditions (welding intensity and travel speed) for butt joints of 2205 duplex stainless steel sheets using plasma-arc welding (PAW). Minimum net energy input for proper operative and metallurgical weldabilities is studied using two different welding modes: the melt-in or conduction mode and the keyhole mode. The influence of the welding parameter for each mode on the dimensions and shape of the welds and on their ferrite contents is investigated.

Serizawa.Hisashi et al [3] studied weldablity of thick F82H ferritic/martensitic steel plate to minimize the total heat input by new heat source. They studied through the serial computations of thermal elastic–plastic analyses using FEM and conclude as follows, (a) A full penetration of 32 mm thickness plate could be produced as a combination of a 12 mm deep first layer generated by a 10 kW fiber laser beam and the upper layers deposited by a plasma MIG hybrid welding with Ar + 2%O shielding gas.

(b) The appropriate and minimum size for the basic test of weldability under EB welding of 90 mm thick plate might be 200 mm in length and 400 mm in width where the welding length should be about 180 mm. **(Figure 1)**

Sharma.R.S, and Pal Molian[4] In this paper they investigated, weldability results of 1030 nm, 6 kW Yb:YAG disk laser welding of various combinations of advanced high strength steels (transformation induced plasticity steel, dual phase steel and boron steel) of 1–2 mm thickness. Weldability is expressed in terms of penetration, weld profile, weld defects, microhardness and melting efficiency. However, the higher percentage of alloying content and thermal cycle in welding, limits its weldability resulting in inferior microstructure and mechanical properties of the weld. In this paper, a study of weldability of different combinations of advanced high strength steels (AHSS) using a 6 kW Yb:YAG laser is reported. A high power laser beam produced by TRUMPF (TruDisk 6002), transported to the work location using fiber optic technology was used and they conclude that (1)Yb:YAG laser produces excellent welds without any defects such as porosity, undercut, burn through and humping. 2. Very high microhardness values were noted in some fusion zones.3. Softening in the heat affected zone was observed in DP980

Qing-cai. LIU et al [5] studied that Ni,si, based alloy typically has poor weldability due to its lower ductility. **A** limited amount of work has been performed on the weldability of Ni,si, based alloys. Therefore, the effect of heat treatment and welding parameters on weldability of the alloys and the relationship between the weldability and microstructure were studied. No research on weldability of Ni, Si-based alloys has been reported. Therefore, the weldability of a Ni, Si-based alloy was investigated using tungsten inert-gas (TIG) welding (or GTAW: gas tungsten-arc welding) with and without filler metal and they conclude that weldability of the Ni-Si-Nb-B alloy in the as-cast condition is better than that of the heat-treated materials and finally they found that cast Ni, si, based alloys could be successfully welded after preheating at 600 ^{O}C.

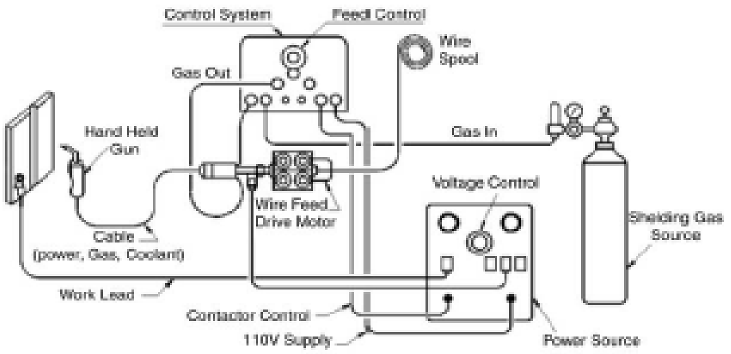


Fig 1. Schematic diagram of GMA Welding system

Mendez,J.,et al[6]studied Weldability of austenitic manganese steel. For this purpose they take Hadfield’s manganese steel, nominally Fe–1.2%C–13%Mn, is an alloy of inherent toughness, work-hardening characteristics and excellent resistance to some types of adhesive and abrasive wear. However, due to its low yield strength, it may be deformed markedly before its work-hardening become effective. In certain applications such as railroad crossings and rock-crushers, this can be a disadvantage.

During welding, precautions have to be taken to avoid overheating and the attendant carbide precipitation which may lead to subsequent early failure.

Three different electrode compositions were used to overlay-weld austenitic manganese steel cast in the form of rail heads. Two of the electrodes were obtained commercially and the third was of novel chemical composition and was produced in laboratory. Mechanical tests were then carried out to simulate the battering deformation likely to result from in-service exposure. The procedure highlighted the work-hardening characteristics and resistance to plastic flow of the weld deposit and base material, one of which consisted of the standard and they conclude that electrode containing molybdenum produced a weld overlay which showed better work-hardening, characteristics and deformation resistance than those of the other two commercial electrodes studied. The low carbon–1%V and –2%V Hadfield steel exhibited excellent resistance to deformation, but low work-hardening characteristics.

Datta.R,et al[7] studied weldability properties of SAILMA-450 HI plates employing the gas metal arc welding process and carbon dioxide gas for this purpose Implant and elastic restraint cracking tests were conducted to assess the cold cracking resistance of the weld joint under different welding conditions resistance of a steel to two basic types of weld cracking, cold and hot cracking, forms the basis of weldability assessment (Ref 13-15). Cold cracking, also referred to as hydrogen induced cracking (HIC). For study purpose a comparative analysis of weldability properties for the GMAW and the shielded metal arc welding (SMAW) processes was attempted and they conclude that at higher heat input levels good resistance to cold cracking.

Lippold.J.C.,and Kotecki.D.J.,[8] said Substituting a Ni-Cu consumable for a conventional stainless steel welding consumable, such as those based on 308L, poses several issues related to weldability. Welds deposits made with the 308L composition are resistant to solidification, liquation, and ductility-dip (DDC) cracking under most arc welding conditions since they solidify under the primary ferrite-austenite (FA) solidification mode.

Chen.Xizhang, et al [9] discusses the weldability of CMLA steel they studied that weldability of CMLA depend upon the chemical composition too. Some weldability analyses have been done based on a variety of chemical compositions. Thermal–physical simulation is a good method to analyze the weldability of new materials, especially for the weld heat affected zone and conclude that CMLA steels shows good weldability on post weld heat treatment.

Correa E.O.,et al [10] investigate the weldability of iron-based powder metal alloys (Fe–Ni, Fe–Ni–P alloys) using the pulsed gas tungsten arc welding process (GTAW) with three different filler metals (AWS R 70S-6, AWS R 309L, AWS R Fe–Ni). Results revealed that the Fe–Ni powder metal alloy does not present any metallurgical difficulty concerning the weldability for all types of filler metal studied**.** Among several factors influencing the weldability of this kind of alloys, authors outlined that a careful control of the heat input is required to avoid a higher dilution of base metal and, consequently, the occurrence of solidification cracks.

Rak.I, et al [11] studied to investigate the coarse-grained heat-affected zone (CGHAZ)
microstructure and crack tip opening displacement (CTOD) toughness of grade StE 355 Ti-microalloyed offshore steels and suggested on an increase of alloying elements generally causes a deterioration of weldability and HAZ toughness if the interrelationship between elements is not finely balanced.

Permyakov.I.L, et al [12] formulated Criteria for evaluating weldability on the basis of methods simulating welding thermal cycles and analysis of austenite polymorphic transformation kinetics in the thermally affected zone. One of the main production parameters affecting weldability is heat input, whose regulation makes it possible to form reliable fusion and the required geometric formation of joint metal and they proposed that the main weldability criterion in using the simulation method is cooling rate, which is closely connected with the amount of heat input during welding

Xiaoyun. Zhang.,et al [13] studied that how to improve weldability of dual-phase steel by adjusting electrode force during spot welding process they state that electrode force is the most important factor that affects the weldability and conclude that using high holding force (5 kN) is also good to improve weldability.

Lippold.J.C, [17] state that a number of weldability tests have been developed over the years to
Evaluate and quantify material weldability. Many of these test techniques have focused on the phenomenon known as “hot cracking” this research work is associated with hot cracking and other forms of elevated temperature cracking associated with welds and he result that the quest to quantify weldability with the goal of avoiding (or at least predicting) susceptibility to weld cracking remains elusive. This elusiveness arises from the fact that most of the cracking mechanisms are still not well understood and there are relatively few standardized tests to measure weldability. **(Figure 4a, 4b and 4c)** and **(Table 1)**

Yushchenko. K.A. and Derlomenko.V.V[18] investigated that weldability changes with change in the technology and treatment of joints and we can evaluate degradation (the index of weldability) due to the formation of hot and cold cracks in the weld and HAZ, hydrogen brittleness, corrosion cracking, etc and they provide the weldability of different materials **(Table 2)** and conclude that Weldability determines the degree of degradation of the properties of separate parts and the joint as a whole; it has to be calculated as an energy integral parameter.

Table 2. Weldability of Different Materials with Regard for Their Aggregate State in the Joint Zone

Material	**Weldability**	**Weldability (joinability) of materials with regard for their aggregate state**		
		Liquid	Solid phase	Gas-vapor phase
High-strength aluminum alloys	Limited	Good	Limited	Good
High-strength titanium alloys Good	Limited	Limited	Limited	Good
High-strength steels	Difficultly-weldable	Difficultly-weldable	Limited	Good
Nickel alloys	Non-weldable	Non-weldable	Limited	Good
Intellectual alloys	Limited	Limited	Limited	Good
Granular alloyed powder materials	Limited	Limited	Limited	Good
Amorphous and microcrystalline materials	Limited	Limited	Unexplored	Good
Nanostructural materials	Non-weldable	Non-weldable	Limited	Limited
Polymeric composite materials	Non-weldable	Non-weldable	Limited	Good
based on Al (Al + B_2 Al + SiC)	Non-weldable	Non-weldable	Non-weldable	Good
based on Ti (T_3 Al (α-phase), TiAl,T_3 Al (α-phase))	Non-weldable	Non-weldable	Good	Good
Adapted composite materials	Non-weldable	Non-weldable	Limited	Good
Metal-polymeric materials	Limited	Limited	Limited	Good

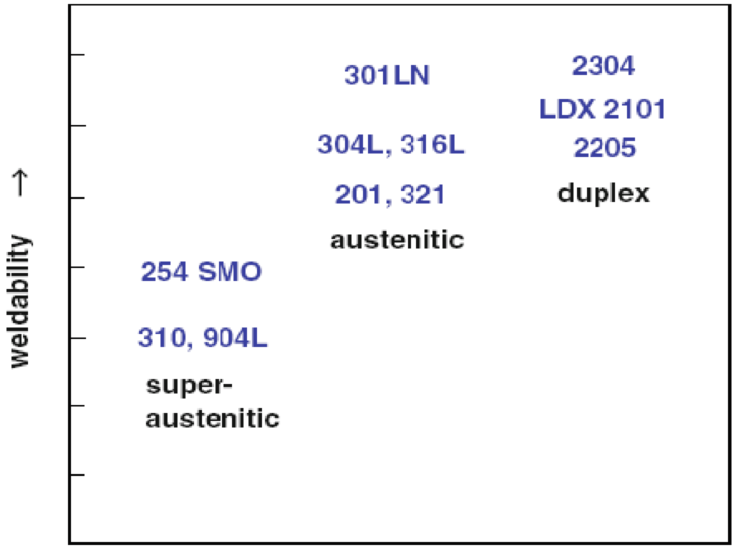
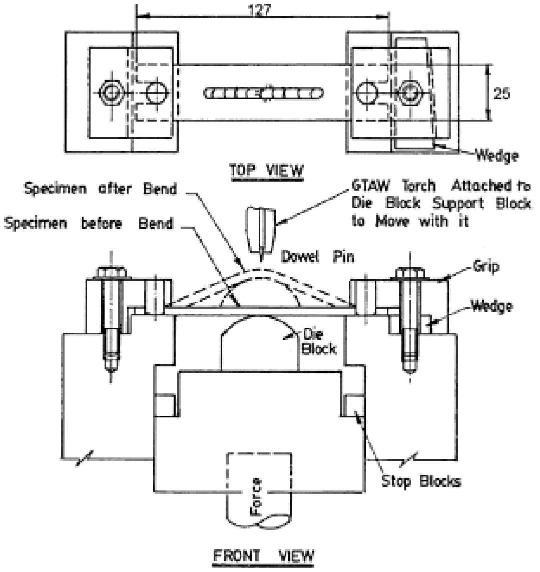


Fig.2 Comparision of weldability of Stainless Steel grade based up

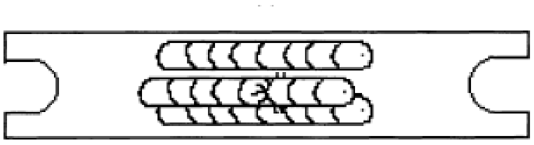
4. Methods of Weldability Tests for hot and cold cracking

Sowards.J.W.,et al [14] studied weldability of SS and evaluate the weldability of SS by performing different Weldability test. For this purpose they performed the Transvarestraint, hot ductility, and strain-to-fracture tests to assess cracking susceptibility of weld deposits to solidification, weld metal liquation, and ductility-dip cracking weldability and conclude that Cast pin tear testing revealed that increasing dilution by Type 304L increased the solidification cracking susceptibility and hot ductility of the Generation III GTA welds was higher than Generation II SMA welds and the Generation II welds and Ductility-dip cracking was observed in Transvarestraint test coupons at levels of 2–3% strain. The temperature range of cracking was estimated using an approach similar to SCTR.



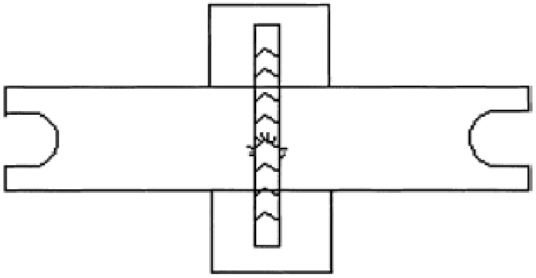
(a)

Fig 3- Schematic diagram of the Varesetraint test equioment for study of hot cracking during welding:
(a) specimen configration and test procedure;



(b)

(b) Weld orientation in the longitudial mode showing three-bead test techniuqe for fusion zone,BMHAZ,WMHAZ cracking.



(c)

(c) Weld crientation in the transvarsetraint mode.

4.1 The Transverse Varestraint Test

Chandrasekharaiah M.N[16] investigated that the weldability of the material should be established with adequate laboratory tests in order to minimise the tendency towards hot and cold cracking susceptibilities and author told that among the stainless steel austenitic stainless steel are 90% used for fabrication as they possesses good weldability. To evaluate the cold cracking susceptibility controlled thermal severity **(Figure 6)** and implant tests have been used. The demerit of this test is that the plate thickness determines both the HAZ hardening tendency as well as restraint values which cannot be varied independently. He also conduct the test to determine the solidification cracking for this purpose author performed a varestraint test and conclude that If the ductility is lowered sufficiently by the persistence of the liquid films, cracking may result longitudinal to the weld bead. Hence, during welding of carbon steels, low alloy high strength or stainless steels, adequate data on the weldability of the material including carbon equivalent, hydrogen induced cracking, solidification cracking, lamellar tearing etc. should be established.

Carl E. Cross, et al [15] found that uses the standard weldability test methods and crack evaluations for arc welding are not always suitable for laser welding from a metallurgical standpoint, alloy rankings based upon arc welds do not necessarily reflect accurately upon laser weldability. One case in point is the shift in solidification mode due to rapid solidification conditions (favoring primary austenite) when laser welding, thereby lowering weldability. Keyhole instability in laser welding is another factor that may influence cracking susceptibility and they summarized that CTW test has been applied to evaluate the laser weldability (i.e. resistance to solidification cracking) of several different grades of stainless steel, including super-austenitic, austenitic, and duplex. This test, which involves the application of transverse strain during welding, required displacement rates in the range 0–1 mm/s to generate centerline solidification cracking. Unlike most laser weldability testing of the crack-no crack type, the CTW test allows for the possibility to quantify critical conditions needed for cracking

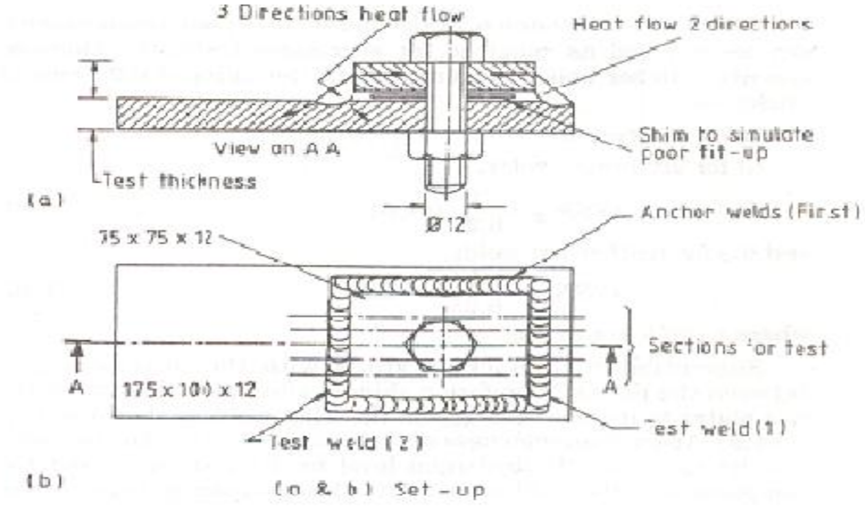


Fig.6 Controlled thermal severity test,(a and b) set up

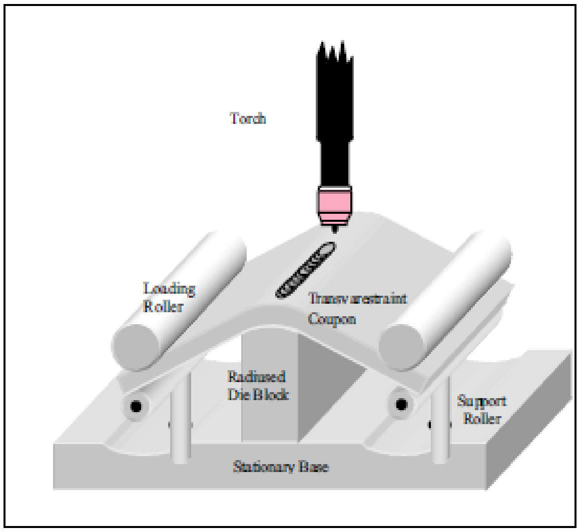


Fig.4a.Schematic of the varestraint test for evaluating weld solidification cracking susceptibility.

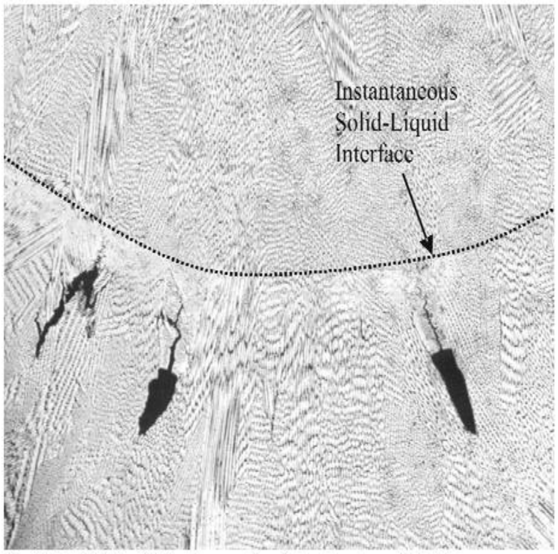


Fig.4(b) Weld Solidification on Cracking in a type 310 SS transverse Varestrint specimen

SCTR can be calculated using the following relationship, where V represents the welding velocity.

$$SCTR = [Cooling\ Rate]\times \square MCD/V]$$

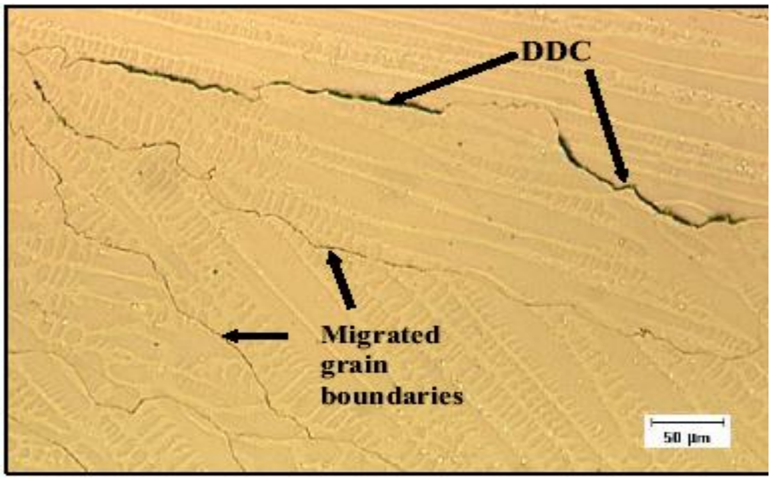


Fig.4c.Ductility-dip cracking along migrated grain boundaries in fully austenitic weld metal

4.2 Houldcroft Test for Determining the Weld Cracking Sensitivity

Talat[19] described the important factors governing weldability of steels, such as influence of alloying elements, combinations of base material and filler materials and edge preparation for welding and told that numerous tests have been developed to determine the weld cracking sensitivity of Steels and its alloys. The best-known test for sheets is the Houldcroft ("fish bone") test. This can be conducted with or without filler metals. The specimen consists of a rectangular plate with eight grooves cut to different depths on both sides (**Figure 5**).

The specimen dimensions, distance between grooves as well as groove width and depth depend on the sheet thickness. At the starting end of the weld in the middle of one side, cracks can form and grow due to the somewhat higher stress existing here. The grooves reduce the stress in steps so that the crack stops growing. The length of the crack formed is an indication of the crack sensitivity of the aluminium alloy tested.

Houldcroft Test for Determining the Weld Cracking Sensitivity

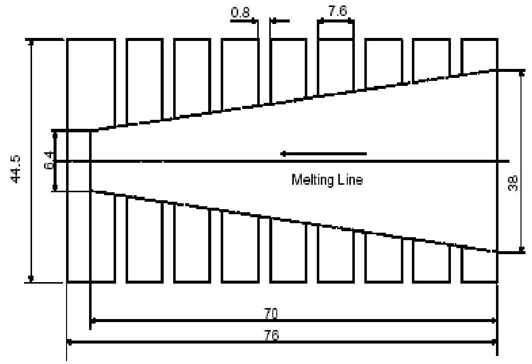


Fig.5 Houldcroft Test for determine the weld cracking sensitivity

Table 1. Solidification Cracking Temperature Range (SCTR) values determined using the Transverse Varestraint Test.

Material	SCTR (°C)
Duplex SS Alloy 2205, FN 100	26
Type 304L SS, FN 6	31
Duplex SS Alloy 2507, FN 80	45
Type 316L SS, FN 4	49
Superaustenitic SS, AL6XN	115
Ni-base Alloy 690	121
Type 310 SS	139
Ni-base Alloy 625	200
A-286	418

Shankar.V.,et al[20] they investigated that fully austenitic microstructure and the presence of titanium lead to high susceptibility to hot cracking during welding. longitudinal and transverse Varestraint (Transvarestraint) hot-cracking tests were used to evaluate fusion-zone and HAZ cracking and results showed that titanium increases cracking in the fusion zone by 15 to 20 % in the range of Ti levels. Hot cracking is considered a problem in the welding of austenitic stainless steels, particularly those that are fully austenitic and contain elements such as titanium and niobium. cracking depends on metallurgical factors such as grain size etc.The hot-cracking susceptibility of the materials was tested on a Moving Torch Varestraint Hot-Cracking Test Device Model LT1100 **(Figure 3a,3b,3c)**. Varestraint test specimens of the dimensions 125x25x3 mm were prepared with the length along the rolling direction. The tests were conducted in the longitudi-nal as well as in Transvarestraint modes and they conclude that Fusion-zone cracking was higher for Ti-bearing fully austenitic D9 alloys than for the FA-mode type 321. The variation of cracking with composition indicated that the Ti must be controlled to less than 0.3% and 3 times the (C + 0.857N) level, to ensure good weldability

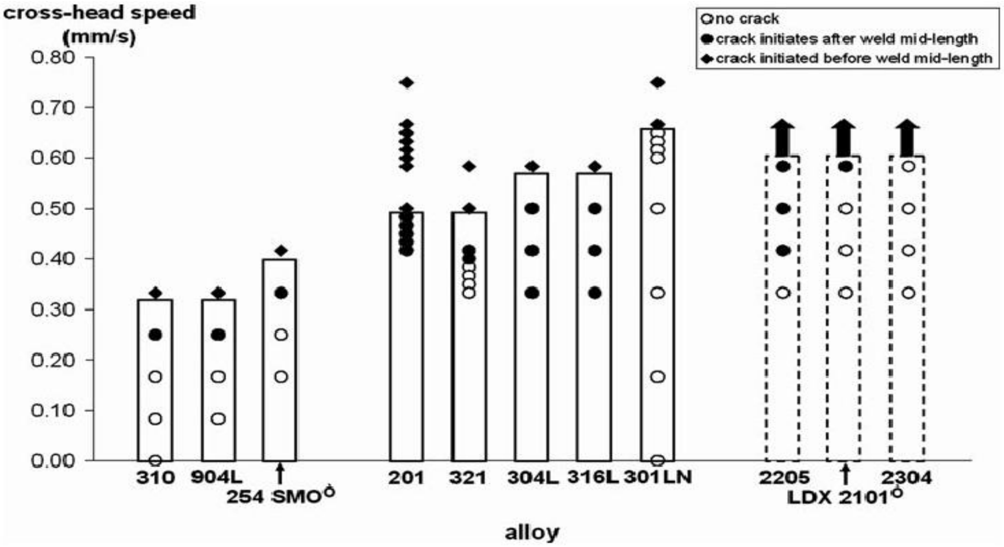


Fig. 7 Comparison of CTW test results for super-austenitic, austenitic, and duplex stainless steels showing observed solidification cracking behavior varying with applied cross-weld displacement rate (i.e. cross-head speed)

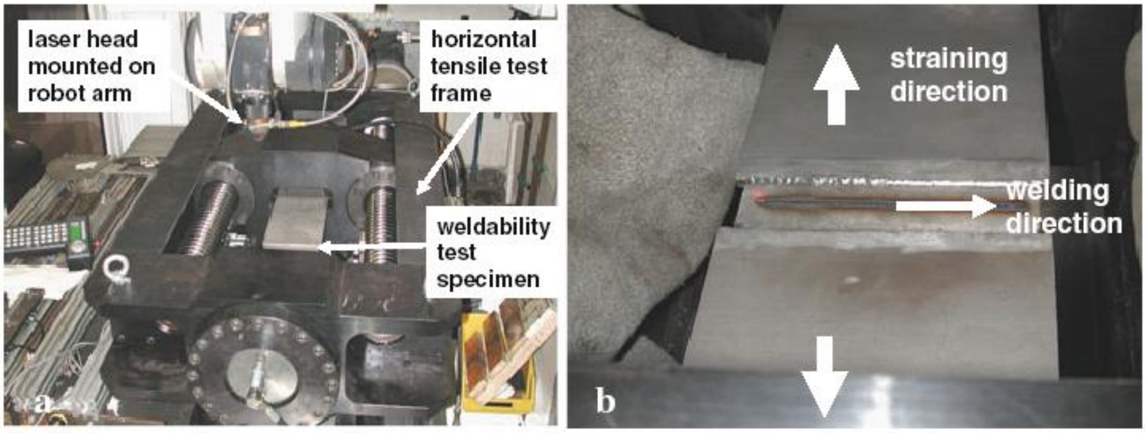


Fig.8 Controlled Tensile Weldability (CTW) test fixture showing overview of (**a**) test frame and (**b**) test specimen

5. Conclusion

The weldability of engineering materials continues to be a topic of considerable interest and relevance in the manufacturing community. The current study indicates that the hot and cold crack influence the weldability of steels and its alloys too much. The study of the previous work reviews states that a number of weldability test techniques currently exist for quantifying elevated temperature cracking susceptibility in Steels materials While these tests provide improved quantification of weld cracking susceptibility, efforts must continue to optimize and eventually standardize weldability test techniques. True quantification of material weldability will not be possible until standardization of these and other tests is achieved and tests that measures the degradation in ductility are as a function of temperature and time in the post weld heat treatment temperature range. Previous study also indicates the fact that most of the cracking mechanisms are still not well understood and there are relatively few standardized tests to measure weldability. Some researcher studied that Weldability (joinability) is a physical property of a material that should be certified. As a criterion of the weldability of a material, it is expedient to use the degree of its degradation, which can be controlled with the help of a universal energy criterion or a complex of parameters.

During the welding of carbon steels low alloy high strength or SS,adequate,data on the weldability of the material including carbon equivalent, hydrogen induced cracking, solidification cracking, lamellar tearing etc should be establish. Several testing methods are available to evaluate the cracking susptibility. Heats with excessive sulfur content may experience HAZ cracking or weld centerline cracking,especially in alloys rich in austenite stabilizers. The degree of cracking is largely dependent upon the solidification mode P and S content provide some indication of the cracking potential for a given solidification rate.

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