Use of Liquid Metal Embrittlement for Development of a Weld Spliting Technique for Sectioning Austenitic Stainless Steel Plates

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INTRODUCTION

It is well known that fusion welding process cannot be used for welding austenitic stainless steel with copper and if by any chance, copper comes into contact with stainless steel during welding operation and stresses of sufficient magnitude are present in the material, it results in the cracking of stainless steel. The reason for this cracking is attributed to the phenomenon of Liquid Metal Embrittlement (LME) which refers to the degradation in mechanical properties of some metal/alloys when they are stressed in contact with certain liquid metal environments. In other words, cracking can be induced in austenitic stainless steel (in stressed condition) by bringing it in contact with a suitable liquid metal embrittler. One of the ways to achieve this objective is by the weld deposition of embrittler. Therefore the phenomenon of liquid Metal Embrittlement appears to have the potential to be exploited for the development of a dissimilar weld splitting technique for sectioning stainless steel components, although very limited efforts have been made to tap the beneficial effects of this phenomenon. The technique has the advantage of sectioning stainless steel components without producing fines or smoke, and the disturbances to the far side of material are minimized. This technique is suitable for application in dismantling irradiated components, where production of radioactive fines during cutting are a source of major concern, and in cutting materials in areas with limited access. P.A. Titzler and C.R.Allen reported successful splitting of hexagonal duct by using both GMAW and GTAW with copper filler wire /1/. In France, this dissimilar weld splitting method has been successfully tested on three PHENIX fuel sub assemblies /2/. This paper describes the work done in authors' laboratory for the development of Weld splitting technique for sectioning austenitic stainless steel. It is for the first time that the effects of various parameters have been studied in a comprehensive manner lo optimize the efficiency of the cutting process and to understand the LME as applied to cutting technology by dissimilar weld method.

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Characteristics of Liquid Metal Embrittlement

In liquid Metal Embrittlement, a metal which normally fails by ductile fracture, drastically alters its mode of failure to a very brittle form of either transgranular or intergranular cleavage. Apart from the reduction in ductility, the tensile test stress—strain curve of the substrate remains largely unaltered, with the elastic moduli and proof strength remaining largely unaffected (Fig.1)

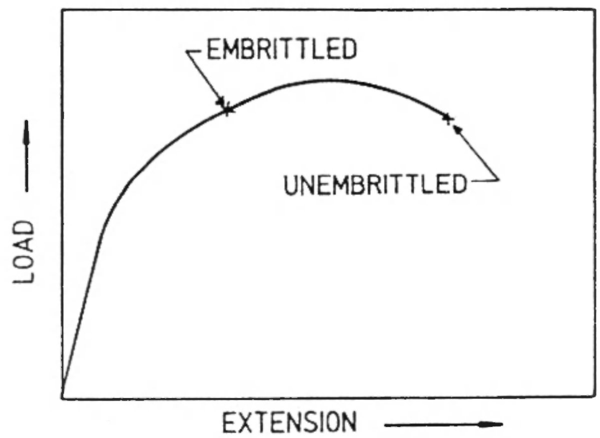

Fig. 1 . The effect of LME on the loaf Vs extension diagram (Schematic)

The phenomenon of of LME exhibits ductile to brittle and brittle to ductile transitions (Fig. 2) i.e. embrittlement is effective only over a temperature band /3/. The width and depth of ductility trough, as shown in Fig. 2, depends on metallurgical parameters and exposure conditions such as microstructure and strain rates

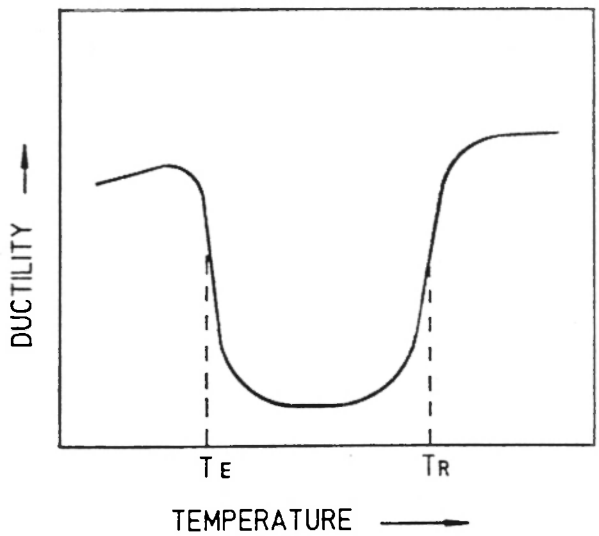

Fig. 2 : The effect of LME on the variation of Ductility with temperature (Schematic)

For many systems embrittlement occurs well below the melting point of the embrittler in which case it is termed as Solid Metal Embrittlement (SME). Severity of embrittlement is significantly effected by changes in the chemical composition of the solid as well as of the environment. The crack growth rates produced by liquid metal environment tend to be extremely fast. However some embrittlement couples show delayed failure. The interaction between embrittler and substrate is specific i.e. only some metals are embrittled by only some environments.

Prerequisites For Embrittlement

The prerequisite conditions for embrittlement to occur are :

(a) embrittler must be in direct contact with the substrate.

(b) Stressed state should be one in which either primary or secondary tensile stresses are present and

(c) temperature should be near the melting point of the embrittler.

Dissimilar Weld Splitting Model

A simplified view of the weld splitting model is presented Fig. 3. The area behind the transition point expands due to thermal heating while the area ahead of it remains relatively cool. This temperature difference gives rise to differential rate of expansion of material around the transition point thereby creating a moment around this point and pulling the material apart at the area weakened by the molten embrittler.

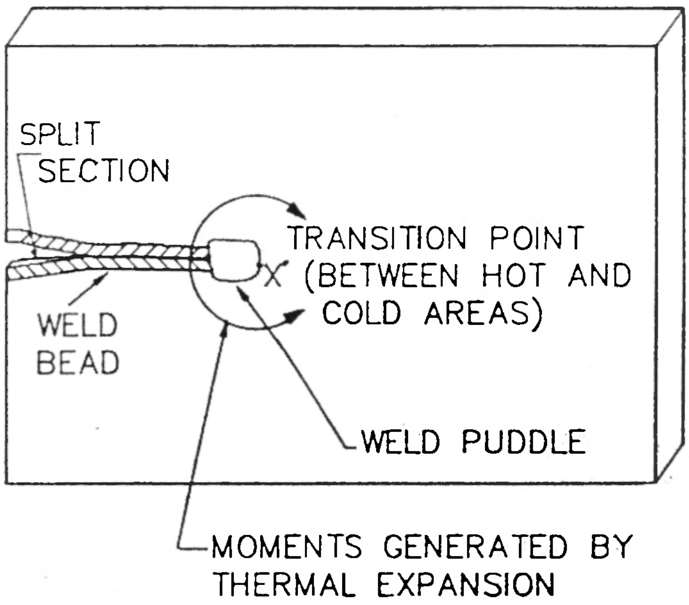

Fig. 3 : Weld Splitting Model

EXPERIMENTAL

Search For A Suitable Embrittler

Initial testing of liquid metal facilitated splitting technique was started using copper as the embrittler. This involved deposition of copper 3.24 and 1.6 mm thick AISI 304 stainless steel plates (300 X 75 mm) by Gas Tungsten Arc Welding (GTAW) process. This resulted in the development of small transverse cracks (across the length of weld bead) but no longitudinal crack (along the length of the weld bead) was noticed. Even the presence of tensile stresses in the material (produced as a result of bending the plates at 90 degree) did not result in any marked improvement. Metallographic examination revealed the presence of some underbead microcracks which could not develop into a macroscopic crack.

Consequent to the failure of copper to facilitate easy splitting of stainless steel plates, brass was used as the embrittler which greatly enhanced the severity of the embrittlement. Long longitudinal cracks were developed in 1.6 mm thick stainless steel plates (fig. 4). Chemical composition of the brass filler used in the experiment was 60 Cu/40 Zn. The details of the experiments are summarized in Table 1.

TABLE 1- SEARCH FOR A SUITABLE EMBRITTLER
Welding process used : GTAW

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
WITH COPPER AS EMBRITTLER					
X1	AISI 304	300X75X1.6	As-received	45A	A few transverse Cracks noticed
Y1(1)	AISI304	300X75X3.25	As-received	45A	-DO-
Y1(2)				60A	
X2	AISI304	300X75X1.6	Bent 90°	45A	No cracking
Y2	AISI 304	300X75X3.25	Bent at 90°	45A	-do-
WITH BRASS AS EMBRITTLER					
101A	AISI 304	300 X 75 X 1.6	As-received	45A	Long longitudinal
101B				35A	cracks developed

NATURE OF CRACKING

Metallographic examination of the specimens revealed severe intergranular attack, as shown in Fig. 5

Fig 5 : Nature of Liquid Metal Induced cracking in stainless steel.

Various zones shown in this photomicrograph are : Zone A-brass deposit, Zone B - dendritic region of the substrate which underwent fusion during welding and zone C-parent metal showing intergranularly. SEM fractographic examination of the fracture surface also showed intergranular nature of cracking (Fig. 6). Detailed study of the fracture surface was hampered by the presence of solidified brass layer on the fracture surface as can be seen in Fig. 6.

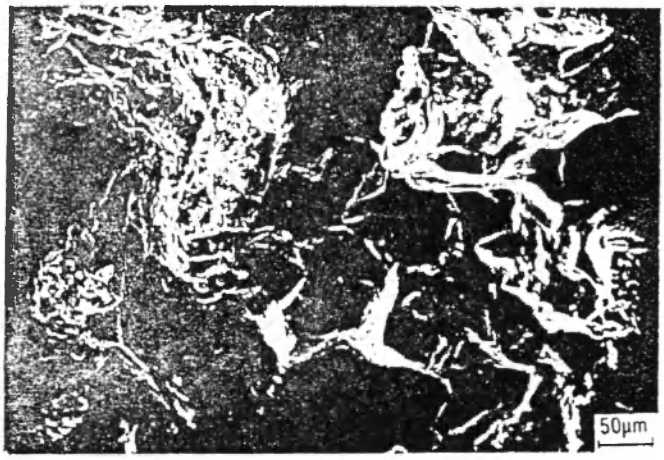

Fig. 6 : SEM Fractograph showing Intergranular nature of cracking solidified layer of brass is also viseable on the surface)

It is generally noticed that crack length on the top side of the plate (on which embrittler desposition is made) appears to be shorter than that on the bottom side of the plate. Metallographic examination of the specimen near the crack tip region shows that the cracking starts at the interface of the embrittler and substrate and propagates through the thickness of the plate, as shown in Fig. 7. Cracking of the embrittler deposit on the top surface of the plate (refer Fig. 5) was mainly due to tensile stresses that the brass deposit was subjected to as a result of cracking of the substrate. If stresses so developed are not sufficient to cause cracking in the embrittler deposit, crack would not be visible on the top surface. Moreover if weld arc is extinguished at some point during the course of weld deposition of embrittler, reinitiation of already developed LME induced crack would require additional heat input to fuse the already laid brass deposit.

Effects of Various Parameters on the Susceptibility to Cracking

Thickness of Plate

It has seen that thin plates (1.6 mm thick) were consistently sectioned while thicker plates (3.24 mm thick) were relatively more difficult to split (refer Table 2). In the latter case, the material area was too large and moment developed as a result of differential rate of expansion of material around the arc zone may not be sufficient to overcome the resisting forces of the material mass, thus necessitating either the application of external tensile/shear load or the development of larger heat affected zone by increasing the heat input) to assist in separating the material apart.

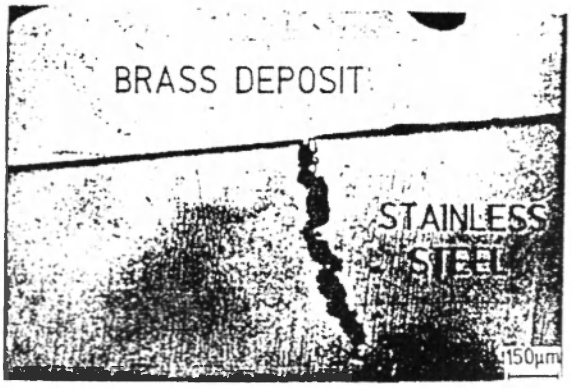

Fig. 7 : Liquid metal induced cracking of austenitic stainless steel starting from the interface of embrittler and substrate.

TABLE 2 - EFFECT OF THICKNESS
Welding process used : GTAW Embrittler : Brass

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
101A	AISI304	300X75X1.6	As-received	45A	Long Long-itu-dinal
101B				35A	Cracks dev-eloped
01	AISI304	300X75X3.25	As-received	30A	No cracking
02	AISI304	300X75X3.25	As-received	40A	No cracking
A02A	AISI316	300X75X3.25	As-received	25A	No cracking
A20B				40A	No cracking
A01A	AISI316	300X75X3.25	As-received	45A	No cracking
A01B				35A	No cracking

EFFECT OF WELD HEAT TREATMENTS

It is noticed that cracks developed in the stainless steel plates stopped after propagating some distance along the length of the weld bead in fact, these cracks stop because of limited/interrupted supply of embrittler to the crack tip. The arrested crack can be made to propagate further by restoring the supply of embrittler to the crack tip. Methods of post and pre weld heat tratments were tested to enhance the efficiency of splitting operation. Details of these experiments are presented in Table 3.

Method of post weld heat treatment involved heating of weld area by an oxy-acetylene torch (brazing torch No.2) which resulted in the opening up of the already developed crack and making it to propagate further along the length of the weld bead.

Heating of the stainless steel plate (by carburising oxy- acetylene torch) before weld deposition of embrittler greatly enhanced the splitting efficiency *(refer Fig.8). Pre weld heat treatment significantly reduces the cooling rate thereby helps in keeping the embrittler in molten condition for a longer time.

TABLE 3 - EFFECT OF WELD HEAT TREATMENTS
Welding process used : GTAW

Embrittler : Brass

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
023	AISI 304	150X45X3.25	As-received	30A	No cracking
024	AISI 304	150X45X3.25	Plate pre-heated with carbursing torch	30A	of plate length
101A	AISI 304	300X75X1.6	As-received	45A	Long longitudinal
101B				35A	cracks deve-loped. Post-weld heating by oxy-acety-lene torch (brazing torch No.2) helps these cracks to propagate further

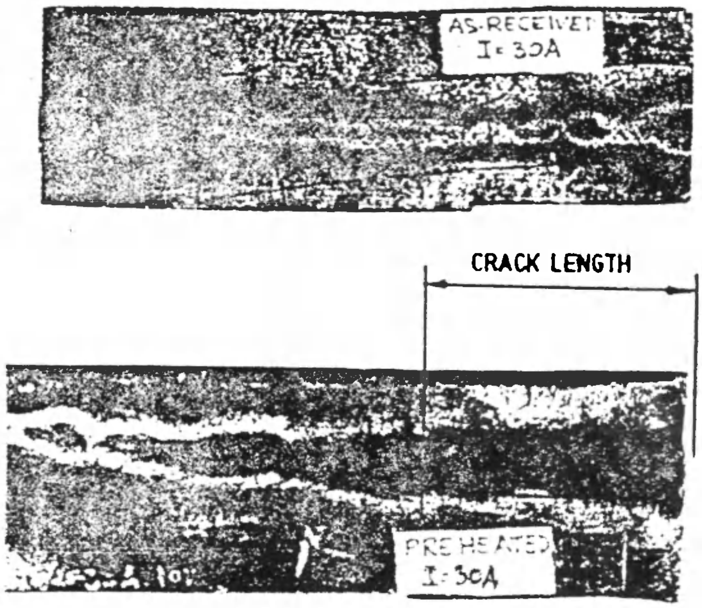

Fig. 8 : Effect of embrittler on stainless steel plates in as- received and propagated conditions.

Effect of Bending

To study the effect of tensile stress (developed as a result of bending) on the relative ease of splitting, embrittler was deposited on the convex surface of the bent stainless steel plates (as shown in Fig. 9) which facilitated easy splitting of stainless steel plates. An improvement in the ease of splitting was also noticed with the increase in degree of bending (refer Table 4). 3.24 mm thick stainless steel plate bent at 30 degree (included angle) was completely partitioned while plates bent at 60 and 90 degree had undergone only partial spliting (Fig. 10).

TABLE 4 - Effect Of Bending Welding Process Used : GTAW Embrittler : Brass

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
A02A	AISI 316	300X75X3.25	As-received	25A	No cracking
A02B				40A	No cracking
A01A	AISI 316	300X75X3.25	As received	45A	No cracking
A01B				35A	No cracking
A03	AISI 316	300X75X3.25	Bent at 90 degree	35A	Carck length =35% of plate width
A04	AISI 316	300X75X3.25	Bent at 60 degree	35A	About 90% splitting
A05	AISI 316	300X75X3.25	Bent at 30 degree	35A	Almost complete splitting
03	AISI 304	300X75X3.25	Bent at 90 degree	40A	Crack length = 60% of p late width
102	AISI 304	300X75X1.6	Bent at 90 degree	25A	Crack Length = 40% of plate width
103	AISI 304	300X75X1.6	Bent at 90 degree	40A	Almost complete splitting
104	AISI 304	300X75X1.6	Bent at 60 degree	20A	complete splitting

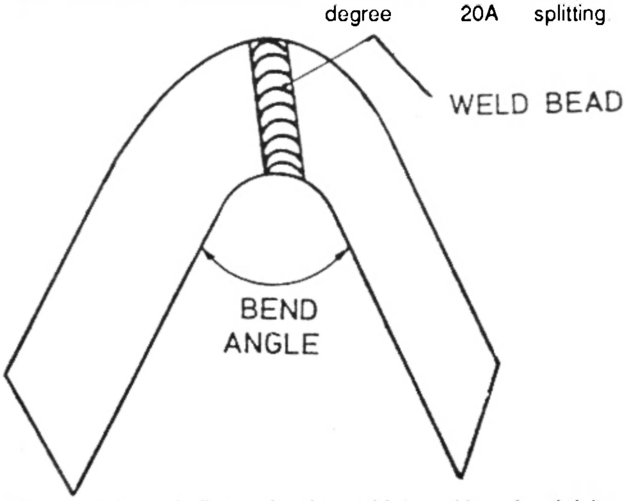

Fig. 9 . Schematic figure showing weld deposition of embrittler on the convex surface of a bent plate

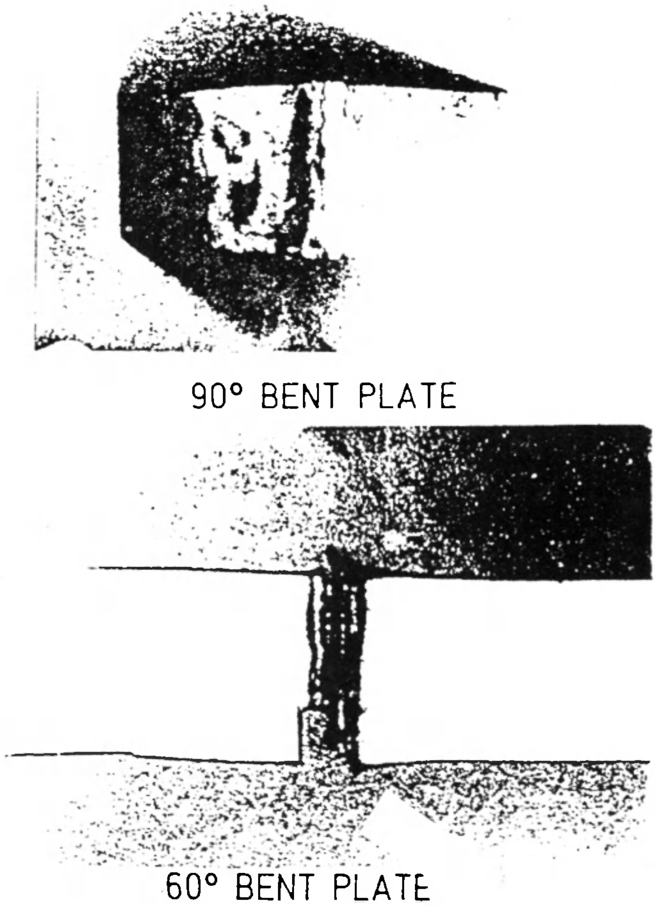

Fig. 10 : Effect of Bending of plates on the susceptibility to liquid metal induced cracking.

Effect of Cold Rolling

Susceptibility of cold rolled stainless steel plates to undergo liquid metal induced cracking was tested by the weld deposition of embrittler on the cold rolled plates. Stainless steel plates (AISI 316) of the original thickness of 3.24 mm were subjected to different degrees of cold work viz. 20%, 30%, 40% and 50% by cold rolling and the weld deposition of embrittler was made along and across the direction of rolling. Results of these tests, as presented in Table 5, clearly indicate an enhanced susceptibility of cold rolled plates to undergo liquid metal induced cracking. 50% cold rolled plate was almost completely partitioned after weld deposition along the rolling direction (Fig. 11) while plates with lesser degrees of cold work showed only partial splitting. It is to be noticed that as received plate of 3.24mm thickness did not show any macroscopic cracking with the same or even higher heat input.

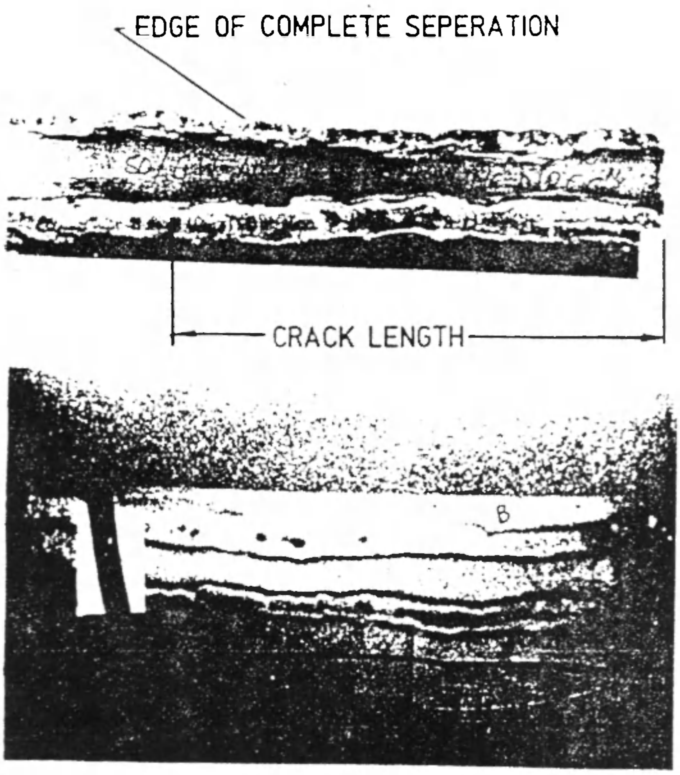

Fig. 11 & 12 : Effect of weld deposition of brass on 50% cold rolled stainless steel plates along and across the rolling direction respectively.

TABLE 5

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
ON AS-RECEIVED PLATES					
A02A	AISI316	300X75X3.25	As-received	25A	No cracking
A02B				40A	No cracking
A01A	AISI316	300X75X3.25	As-received	45A	No cracking
A01B				35A	No cracking
ON COLD ROLLED PLATES					
Case 1 : Brass deposition along the rolling direction (original plate thickness = 3.25 mm)					
A06	AISI316	300X75X2.65	About 20% cold rolled	40A	Crack Lgh. 25% of plate lgh.
A07	AISI316	300X75X2.33	About30% cold rolled	40A	Crack lgh =35% of plate lgh
A08	AISI316	300X75X1.98	About 40% cold rolled	25A	Crack lgh. =30% of plate lgh.
A09	AISI316	300x75x1.65	About 50% cold rolled	40A	Almost complete splitting
Case 2 : Brass deposition across the rolling direction (original plate thickness = 3.25 mm)					
A016	AISI316	300x75x2.69	About 20% cold rolled	40A	Small hairline cracking
A017	AISI316	300x75x2.36	About 30% cold rolled	40A	Small hairline cracking
A018	AISI316	300x75x1.93	About 40% cold rolled	40A	Small hairline cracking
A019	AISI316	300x75x1.4	About 50% cold rolled	40A	crack length =118 mm

Directions of rolling

Cold rolled stainless steel plates exhibited much less susceptibility to cracking when the embrittler deposition was made across the direction of rolling than that observed in the earlier case when the embrittler deposition was made along the direction of rolling (refer Table 5). In this case, only 50% cold rolled plate showed partial cracking (Fig. 12) while plates with lesser degree of cold work developed only hair line cracks. However, the susceptibility to cracking was still better than that found in the case of stainless plate in the as-received condition.

Effect of presence of weld in the base metal

Presence of weld in the material brings about significant microstructural changes not only in the weldment but also in the heat affected zone(HAZ). The welding process also induces large amount of residual stresses in and around the weld. The efficiency of liquid metal facilitated cutting process is likely to be affected by these welding induced changes in the material.

In the heat affected zone

The effect of microstructural changes in the HAZ of a weld on the relative ease of splitting was determined by the deposition of embrittler in the HAZ of a weld in a 3.24 mm thick stainless steel plate. HAZ facilitated easy splitting of the plate (Fig. 13) while 3.24 mm thick plate in the as-received condition did not show any cracking (refer Table 6). Relative ease of splitting in the HAZ can be attributed to grain coarsening.

TABLE 6 : EFFECT OF PRESENCE OF WELD IN THE MATERIAL

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
021	AISI304	150X45X3.25	Brass deposition on weldment	30A	No cracking
110	AISI304	200X50X1.6	- do	30A	No cracking
022	AISI304	150X45X3.25	Brass deposition in the HAZ	30A	Crack length=75% of plate length

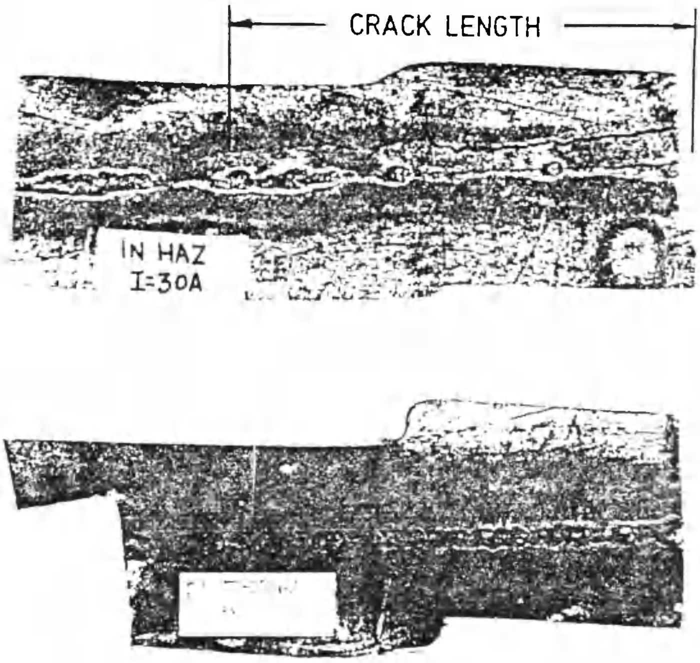

Fig 13 & 14 : Effect of weld deposition of brass on HAZ and weld.

On the weldment

Weld region is usually associated with residual stresses (tensile at the center of the weld and compressive in the HAZ) therefore expected to facilitate splitting /4/. However embrittler deposition on the weldment did not result in any macroscopic cracking (Fig. 14). Even 1.6 mm thick stainless steel plate, which were consistently sectioned in the as-received condition, did not show any cracking when embrittler deposition was made on the weldment of the plate (refer Table 6). This observation was surprising because it was expected that residual tensile stresses present in the weld bead should assist the LME process. Metallographic examination of the cross-section of this specimen revealed the presence of three zones viz, brass deposit, intermediate zone (portion of the original weldment which underwent fusion during weld deposition of embrittler and therefore contains sporadic brass islands in the stainless steel dendritic matrix) and the original weld region. Some fine cracks were observed in the intermediate zone and original dendritic zone (fig.15) while grains adjacent to the weld showed extensive intergranular penetration of brass (Fig. 16). These observations clearly indicate the superior resistance of stainless steel weldment to liquid metal induced cracking due to its entirely different microstructure. Even the residual tensile stresses are not able to induce embrittlement in this type of dendritic microstructure, where well defined grain boundaries are absent indicating the strong influence of grain boundaries on the embrittlement process.

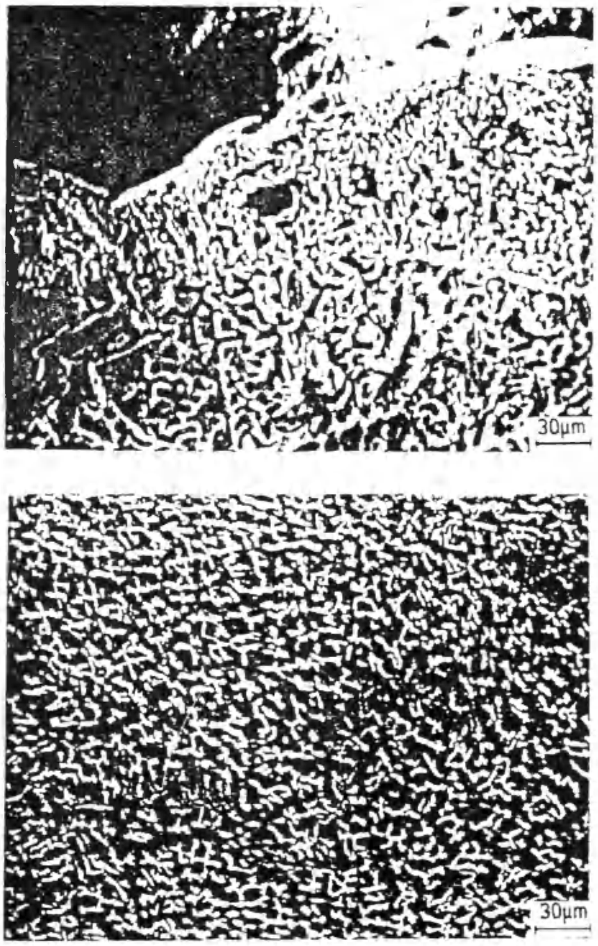

Fig. 15 : Fine discontinuous cracking in the Weldment

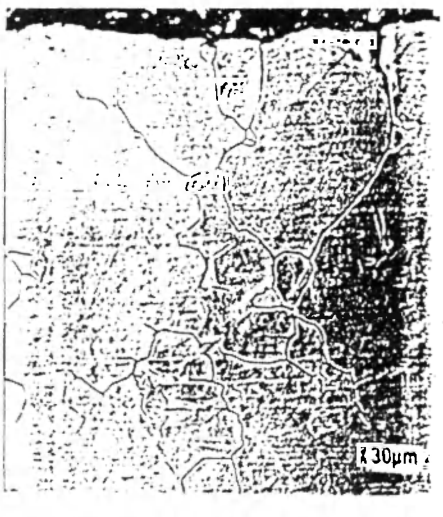

Fig. 16 : Intergranular cracking adjacent to weldment

Effect of sensitization

Since molten brass attack austenitic stainless steel in intergranular way, intergranular precipitation of chromium carbides as a result of prolonged exposure of austenitic stainless steel to the temperature regime of 773 K - 1073 K (termed as sensitization') is likely to influence the nature of embrittlement. To study the effect of sensitization on the susceptibility of material to undergo liquid metal embrittlement, weld deposition of embrittler was made on a piece of austentic stainless steel, sensitized by heat treating it at 973 K for 5 hours. Details of the experiments are summarized in Table 7. 3.24 mm thick sensitized stainless steel plate was found to be very much easier to split (Fig. 17) while a similar plate in the annealed condition did not exhibit any cracking. Metallographic examination of the specimen from this plate revealed the development of the bands of desensitized microstructure on both sides of the weld zone while regions for away from the weld which were not exposed to high temperatures, retained their original sensitized microstructure (Fig. 18). To confirm that this desensitization' effect was due to dissolution of chromium carbides during welding, one piece of sensitized stainless steel from the same plate was fused locally by passing a TIG torch over it (using same amperage). Metallographic examination of this specimen also revealed about 3 mm wide band of desensitized microstructure on both side of the fusion line.

TABLE 7 — EFFECT OF SENSATION
WELDING PROCESS USED : GTAW

Plate No.	Material	Size (mm)	Condition	Welding Current	Result
023	AISI304	150X45X3.25	As-received	30A	No cracking
025	aisi 304	150X45X3.25	Sensitized (700°C/5HR AQ)	30A	Crack length =80% of plate length

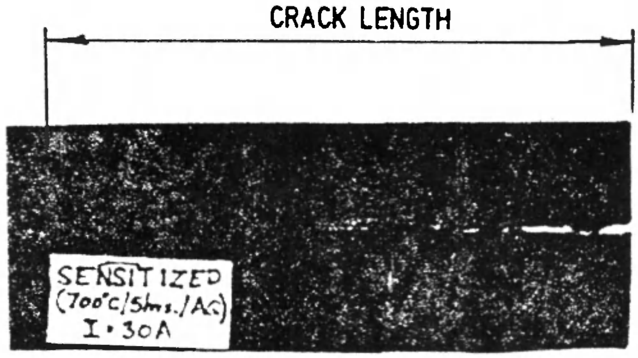

Fig. 17 : Effect of weld deposition of brass on sensitized (973K\5hours) Austenitic Stainless Steel plate.

In the desensitized band of microstructure, some isolated chromium carbide presipitates could be noticed which clearly implies that the dissolution of chromium carbide precipitates is a time and temperature dependent phenomenon and complete dissolution of carbides could not be achieved during the course of welding. From the end microstructure, it is not possible to predict the extent of desensitization of sensitized stainless steel plate at the stage it came

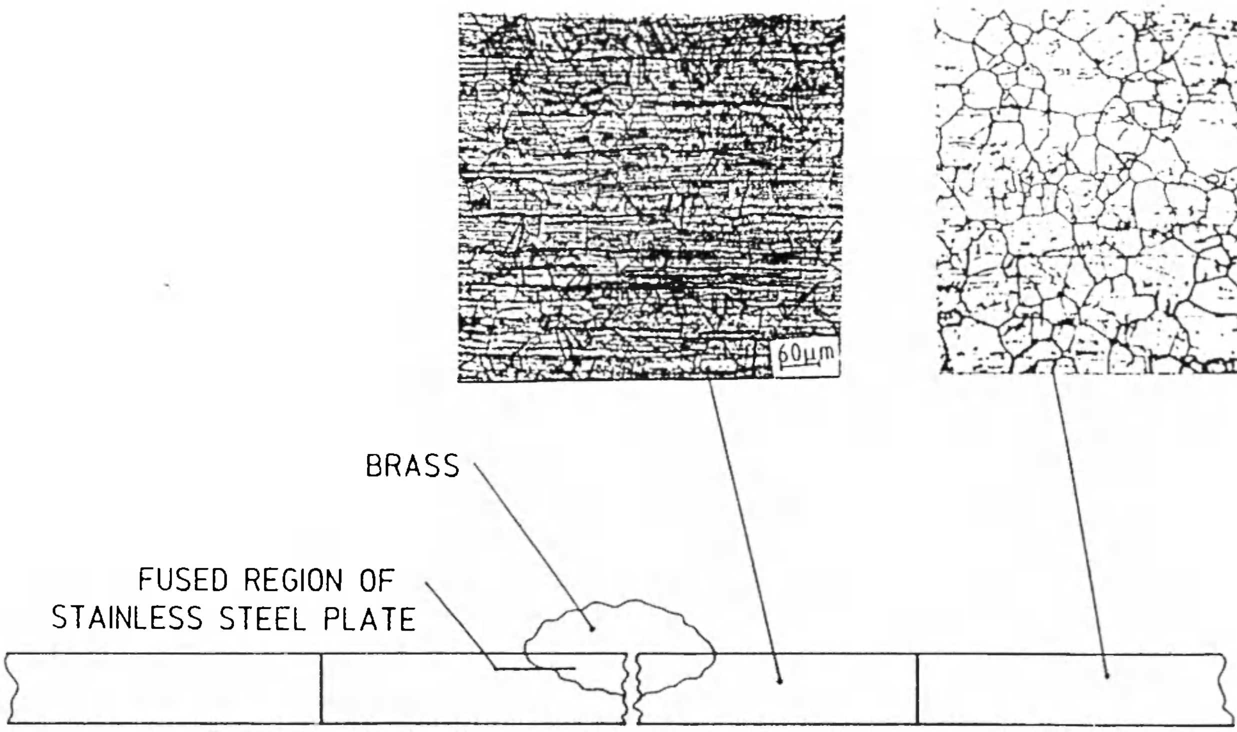

Fig. 18 . Desensitisation effect produced in sensitized stainless steel plate as a result of welding

in contact with the embrittler. Crack growth rate of liquid metal induced cracking is quite fast and cracking starts when molten embrittler comes in contract with stainless steel surface. The microstructure of material at the time of crack initiation depends on the kinetics of carbide dissolution and the time that materials spends above the carbide dissolution temperature (function of heating and cooling rates).

Discussion

The dissimilar weld splitting technique using brass as the embrittler has been found to facilitate easy cracking and splitting of austenitic stainless steels. This technique has been successfully demonstrated on 1.6 mm thick stainless steel plate. Higher thickness plates can be sectioned by employing proper pre and post weld heat treatment with the application of external tensile/shear load. Residual tensile stresses present in the material either due to service loading or introduced during fabrication process will definitely assist in easy splitting of the material. Welding parameters were optimized to achieve easy cracking of stainless steel plates. Use of pre and post weld heat treatments were found to be beneficial to improve cutting efficiency. Presence of cold working (induced by cold rolling) in the stainless plates has been found to have enhanced the splitting efficiency. However, spilitting efficiency is critically dependent on the direction of cold rolling. The rolled plates exhibited better susceptibility to cracking when embrittler deposition was made along the direction of rolling. Microstructural changes in the material as a results of welding process affect the susseptibility to cracking when embrittler deposition was made along the direction of rolling. Dendritic microstructure of the weldment exhibited superior resistance to liquid metal induced cracking . Sensitization of the stainless plate brought about significant improvement in the susceptobility of the stainless plate to undergo liquid metal induced cracking.

Summary

Weld spilitting (dissimilar weld embrittlement) of austenitic stainless steel is possible using brass as the embrittlerr. However, tensile stresses (applied or residual) must be present to assist the splitting action. The magnitude of loads required to produce the required stress depends upon the materials history, material geometry, section thickness and microstructure. This technique once properly developed can find useful applications for cutting/dismantling of irradicated austenitic stainless steel components and for cutting in areas with limited access.

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