EFFECT OF PREHEATING ON HOT CRACKING SUSCEPTIBILITY OF WELDED AUSTINITIC STAINLESS STEELS

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ABSTRACT

The hot cracking tendency of austenitic stainless steels weld metal fusion zone and heat affected zone (HAZ), have been the subject of many intensive investigations over the past 25 years. Several important observations have been made, and valuable relation between significant variables and hot cracking susceptibility has been drawn. Hence, this work is intended to study the effect of preheating on hot cracking susceptibility of preheated austenitic stainless steel samples.

The varesrtaint test permitted the simultaneous evaluation of the hot crack susceptibility of fusion zone at fixed applied strain of 5% and fixed welding condition. However, different preheating conditions were applied at 100° C, 200° C and 300° C. To evaluate hot cracking susceptibility of fusion zone, the total crack length and total number of cracks were measured on the specimen surface using high resolution digital camera photography, the image of which was viewed on the PC at high magnification. In addition, microscopic investigations were conducted using optical microscope to observe the microstructure in the fusion zones.

Experiment results showed a remarkable effect of the applied preheating. Preheating resulted in the reduction of the number of cracks and the total length of cracks by 33% and 40% respectively at 200ºC. By increasing preheat temperature beyond 200° C both the total number of cracks and total length of cracks increased with increasing preheating temperatures.

Keywords: *Hot Cracking, Preheating, Solidification, Austenitic Stainless Steel.*

الملخص

يعتبر تشرخ لحام سبيكة الصلب الأوستينيتي الغير صدئ و المعدن المجاور للحام موضوع العديد من الأبحاث خلال الخمس و عشرون عام الماضية. وعليه فإن هذا البحث يقوم بدراسة إمكانية تخفيف التشرخات أثناء اللحام (Hot Cracking) باستخدام التسخين قبل إجراء عملية اللحام إلى درجات حرارة ١٠٠و ٢٠٠و ٣٠٠ درجة مئوية.

يمكّن اختبار الانفعال المتغير (Varestraint) من تقييم حساسية منطقة الانصهار للتشرخ على الساخن وذلك باستخدام انفعال بمقدار ٥ % وبتثبيت تيار اللحام. وعليه تم قياس عدد الشروخ في منطقة اللحام وأطوالها بالإضافة إلى تحديد أعرض شرخ لكل عينة لتقييم مدى تأثير التسخين. تم ذلك باستخدام آلة تصوير إلكترونية شديدة الحساسية لتصوير العينات ومن ثم عرض الصور على شاشة الحاسوب وتكبيرها للقيام بالقياسات اللازمة.

وتم استخدام المجهر البصري لملاحظة التشرخ في منطقة اللحام عند تكبير x ٢٠٠.

أظهرت النتائج تحسن كبير باستخدام التسخين حيث تم تخفيف عدد التشرخات إلي ٣٣% ومجموع أطوال التشرخات إلى ٤٠% عند استخدام درجة حرارة تسخين ٢٠٠ درجة حرارة مئوية. وعند زيادة درجة حرارة التسخين إلى أكثر من ٢٠٠ درجة زادت نسبة التشرخ.

INRODUCTION

Hot cracking, which occurs during welding, is a major problem that affects the welding and weldability of a number of structural materials. Despite being one of the most investigated phenomena in welding, hot cracking still remains a major problem for many advanced and conventional alloys. It is a form of high temperature cracking that occurs in the fusion zone upon weld cooling. This type of cracking occurs in a variety of engineering alloys, being most prevalent in nickel base alloys and fully austenitic stainless steels. Susceptibility to these forms of cracking can be minimized by using filler metal with compositions such that a small amount of the high temperature delta phase is retained in deposited weld metal. Unfortunately, in certain corrosive environments, the ferrite phase may lead to preferential attack in the weld metal, and at high temperature service, ferrite may promote rapid transformation to the embrittling sigma phase.

Hot cracking has been a major persistent problem in a verity of engineering alloys. Factors affecting weld metal solidification cracking can be considered as either metallurgical or mechanical in origin. The metallurgical factors are related to condition of solidification of the metal, the grain size, presence of low-melting eutectic films. Hence, impurities such as sulfur and phosphorus can increase susceptibility to cracking [Bernasovsky, 1988]. Other elements such Si, Nb, B and Ti enhance cracking susceptibility with austenitic stainless steels [Raghunatha, et al, 1993, LI, 1999]. Although, carbon can reduce hot cracking susceptibility to over 0.1%, delta ferrite in amounts between 5 and 20% at room temperature inhibits hot cracking in many austenitic stainless steels [Ramesh, 1988, Nadezhdin, 1994, Beres, L., 1998].

In fully austenitic weld metal, the hot cracking susceptibility increase for phosphorus and sulfur contents in excess of 0.015% and 0.010%respectively. Test revealed that an extra-low P and S (both less that 0.002%) austenitic stainless steel exhibits superb hot cracking resistance comparable to that of type 304, even in full austenitic weld metal. Niobium has detrimental effect on fully austenitic weld metal, since the hot cracking susceptibility increase considerably when the Niobium content exceeds 0.30%. The same tendency is also observed in the heat affected zone of welds [Ogawa, T., 1982].

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A fully stabilized austenitic alloy D9, 15Cr-2Mo stainless steel with titanium addition was prone to hot cracking during welding. Hence the fusion-zone and HAZ cracking susceptibility of alloy D9 was studied at three titanium levels, 0.22%, 0.32 and 0.24% all other elements remaining constant. Using longitudinal and transverse Varesrtaint test to evaluate hot cracking susceptibility in fusion-zone and HAZ, the results showed that in the D9, the ratio of Ti to C and N must be controlled to minimize cracking. [Shankar, 2000].

Other work envisaged a trimetallic joint involving modified 9Cr-1Mo steel and 316LN austenitic stainless steel as the base materials and Alloy 800 as the intermediate piece. Four consumables were examined: 316, 16-8-2, Inconel 82 and Inconel 182. The comparative evaluation was based on hot cracking test and estimation of mechanical properties and coefficient of thermal expansion. While 16-8-2 exhibited resistance to solidification cracking, the Inconel filler material also showed adequate resistance; additionally, the latter were superior from the mechanical property and coefficient of thermal expansion view-point. It was concluded that for the joint between Alloy 800 and 316LN the Inconel filler materials offer the best compromise [Shankar, 2000].

New austenitic stainless steel, NAR-AH-4, which consists of low Si-23% Cr- 11.5% Ni- 0.2% N-B-REM (Rare Earth Metal) have been developed for the application of high temperature components (up to 1000 degree C) in thermal power plants and chemical plants. The corrosion and erosion resistance of developed steel with high content of chromium and slight amount of REM is excellent in forming adherent chromia oxide film on a surface. The creep rupture strength is considerably higher than that of type 310S (25Cr-20Ni) and Alloy 800H (20Cr-32 Ni-Al, Ti) due to the addition of nitrogen and boron. The resistance to weld hot cracking sensitivity of this steel is better than type 310S and high silicon content austenitic stainless steel, due decreasing silicon content (0.3%) and optimum ratio chromium equivalent to nickel equivalent. In addition, this steel has an economical advantage over type 310S and Alloy 800H. These results indicate that this steel is expected to be widely utilized as a candidate material for high temperature components [Kajigan, 1999].

In order to avoid hot cracking during weld solidification austenitic stainless steel weld metals should contain about 2-10% delta-ferrite. The role of delta-ferrite is equivalent to that of chromium in altering electrochemical parameters, but the exact role of delta-ferrite in affecting the passivity of the weld is not known. The role of delta-ferrite on the dissolution characteristics of the passive films formed on the austenitic stainless-steel weld metal is investigated. Results showed that every specimen, by virtue of its different ferrite content, developed a passive film having a different chemical composition and the potential arrests are found to be different even in a single group of weld-metal specimens [Pujar, 1999].

A study aimed at understanding the influence of dynamic stress, induced by thermal and mechanical loading, on weld metal hot cracking. The study attempts to resolve the relationship between the dynamic stress distribution in the specimen, particularly near the

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trailing edge of the pool and the observed cracking behavior in a Simgmajig test specimen. The results of this study indicated that for hot cracking to occur, there exists a dynamic relationship between the metallurgical and mechanical factors, which can be influenced by the welding conditions and mechanical restraint [Zacharia, 1995].

Effect of welding parameters and augmented strain on hot cracking susceptibility of Alloy800 were studied using Varestraint tests. The test results revealed that the hot cracking susceptibility of alloy 800 increase with increasing the heat input and augmented strain level. This emphasizes the role of constraint either internally induced or externally applied to the welded structure. A cracking threshold or the minimum augmented strain below which no hot cracking takes place was found to be 0.25 for alloy 800. Also, the Critical Strain Rate to Time (CSS) required to cause cracking was found to be 6.25×10^{-3} Sec^{-1} at welding condition of 100 Amp, 13 Volt and 140 mm/min [Zaghloul, 1994].

Based on the mechanical point of view of hot cracking in weldments, a new method, accomplished by synchronous rolling during welding (SRDW) along both side of the weld at a suitable distance behind the welding arc, has been developed for prevent weld hot cracking. Results showed that weld hot cracking can be effectively prevented and the mechanical properties of welded joins can also be improved by the new method. It is an important new solution to weld hot cracking in welding of sheet metals [Lio, 1994].

Another means to prevent weld hot cracking is to use intensive trailing cooler with welds which was investigated by Xitang and Qingyu. Hot cracking initiated from the crater and extending backwards has been reproduced using a welding fixture with variable restrain. Welding with a trailing cooler can effectively prevent this kind of hot cracking and is feasible in welding production. The temperature field and the strain distribution have been analyzed using the non-linear finite element method. The results of the experiment and the numerical simulation expound the mechanism of the prevention of hot cracking [Tian, 2000].

Hence, this paper intends to investigate the use of preheating of stainless steel 304 base metal before laying welding beads of SS 310 to improve hot cracking susceptibility of austenitic stainless steel.

EXPERIMENTAL PROCEDURE

1. SPECIMEN MATERIAL AND WELDING PARAMETER

A rectangular 6 mm thick plate specimen of austenitic stainless 304, in the hot rolled condition is used as a base material. Table 1 shows the nominal chemical composition.

Table 1. Chemical Composition, (wt. %) of 304 Stainless Steel Plates.

	C	Mn	Si	S	P	Cr	Ni
Wt. %	0.05	0.84	0.47	0.006	0.027	18.48	8.69

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Austenitic stainless steel Type 310 25Cr/ 20Ni filler metal was used in this investigation with chemical composition as shown in table 2.

Table 2. Chemical composition, (wt. %) of 310 Filler Metal Rod

	C	Mn	Si	S	P	Cr	Ni	Mo	Cu
Wt. %	0.096	1.67	0.31	0.001	0.015	24.34	20.34	0.02	0.09

Specimens were prepared with the dimension shown in Figure 1. The tungsten inert gas "TIG" process was used for weld metal deposition. The parameters of welding are given in Table 3.

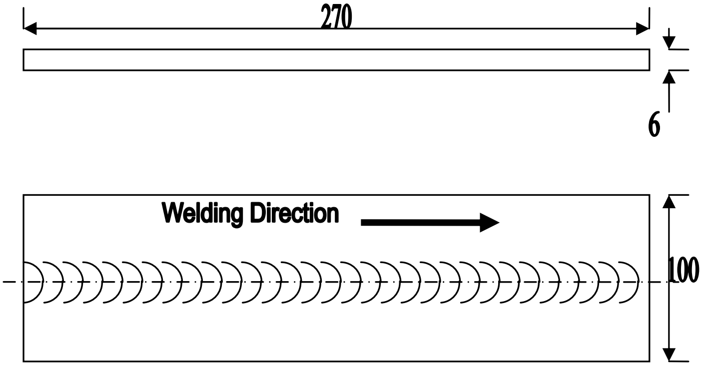

Figure 1. A rectangular specimen of base material for weld deposit (dimension in millimeters)

Table 3 Welding Parameters

Welding Process	TIG Process
Shield Gas	Argon
Welding Voltage	30 ± 1Volt
Polarity	DC
Welding Current	165 Amps
Welding Speed	8 mm/Sec

Manual welding was carried out by an experienced welder (who has twenty five years in industrial welding experience and welding research).

2. VARESTRAINT HOT CRACKING TEST

The Varestraint test attempts to reproduce some aspect of the material response to the welding condition. These tests normally involve the application of external augmented strain or stress whose magnitude is easily quantified. The stress or strain applied is typically of such a magnitude that any restraint by the fixturing and specimen is negligible. This approach allows the metallurgical and compositional factors associated with cracking to be isolated from the

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mechanical factors and permits their effects to be studied and quantified. Simulative tests have been successful in providing an order ranking of the crack susceptibility in families of alloys or among heats of a given alloy [Nelson, 1997]. The original Varestraint methodology has been offered as a standardized way of conducting test which evaluated weld metal zone.

Varestraint testing procedure is shown schematically in Figure 2 which utilizes a small laboratory supported specimen as a cantilever beam. A weld is deposited from left to right on the specimen as The arc travels steadily onward and is subsequently interrupted in the run-off area at C. Figure 3 is a schematic representation showing the typical relation between the observed hot cracking and the location of the weld puddle at the instant of application of the augmented strain.

The longitudinal strain for a specific radius of the die block can be approximated from the equation:

$$\varepsilon\ (\%) \equiv (t/\ 2R) \times 100$$

Where ε is augmented strain, t is specimen thickness and R is radius of the die block.

$$\varepsilon\ (\%) \equiv (\ 6\ \text{mm}/\ 2(60\ \text{mm}) \times 100 = 5\ \%$$

3. CRACK MEASUREMENT

Specimen of weld deposit for different strain and welding current were prepared for microstructure investigation. The test welds were cleaned with acetone and examined both visually as well as optical and scanning electron microscope to view cracks at high magnification.

High resolution digital camera has been used to photograph all samples while a PC has been used to enlarge image for cracks measurement.

Although, previous studies showed that the total crack length was proven to be the best quantitative index of cracking susceptibility of weld material [Zaghloul, 1994], measurements made for each sample included of number, total length and maximum width of cracks.

4. PREHEATING TECHNIQUE

Preheating technique is usually employed to eliminate moisture from the surface of the base metal and particularly to produce a metallurgical structure with required mechanical properties and good resistance to cracking. Preheating reduce the cooling rate in a weld by lowering the temperature gradient between the weld zone and the unheated base metal.

The propane torch is used to preheat the base metal at the weld deposition line and adjacent area to 100°C, 200° C and 300° C (± 4). Welding thermometer is used to measure achieved temperatures. The procedure of the preheat technique is kept uniform throughout the deposit operation.

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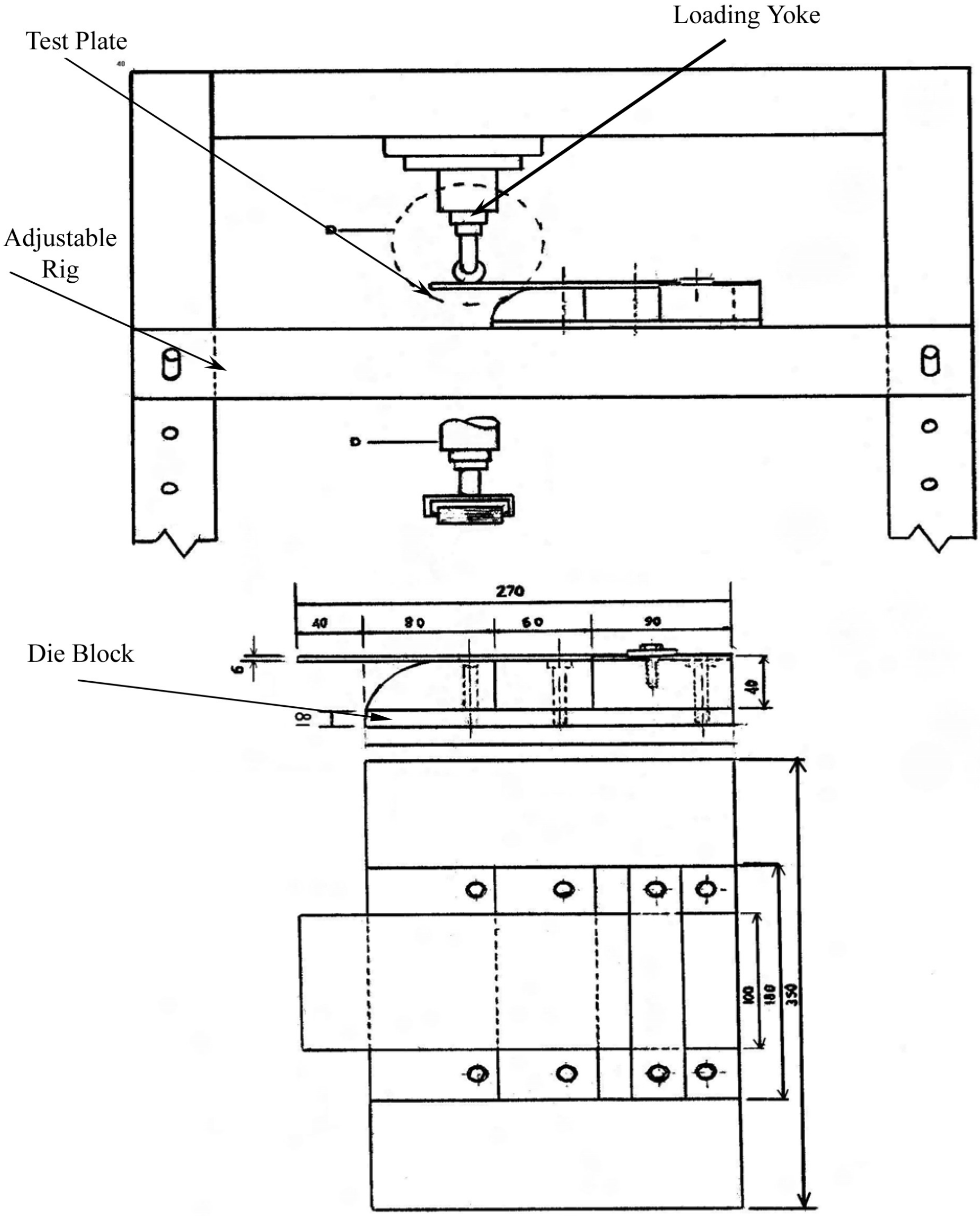

Figure 2. Schematic Representation for The Varestraint test

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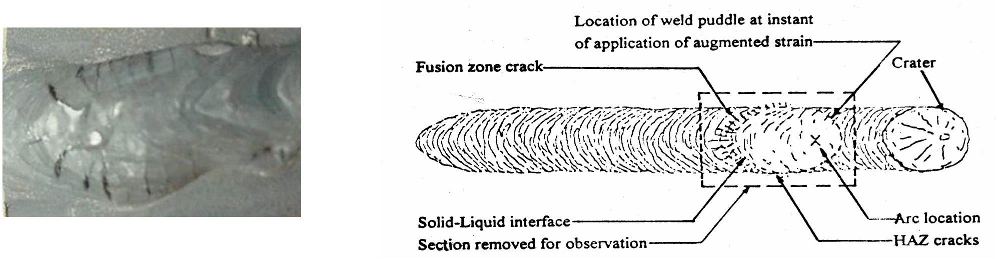

Figure 3. Schematic representation of the section of the section of the weld removed for metallographic observation. Top surface of weld showing location arc, weld puddle and solid-liquid interface at instant of straining.

5. METALLOGRAPHIC EXAMINATION

Specimens of weld deposit for different preheating temperature were prepared for microscopic investigation. Conventional optical microscope was used to observe mode of solidification, the microstructure and their relation to cracking tendency. Scanning electron microscope (JOEL JSM-300) was used to investigate the mode of fracture. Metallographic examination is performed for section corresponding to the dashed rectangular shown in Figure 3. Sections were subjected to suitable metallographic preparation including grinding, polishing and etching.

RESULTS AND DISCUSSION:

Varestraint test were conducted on fusion zone. The test welds were examined using digital camera and PC for magnification as well as optical microscopy to measure the number of cracks (NOC), maximum width of cracks (MWC) and total crack length (TCL).

Figure 4 shows a number of cracks as a function of preheating temperature. The average value for two set of samples have been plotted. It is evident that the number of cracks decreases with increasing preheating temperature with the temperature range 25º to 200º C with an average number of cracks of 16 at 200º C. About 33% reduction in number of cracks was achieved by preheating to 200º C; further preheating to 300º has resulted in 12.5% increase in number of cracks.

It is clear from Figure 5 that the maximum widths of cracks increase with increasing preheating temperature. The maximum width of cracks has increased to 2.5 times when sample was heated from 100º C to 200º C and tripled when heated to 300º C.

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Figure 6 shows the Total Length of Cracks (TLC) as a function of preheating temperature. The average value for two tested samples have been plotted. It is evident that the Total Length of Cracks decrease with increasing preheating temperature between temperature range 25º to 200º C showing an average TLC value of 20.1 mm at 200° C. An increase of preheating temperature resulted in TLC. About 41 % reduction in number of cracks was achieved by preheating to 200° C, further preheating to 300° has resulted in an increase of TLC by 23% (Compared to the original value at 25° C).

Figures 7, 8 & 9 show the microstructures of three preheating conditions at magnification of X 200. The micrographs reveal structures of the weld metal and the extent of precipitation of chromium carbides. The solidification structures of the welds were found to be mostly cellular or cellular dendritic with transgranular (primary) and intergranular microcracks through the weld metal.

The micrographs above show extensive migration of the original solidification boundaries during the post-solidification cooling period. This migration is due to the absence of inclusion or second phase ferrite to pin the boundaries. The reason may be attributed to plastic strain induced by residual stresses due to solidification shrinkage and thermal stresses.

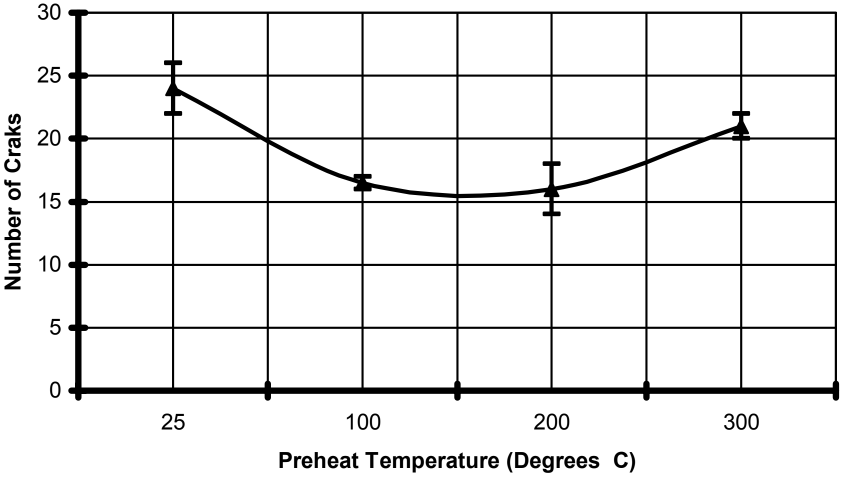

Figure 4. Effect of Preheating Temperature on Number of cracks for SS 310.

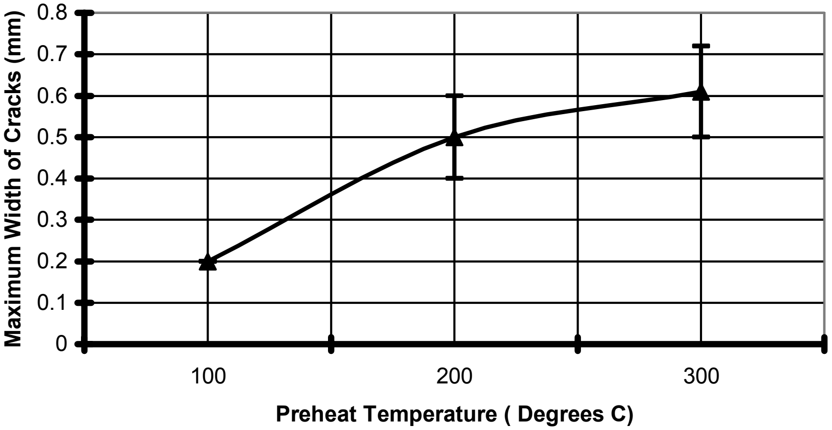

Figure 5. Effect of Preheating Temperature on Maximum Width of Cracks for SS 310.

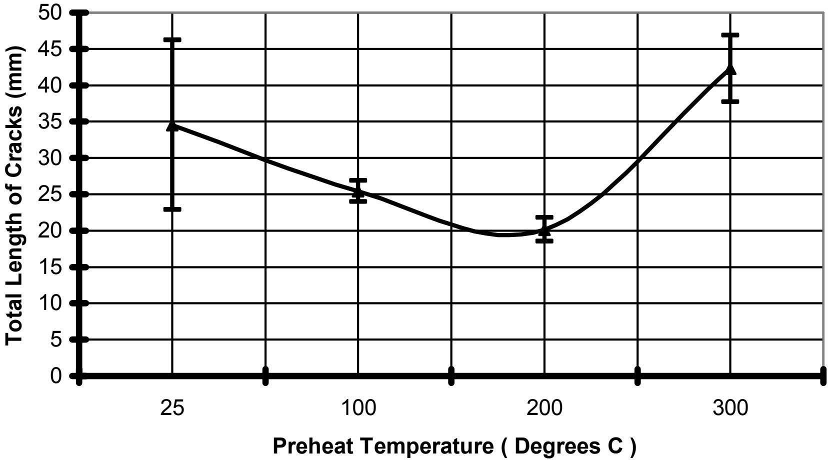

Figure 6. Effect of Preheating Temperature on Total Length of Cracks for SS 310 Weld deposit material.

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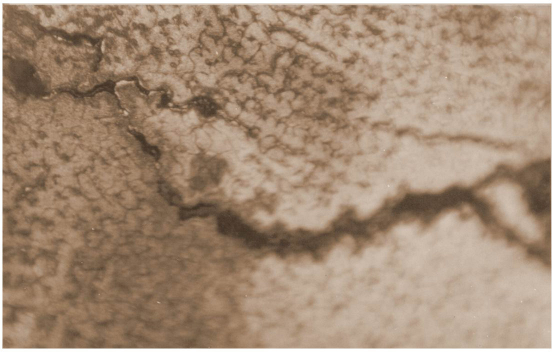

Figure 7 Microstructure of 100° C Preheated Sample (Mag. X 200).

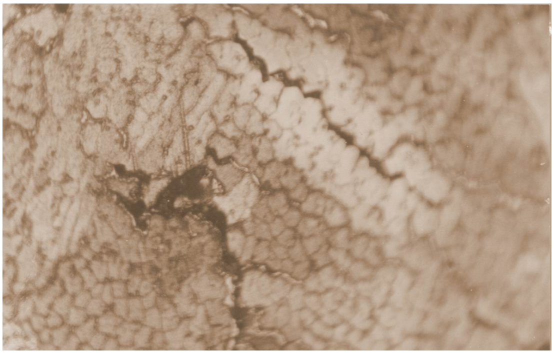

Figure 8 Microstructure of 200° C Preheated Sample (Mag. X 200).

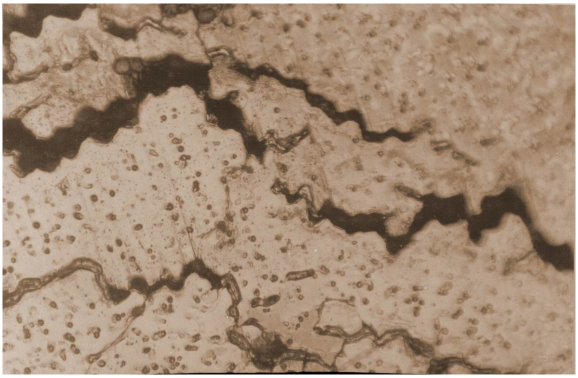

Figure 9 Microstructure of 300° Preheated Sample (Mag. X 200).

In austenitic stainless steel the extent of backfilling is a function of location in the weld and the temperature gradient. Thus, greater backfilling occurs at the center of a weld because the shallowest temperature gradient exists at the centerline. The extent of backfilling is also a function of solidification crack length and width such that the shorter/narrower the solidification cracks, the greater is the backfilling regardless of the location in the weld.

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Apart from evaluating the weldability of stainless steels by measuring the solidification crack length in terms of maximum crack length and or total crack length and number of cracks, the extent of backfilling may also have to be measured and considered in future work.

CONCLUSION:

The effect of preheating on the hot cracking of 310 austenitic stainless steel weld deposits has been studied and the results can be summarized as follows:

The hot cracking susceptibility decreases with increasing preheating temperature up to 200 º C beyond which hot cracking increases. This is may be attributed to the reduction of temperature gradient which reduces shrinkage stresses resulting in the reduction of hot cracking susceptibility. Raising the temperature to about 300º C has assisted in increasing heat intensity during welding and reduced cooling rate of weld deposit giving room for ductility-dip cracking to occur. The ductility-dip for austenitic stainless steel falls just below recrystallization temperature. If sufficiently high strain develops as the metal cools through the ductility-dip temperature range, cracking occurs. This may explain the increase of maximum width of cracks with increasing temperature.

Microstructure investigation has shown transgranular and intergranular cracks through weld metal.

REFERENCES:

1. Beres, L., July 1998, " Proposed Modification to Schaeffler Diagram for Chrome Equivalents & Carbon for more Accurate prediction of Martensite content," *Welding Journal*, pp. 273s-276s.
2. Bernasovsky, P., Kolman, M., 1988," Resistance of austenitic Corrosion resistance steels to liquation cracking during welding," *ZVARACSKE SPRAVY*, pp. 1-10.
3. Kajigan, I., Namba, K., Nishiyama, Y., Sawaragi, Y. , 1999,"Development of a new heat resistant austenitic stainless steel 'NAR-AH-4' ", American Society-of-Mechanical-Engineers, Power-Division-(Publication), pp. 641-651.
4. LI, L., Messler, R.W. JR., December 1999, " Effect of Phosphorus & Sulphur on susceptibility to weld hot cracking in austenitic stainless steel," *Welding Journal*, pp. 387s-396s.
5. Lio, W. , Tiaw, Y., Zhang, X., September 1994, " Preventing weld Hot cracking by synchronous Rolling During Welding," *Welding Journal*, pp. 297-304.
6. Nadezhdin, A., Cooper, K., Timers, G., September 1994, " Effect of Ferrite on Cast Stainless Steels," *Materials Selection & Design*, pp. 62-65.
7. Nelson, T.W., Lippold, J.C., Lin, W., Baeslack, W.A. III, May 1997, " Evaluation of the circular patch test for assessing weld solidification cracking, part I development of a test method," *Welding Journal*, pp. 110-119.

Top

8. Ogawa, T., Tsunetomi, I., 1982, "Hot Cracking susceptibility of Austenitic Stainless steel," *Welding Journal*, pp. 82s-93s.
9. Pujar, M.G., Dayal, R.K., Gill, T.P.S., Malhtra, S.N., October 1999, "Role of delta Ferrite in the dissolution of passive films on the austenitic stainless steel weld metals," *Journal of Martial Science letter*s, pp.823-826.
10. Raghunatha, T. B., Prasad, R. K., Iyer, K.J.L., March 1993," Effect of chemical composition and ferrite content on room temperature SCC behavior of austenitic weld metals," *Corrosion* ,pp. 248-254.
11. Ramesh,R., Nair,P. Kesavan, Rao,K. P., June 1988, " Ferrite transformation in austenitic weld metals," *Journal of Materials Science*, pp. 616-620.
12. Shankar,V., Gill,_T.P.S., Terrance, A.L.E., Mannan,S.L., Sundaresan, S., December 2000, " Comparative Evaluation of welding consumables for dissimilar welds between 316LN Asutenitic Stainless steel & Alloy 800," *Journal of Nuclear material*, pp. 65-76.
13. Shankar,V., Gill,_T.P.S., Terrance, A.L.E., Mannan,S.L., Sundaresan, S., December 2000, "Relation between microstructure, composion and hot cracking in Ti-Stabilized Austenitic stainless steel Weldments," *Metallurgincal and Material Transaction Physical Metallurgy and Material Science*, pp. 3109-3122.
14. Tian, X., Shi, Q., January 2000, " Preventing weld Hot cracking by welding with an intensive trailing Cooler," *Journal of Material Processing Technology*, pp. 30-34.
15. Zacharia, T., July 1995, " Dynamic stresses in weld metal hot cracking," *Welding journal*, pp. 164S-172S.
16. Zaghloul, M.B., Sadek, A.A., El-Batahgy, A.M., Hanafy, M., August 1994, "Effect of welding parameters on hot cracking susceptibility of alloy 800," *Quarterly Journal of the Japan Welding Society* ,pp. 335-341.

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