REPAIR WELDABILITY STUDIES OF ALLOY 718 USING VERSATILE VARESTRAINT TEST

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Abstract

The effect of multiple thermal cycles on the weldability of Alloy 718 was investigated using the Versatile Varestraint test. Metallography, SEM fractography, and EDAX analysis were also utilized to study the nature and cause of the fissures occurred during the weldability testing. The results of the Spot-On-Bead (SOB) test, conducted using the Versatile Varestraint test device, showed an adverse effect of multiple thermal cycles on hot cracking susceptibility of Alloy 718. The metallographic and fractographic observations revealed that the Heat Affected Zone (HAZ) cracking mechanisms are associated with the constitutional liquation of (Nb,Ti)C, remelting of Laves phase, and niobium segregation.

Superalloys 1988
Edited by S. Reichman, D.N. Duhl,
G. Maurer, S. Antolovich and C. Lund
The Metallurgical Society, 1988

Introduction

Alloy 718 is a high strength precipitation-hardened Ni-base alloy suitable for service in the temperature range of -250°C to 705°C (1). This alloy was developed primarily for fabricability and, in particular, for weldability. Alloy 718 possesses excellent corrosion and oxidation resistance as well as good tensile, fatigue, and creep properties at elevated temperatures (2). As a result, Alloy 718 weldments have been widely employed in structural components for heat resistance purposes. Although the welding characteristics of Alloy 718 are very attractive, some welding problems may occur, such as poor penetration, microfissuring in the HAZ, and inferior impact toughness and ductility in the weld metal (3). Large shrinkage contraction that occurs after welding may be a practical problem too (4).

It is well known that several high temperature alloys are easily reheated to temperatures in the vicinity of the solidus by multiple thermal cycling during multipass welding, repair welding after fabrication, and repair welding after service (5). With the increased usage of heavy section weldments and expensive welded structures, much concern has been concentrated on the effect of multiple thermal cycling on the weldability of these high temperature alloys, for example, Alloy 718.

In actual welding, Alloy 718 is susceptible to HAZ cracking (6-13). Therefore, reheat cracking (including liquation cracking and ductility dip cracking) may be a problem when weldments are reheated during multipass welding or repair welding. In order to simulate the actual welding cracks that can occur during multiple thermal cycling, a new hot cracking test method, called Spot-On-Bead (SOB) test, was proposed and employed to evaluate the hot cracking susceptibility of Alloy 718.

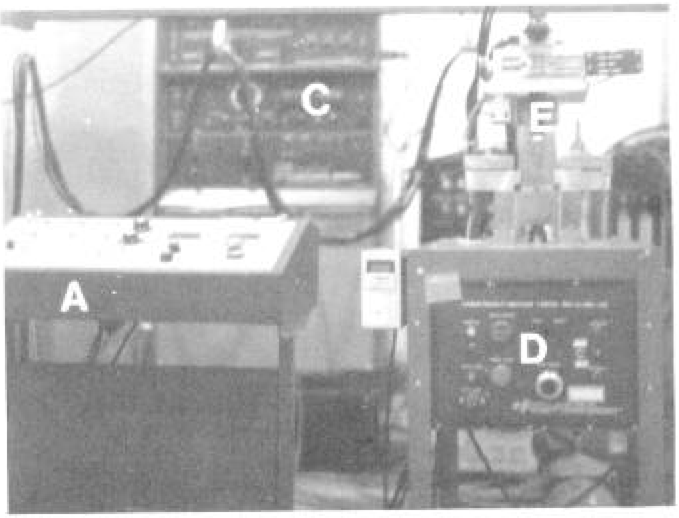
Experimental Procedures

The Versatile Varestraint Test

The Versatile Varestraint test device was proposed and employed to evaluate the hot cracking susceptibility of alloys. It is a modification of the Moving Torch Tigamajig Varestraint test adopted by Lundin et al (14). The Versatile Varestraint test device is shown in Figure 1. The main apparatus is the Varestraint Moving Torch Unit which consists of three major components: the torch moving assembly, the air operated strain assembly, and the electrical control unit. The welding power is applied by the Miller Syncrowave 500. The welding arc time control panel, with a precise delay timer, can control the spot welding time for reproducibility and regulate the time at which the strain is operated. This modification allows the test device to have a multiple capability to permit testing to be accomplished in the normal longitudinal varestraint mode, the trans-varestraint mode, or the spot varestraint mode. With this versatile capability, a new test concept called Spot-On-Bead (SOB) test was developed in this study.

Spot-On-Bead (SOB) Test

In order to reach the maximum utility of the Versatile Varestraint test, a new testing concept combining the longitudinal varestraint mode and the spot varestraint mode was conducted. This new methodology can simultaneously evaluate the hot cracking susceptibility of the fusion zone, the weld metal HAZ, and the base metal HAZ in a single test sample. It is also economical, effective, and time-saving for studying the weldability of multiple pass welding and repair welding.



A - Welding Parameter Controller

B - Delay Time Controller

C - Power Supply

D - Varestraint Tester Controller

E - GTA Torch and Test Fixture

Figure 1 - The apparatus of the Versatile Varestraint test device.

The specimen used for the Versatile Varestraint test is 5" x 1" x 0.125". After finishing by power-driven grinding wheel with 320 grit and cleaning by acetone, the specimen is positioned in the test device and welded by a longitudinal autogenous GTA pass. The position of weld bead should be carefully controlled such that one of the fusion lines lies along the center line of the specimen. The width of the weld bead is wide enough to accommodate the subsequent spot weld puddles. After depositing the longitudinal bead, the specimen is then refinished and recleaned.

The actual testing is accomplished by initiating a stationary GTA weld at the center of the specimen. Sufficient arc time is required to ensure that the specimen reached approximately steady-state thermal conditions. The weld puddle produces a base metal HAZ and a HAZ in the previously deposited weld metal with same area. A second or third spot weld can be superimposed directly on the first spot weld puddle after using a stainless steel brush and acetone to clean the previous spot weld puddle.

As the arc current of the last spot weld is interrupted, a predetermined delay time is counted to allow some solidification of the weld pool to occur prior to bending. Then the air cylinder is extended, forcing the sample to conform to the radius of a preselected die block. A schematic drawing and five SOB tested specimens are shown in Figure 2.

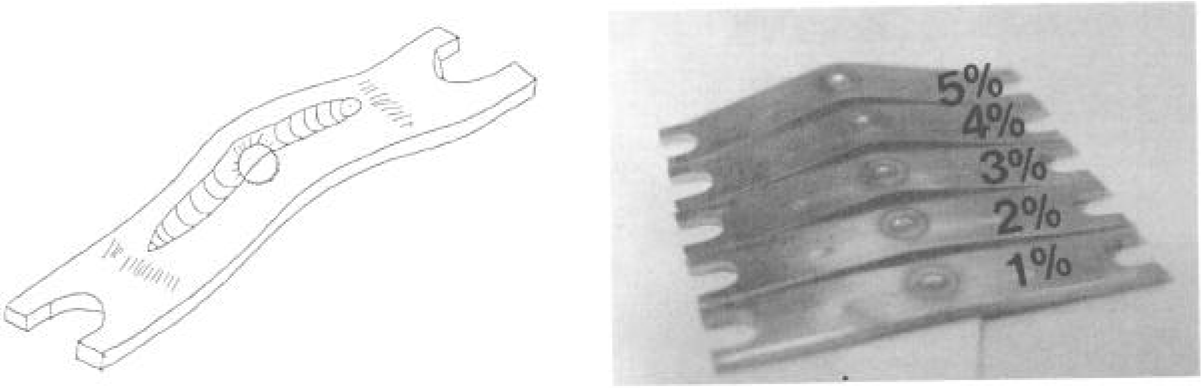


Figure 2 - "SOB" tested specimen used in the Versatile Varestraint test.

Metallographic and SEM Examination

Metallographic samples were cut, mounted, wet ground with a silicon carbide abrasive using 120, 240, 360, and 600 grit paper successively, and polished using alumina powder from 1 μm through 0.05 μm. The etching solution contains 40 ml HCl, 40 ml CH_3OH, and 2 gm $CuCl_2$. The fracture surface of the Versatile Varestraint tested weldments was examined using SEM (Hitachi model 200). The hot cracking surfaces were opened by cutting through the weldment to the crack tips with a diamond wafering saw and then bending the section apart. EDAX analyses were made on special features of the fracture surface and particles of interest in the microstructure of the metallographic samples.

Results

Spot-On-Bead Test

In this study, the Versatile Varestraint test was first introduced to investigate the incidence of hot cracking of alloys. Figure 3(a) shows the general appearance of the SOB tested weld puddles and the induced cracks of Alloy 718. The GTA spot weld was made on the longitudinal weld bead. Therefore, a spot which covers equal parts of weld metal and base metal was produced. Figure 3(b) shows the fusion zone cracking and HAZ cracking in the base metal which occurs in the lower region of the spot puddle. The phenomena of backfilling on the crack tip and liquation on the crack edge are clearly observed. The crack length was measured from the HAZs of the as-welded specimen surface.

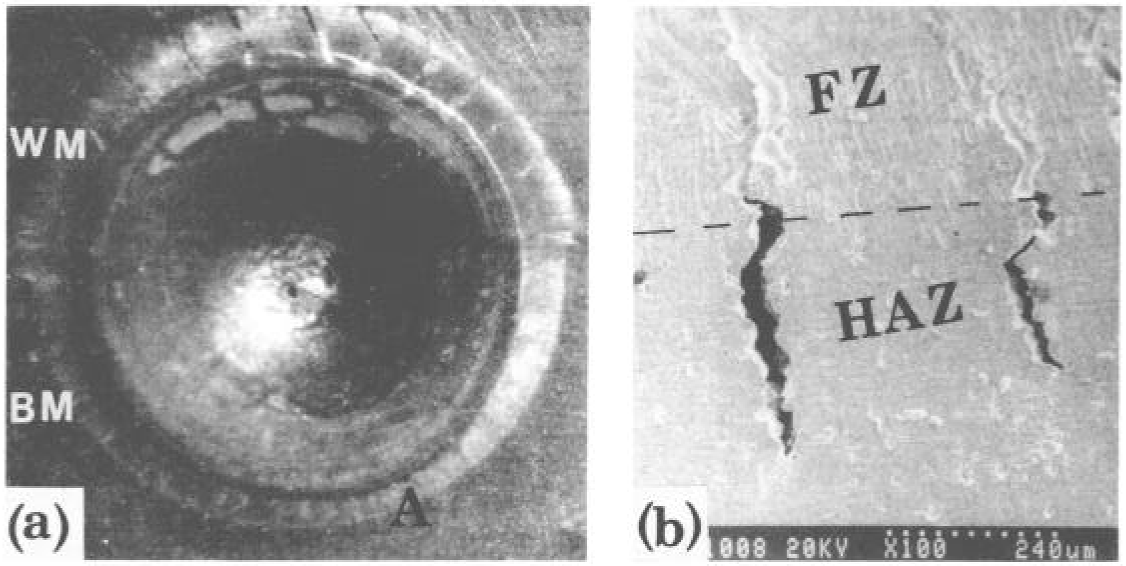


Figure 3 - Hot cracking in the Varestraint tested spot weld: (a) general appearance, and (b) higher magnification of area A.

The relationship between the cracking data, i.e., total crack length and maximum crack length of base metal HAZ and weld metal HAZ and augmented strain, after three thermal cycles, is illustrated in Figure 4. In both the weld metal HAZ and base metal HAZ, the total crack length increases with increasing augmented strain. The total crack length in the weld metal HAZ is larger than that in the base metal HAZ in each thermal cycle. The magnitude of augmented strain has a slight influence on the maximum crack length of both the weld metal HAZ and base metal HAZ. A similar trend can be seen from the results obtained for the "SOB" tested specimens after one and two thermal cycles.

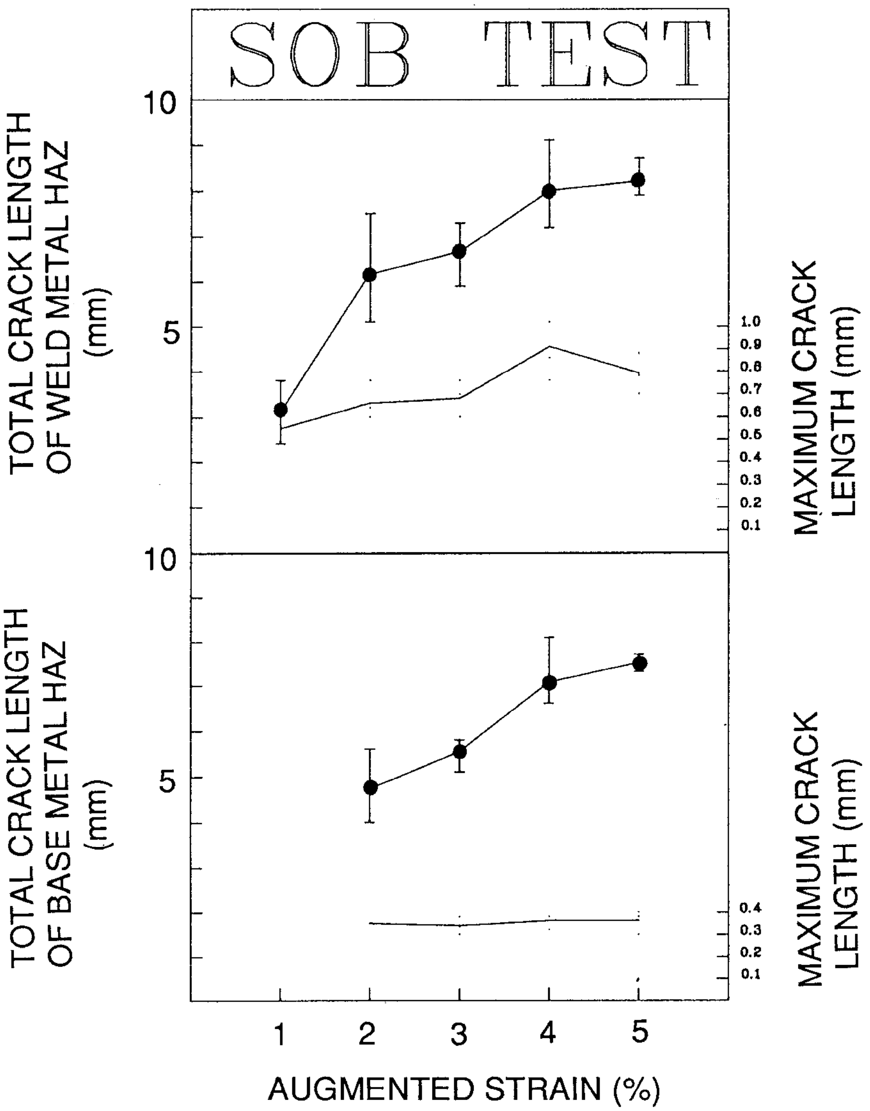


Figure 4 - Cracking lengths versus augmented strain of SOB tested specimens with three thermal cycles.

Figure 5 compares both the total crack length in the weld metal HAZ and base metal HAZ with different numbers of thermal cycles. The total crack length of weld metal HAZ increases with increases in the number of thermal cycles, which indicates that multiple thermal cycling reduces the hot cracking resistance of weld metal HAZ. The increment of total crack length reached 40% when 2% augmented strain was used, and 30% increment with 3% strain as the number of thermal cycles increases from one to three.

Metallographic Observations

After SOB testing, selected sections of tested samples were cut and mounted for metallographic observation. Figure 6(a) illustrates the general appearance of the SOB tested sample, revealing a fusion zone with epitaxial solidification, and both the HAZ region of base metal (BM) and of the weld metal (WM) with different structures. The base metal HAZ cracking is presented in Figure 6(b) at higher magnification. The cracking is intergranular in nature and propagates along the grain boundaries of the base metal HAZ. Some healing reaction may be initiated from the fusion zone (FZ), across the mixed zone (MZ), backfilling the HAZ cracking.

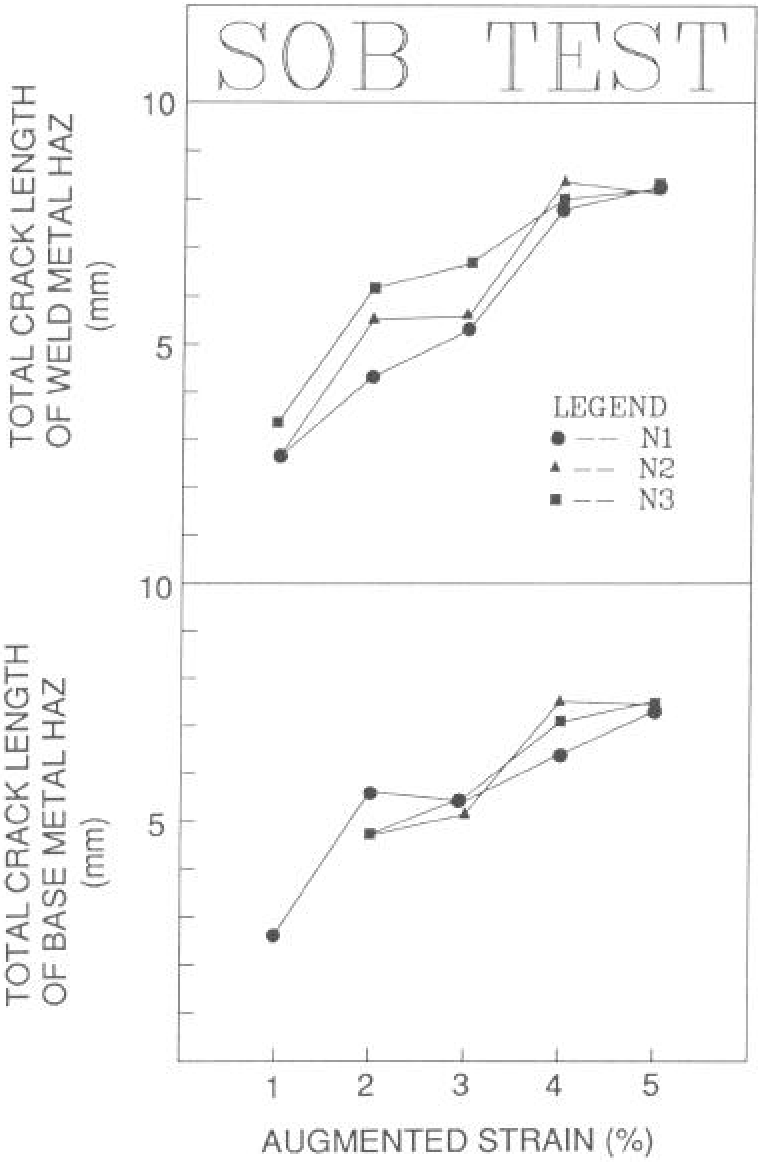


Figure 5 - Comparison of crack lengths of SOB tested specimens with different numbers of thermal cycles.

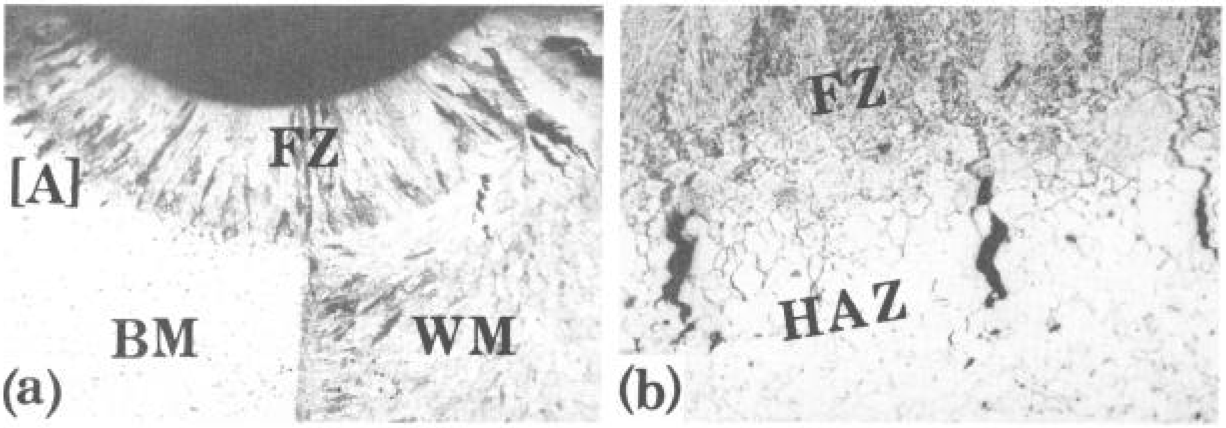


Figure 6 - Microstructures of SOB tested specimen: (a) general appearance, and (b) higher magnification of area A.

In order to clarify the microstructure of HAZs, a polished and etched transverse specimen bent by 3% augmented strain with one thermal cycle was investigated with the scanning electron microscope. Figure 7 shows clustering of niobium carbides in a HAZ crack. The wide crack region reveals that cracking was opened in a semi-liquated condition to accommodate the clustering carbides. In the weld metal HAZ, the predominant constituent is Laves phase, as shown in Figure 7(b). The Laves phase is the terminal solidified constituent of predeposited weld metal, which is remelted by subsequent thermal cycles, and then resolidified as lamellar, eutectic Laves/gamma constituent or blocky Laves phase.

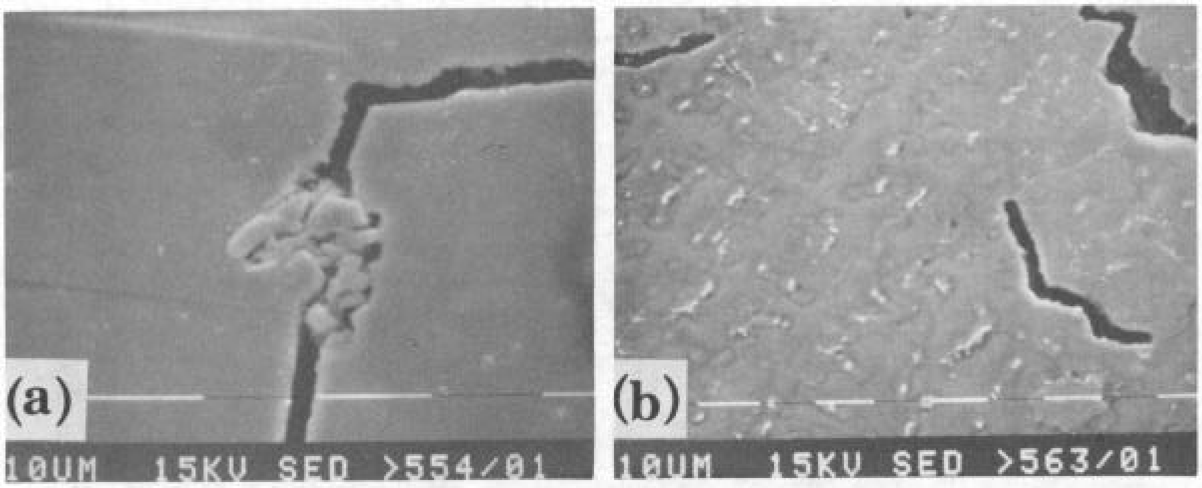


Figure 7 - Microstructures of SOB tested Alloy 718 weld:
(a) base metal HAZ, and (b) weld metal HAZ.

Utilizing the Versatile Varestraint test, the specimen is bent under strain which initiates hot cracks at the solid-liquid interface, which then propagate radially outward, along the grain boundaries of the predeposited weld metal and base metal. When the artificial cracks open, liquid metal from the molten weld pool, in advance of the solid-liquid interface, may be immediately drawn into the cracks by capillary action. This process, which has been termed "backfilling" or "healing", is under investigation using SOB test specimens. Of primary concern is the region near the intersection of the spot weld puddle and the longitudinal weld bead. In this region, backfilling of both HAZ cracks is easier to see, owing to the relative lower stress level. Figure 8(a) shows a typical backfilled crack observed in the base metal HAZ. The constituent in the "backfilled" grain boundaries is lamellar, eutectic-like Laves phase as shown in Figure 8(b).

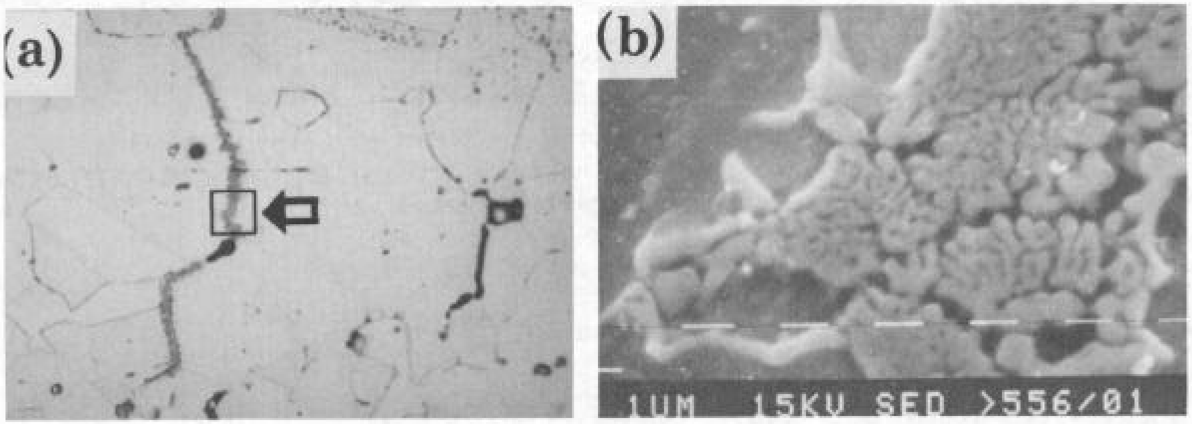


Figure 8 - (a) Backfilled crack in the base metal HAZ of Alloy 718, and
(b) high magnification of constituent in the grain boundary.

Fractographic Examination

In order to reveal the crack morphology, several specimens with different conditions were sectioned and cracks were opened up. Figure 9(a) shows the cracks occurred in both the base metal and fusion zone which experienced one thermal cycle. Three kinds of hot cracking were observed: solidification cracking, liquation cracking, and ductility dip cracking. In the fusion zone the liquated dendritic structure, as shown in area A, was clearly verified to be solidification cracking. In the HAZ region the cracking near the fusion boundary, revealing the liquated intergranular nature of fracture, is liquation cracking. Figure 9(b) illustrates at higher magnification liquation cracking. The fracture surfaces show wavy, rounded shapes coupled with many distinct speckles (15). Figure 9(c), a higher magnification of region C, shows numerous thermal facets which may be slip bands on the fracture surface.

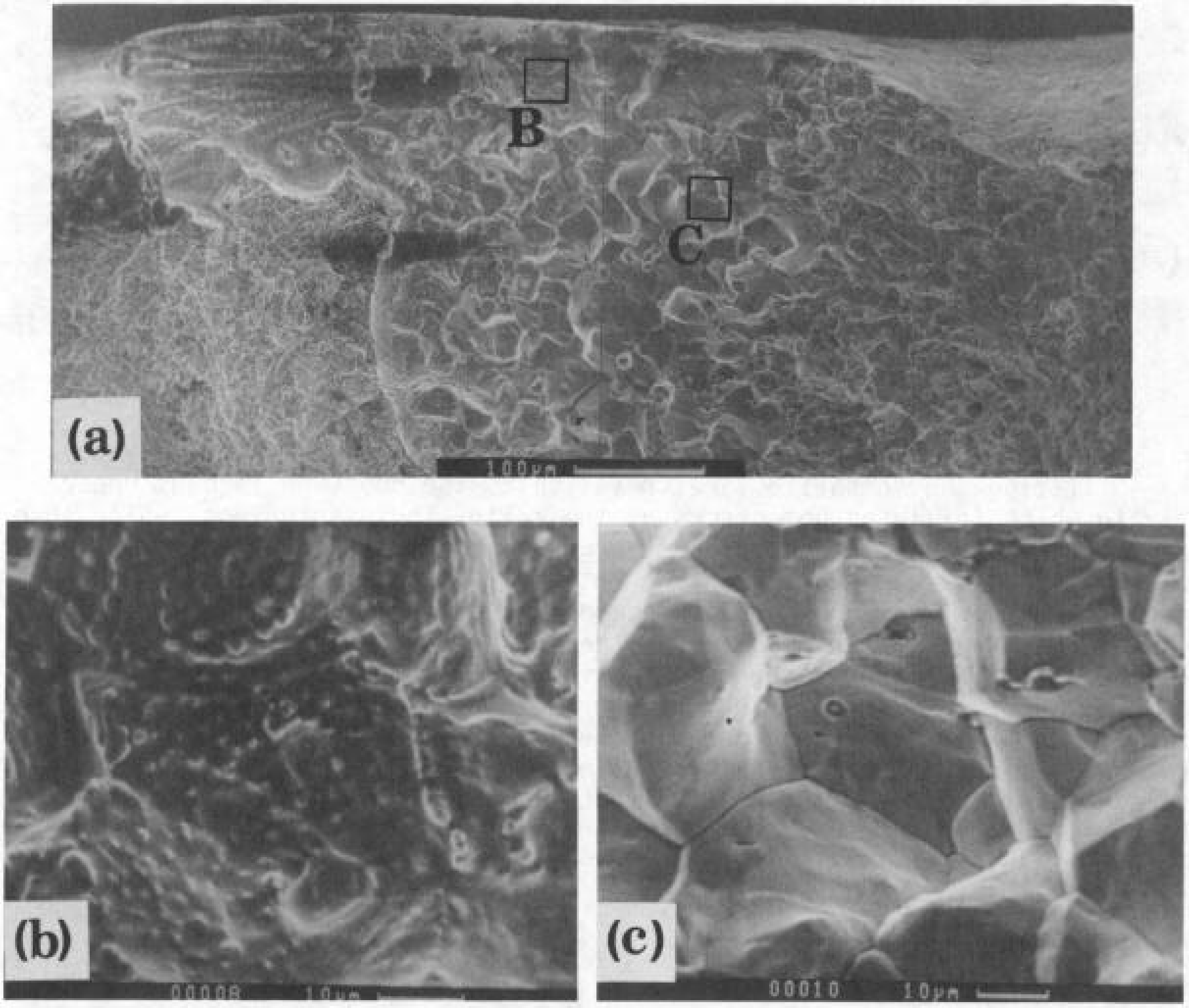


Figure 9 - Fracture surface of SOB tested specimen of Alloy 718 weld: (a) low magnification of cracking surface, (b) high magnification of area B, and (c) high magnification of area C.

Discussion

Nature of the HAZ Cracking

Studies have been reported that hot cracking occurs in the base metal HAZ of Alloy 718 during welding or post weld heat treatment. Investigators have concluded that microfissuring susceptibility is intimately related to the formation of liquid films at grain boundaries during welding. This phenomenon is similar to the liquation cracking proposed for other alloys. But the source of the formation of the liquid films is not clear. Thompson et al (12) found that the formation of intergranular eutectic-type liquid was caused by constitutional liquation of NbC precipitates. Cieslak et al (13) observed that the cause of hot cracking was the presence of eutectic gamma/Laves phase as the low melting interdendritic species.

The present results indicate the preferred cracking site is in the HAZs of the weld metal and base metal. For the case of the base metal HAZ, the primary constituent of the base metal is NbC, and the constituents NbC and Laves phase have been reported to impair the hot cracking susceptibility of Alloy 718. In the weld metal, the terminal solidification constituents are Laves phase and niobium carbides (13). Because the weld metal HAZs are easily reheated to temperatures in the vicinity of the solidus, Laves phase and niobium carbides are no doubt able to remelt and leave NbC back in the matrix or grain boundaries. These partially melted grain boundaries are easily opened into cracks with adequate welding strain.

Effect of Multiple Thermal Cycling

Other investigators (5, 16) have found that multiple thermal cycles imposed on the weld metal HAZ can significantly increase the hot cracking tendency of austenitic stainless steel welds. The degradation of HAZ cracking resistance could be due to decreases in the ferrite level, enhanced segregation, thermally-induced and/or strain-induced precipitation, or accumulation of thermal and restraint strains. The results in Figure 5 indicate a similar tendency, although the alloy involved, Alloy 718, is different than austenitic stainless steel. It was observed that the distribution of Laves phase became loose and small in the weld metal HAZ with thermal cycling (17). The EDAX results showed that the matrix is depleted of niobium after thermal cycling. Therefore, it is proposed that Laves phase is remelted by subsequent thermal cycling, leaving niobium enriched in the matrix or grain boundaries. Grain boundary migration in the weld metal HAZ then increases the degree of segregation by "sweeping up" niobium solute into preferred interdendritic subgrain boundaries as grain coarsening occurs. This sweeping effect plus the constitutional liquation of carbides increase the HAZ cracking tendency of Alloy 718 weld metal.

Conclusions

1. Multiple thermal cycling increases the weld metal HAZ cracking tendency of Alloy 718.
2. Hot cracking occurs primarily along dendritic boundaries in the weld metal HAZ.
3. The constitutional liquation of (Nb,Ti)C, remelting of Laves phase, and niobium segregation are probable causes of hot cracking.

References

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