Selected Mechanical Properties of Inconel 718 and 706 Weldments

Excellent weldability and good tensile strength at room and elevated temperatures are demonstrated, while other tests suggest that fracture toughness should be studied

BY R. A. MAYOR

ABSTRACT. A preliminary study has confirmed the weldability of Inconel 718 and 706 and indicates that joint tensile strengths at room and elevated temperatures closely approach base metal values. Welding parameters were established for manual gas tungsten-arc welding (GTAW) of these alloys for butt, fillet, and plug welds. Weld quality and soundness were established through dye penetrant, radiographic, and metallographic inspections of material samples at various stages of the process. Relative ductility was shown through guided bend tests. Other mechanical properties of the weldments were determined as a function of temperature and heat treatment using transverse weld and T-joint tensile specimens.

Ultimate strength and 0.2% offset yield strength of Inconel 718 weldments at room temperature, 1200 F (649 C), and 1400 F (760 C) was above 90% that of base metal and in most cases exceeded the minimum level specified by AMS 5596 and MIL-Hdbk-5B for base metal. Similar relative results were obtained with Inconel 706, although this alloy showed strength values 15 to 20% lower than Inconel 718. Both alloys were found to be fully weldable to each other. The strength of fillet welds was similar to base metal. Plug welds exhibited an average 30% reduction in strength (in

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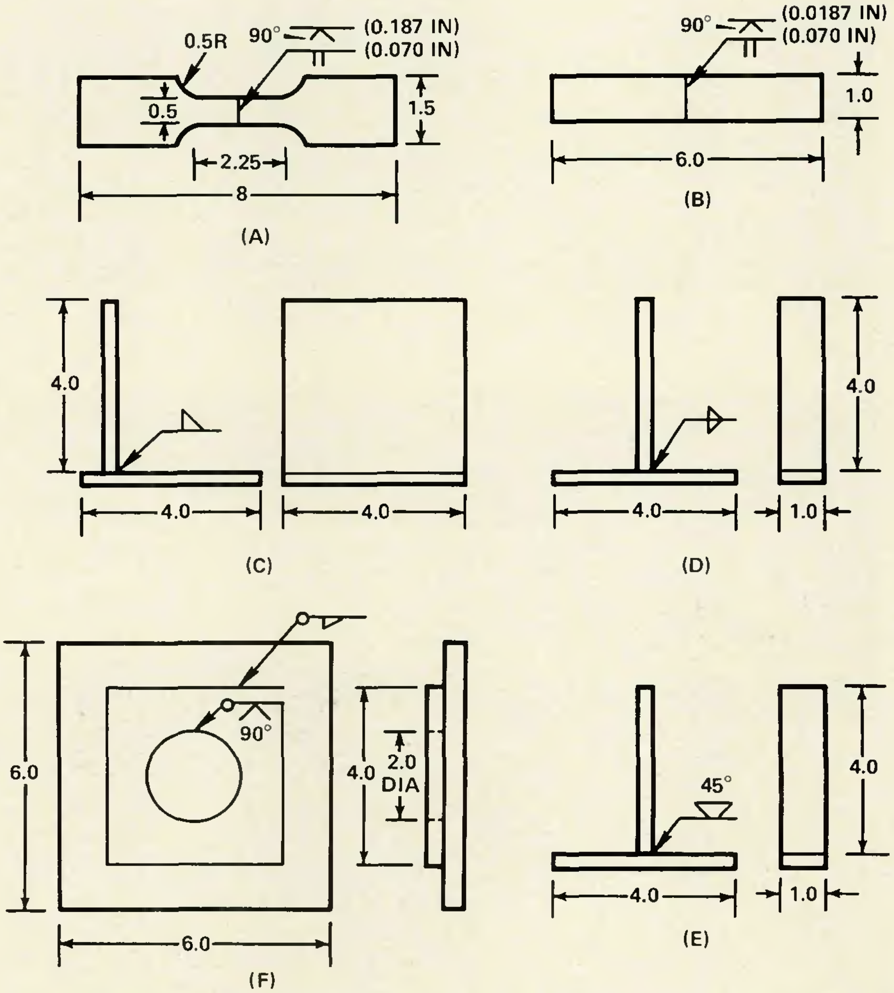

Fig. 1 — Specimen geometry: (a) butt weld tensile, (b) butt weld bend, (c) single fillet weld bend, (d) double fillet weld tensile, (e) plug weld tensile, (f) restrained weld patch

the aged condition) compared to base metal. Age hardening following welding was found to be acceptable without a need for a re-solution treatment.

Introduction

The development of faster and longer-reaching missiles is causing a change in materials selection for primary structures. Conventional missile systems that accelerate at extremely high rates during flight rely on external thermal protection systems to maintain the primary structural members at temperatures below 300 F (150 C). Aluminum alloys covered with an ablative heat shield are the standard structural arrangement found in these missiles. Advanced cruise missiles currently under development are causing a break in the standard pattern mainly for two reasons. First, aerodynamic heating and long soaking times resulting from the required speeds and long ranges cause surface temperatures in excess of 1100 F (600 C). Second, external thermal protection systems must be kept to a minimum to optimize the fuel capacity. The resulting temperatures are in a range beyond the structural capabilities of aluminum alloys, steels and titanium alloys. Superalloys become, then, the appropriate choice for primary structures under these conditions.

Martin Marietta Aerospace has been engaged in the design and manufacturing of prototype missile "hot structures" for the last few years. Trade-off studies have led to the selection of the nickel base alloys Inconel 718 and 706 as the baseline materials for these "hot structures."

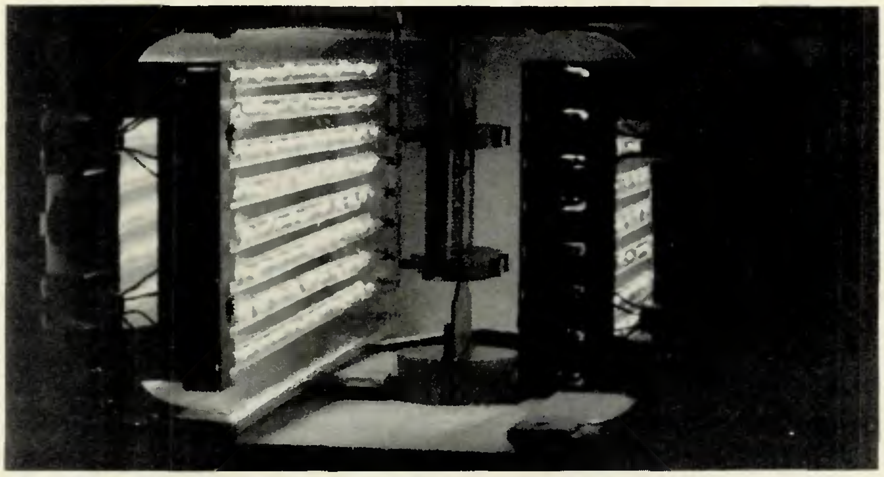

Fig. 2 — Close-up of the quartz lamp arrangement used to test tensile specimens at high temperatures

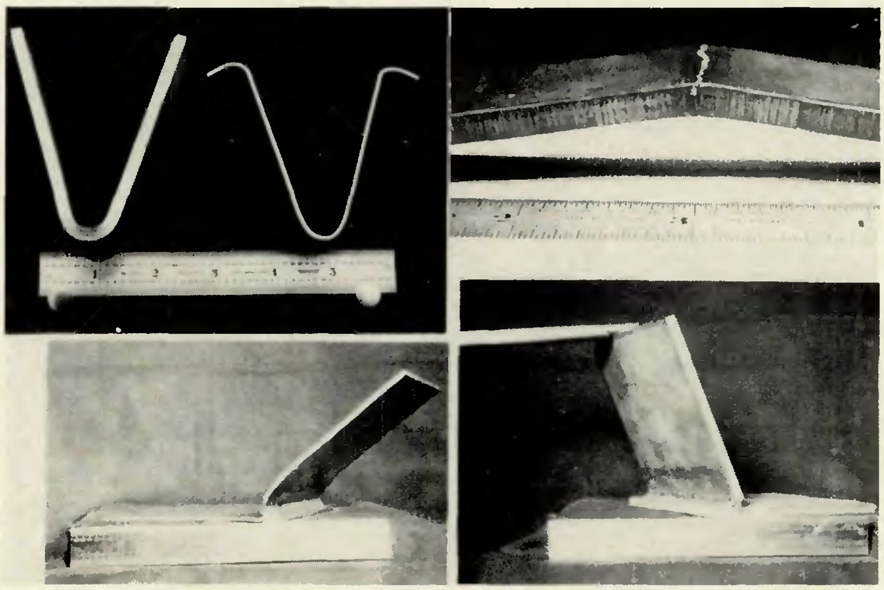

Fig. 3 — Inconel 718 butt and fillet weld bend test results. As-welded specimens (left) exhibited excellent ductility bending completely without failure. The aged specimens (right) broke without much elongation

Manufacturing processes entail extensive application of welding. A weld development program was conducted to establish welding parameters and mechanical properties as functions of temperature, heat treatment, and joint design. The results obtained in this program are reported herein. A detailed description of other processes involved in the fabrication of prototype assemblies is the subject of another publication (Ref. 1).

Experimental Procedure

Materials

Materials tested were nickel base alloys Inconel 718 and 706 per AMS 5596C and AMS 5606, respectively. Filler metal used in welding was 0.060 in. (1.52 mm) diam Inconel 719 per AMS 5832. All sheet material was received in the solution treated condition.

Specimen Geometry

Size and shape of the different specimens used are presented in Fig. 1. These were: (a) butt weld tensile specimen; (b) butt weld bend specimen; (c) single fillet weld bend specimen; (d) double fillet weld tensile specimen; (e) plug weld tensile specimen; (f) restrained weld patch.

Heat Treatment

All test panels were welded in the as-received (solution treated) condition. Aging consisted of 8 h at 1325 ±15 F (718.8 ±8C), furnace cool to 1150 ±15 F (621 ±8C), hold 8 h, and then air cool. Any additional solution treatment consisted of holding at 1750 ±25 F (955 ±14C) from 45 to 60 min and then air cool. All heat treatment operations were done in air.

Mechanical Testing

The number of bend tests (per ASTM Standard E 190 for guided butt weld bend tests, and per the AWS *Welding Handbook* (Ref. 2) for fillet welds) were conducted at the outset of this program mainly to determine soundness and relative ductility of the welds obtained. The butt weld specimens were effectively bent about a specified radius until either fracture occurred, or a 180-degree bend was attained. The ultimate load and angle of bend were recorded. The single fillet specimens were loaded by pushing the legs outward and placing the root of the weld in tension in a manner similar to pulling on a wishbone. Again the ultimate load and angle were measured. Results of these tests were used primarily to establish the initial welding parameters.

Tensile testing of the material was

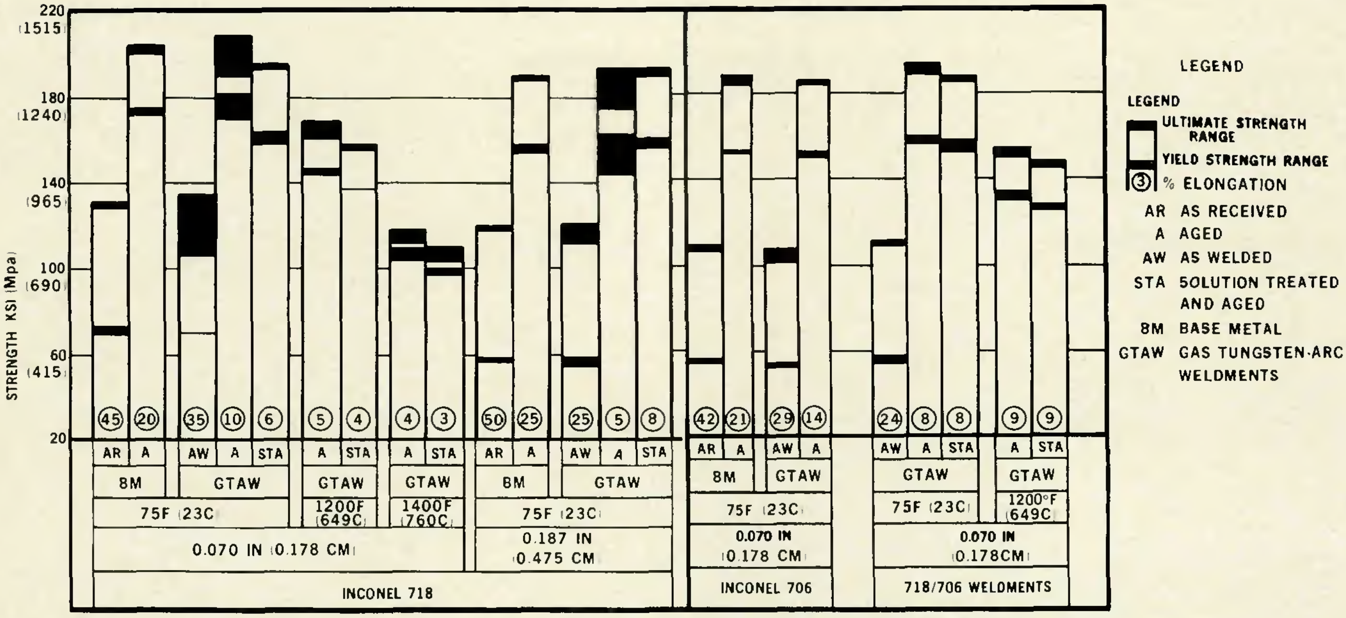

Fig. 4 — Summary of tensile test results

Table I — Summary of Welding Parameters For the Different Welds[a]

Weld type	No. of passes	Current, A, dc
Butt		
0.070 in. (1.78 mm)	1	50-80
0.187 in. (4.75 mm)	9	120-135
Fillet	1	85-100
Plug	8	90
Patch	16	85-100

(a) All welds were made in the voltage range of 5-10V dc with argon shielding (15 cfh) and helium back up; filler metal was 0.060 in. (1.52 mm) Inconel 719.

accomplished under ASTM standard E8 using an Instron universal testing machine. The crosshead speed for all tests was 0.05 in./min (0.02 mm/s). Tests were conducted on base metal (Inconel 718 and 706), single weldments (718 to 718 and 706 to 706), and combination weldments (718 to 706) as a function of heat treatment (as-received, aged, and solution treated/aged), temperature [(75, 1200, and 1400 F) (25, 649, and 760 C)] and thickness [(0.070 and 0.187 in.,) (1.78 and 4.75 mm)].

Welding Parametera

Welding of all specimens was performed manually using gas tungsten-arc welding (GTAW) process. All specimens were cleaned prior to welding with a wire brush and methyl ethyl ketone. A summary of parameters is shown in Table 1.

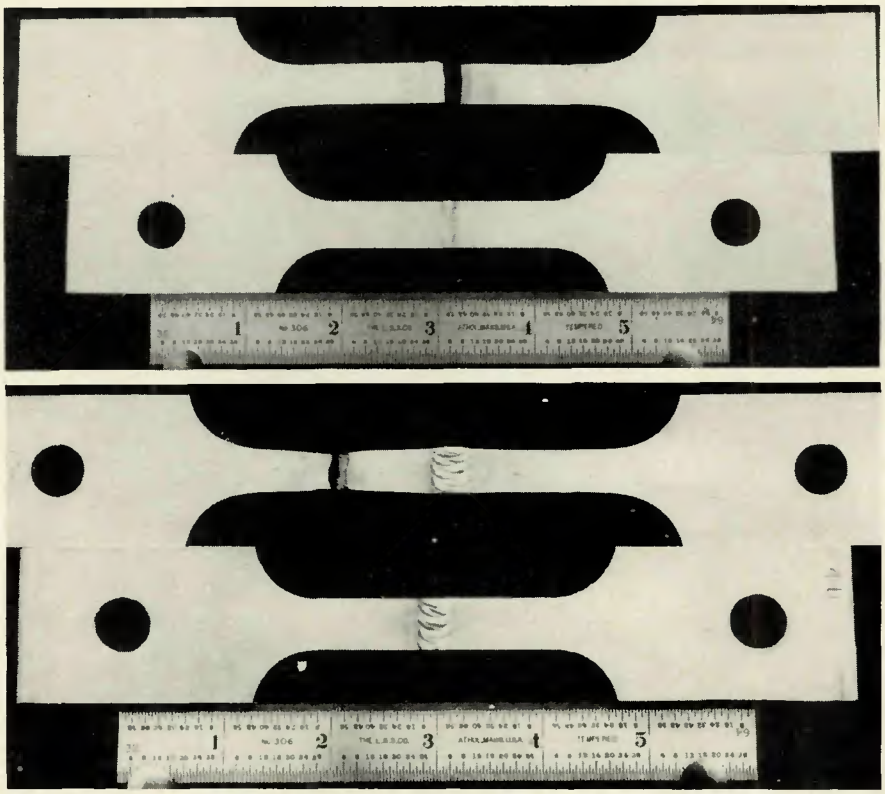

Fig. 5 — Comparison of as-welded Inconel 718 tensile coupons. Considerable elongation is shown in both the 0.070 in. (1.78 mm) thick (top), and the 0.187 in. (4.75 mm) thick (bottom) specimens

Quality Control

All as-welded panels were radiographically inspected according to specification MIL-R-11468, Standard II. Dye penetrant tests were made on the restrained weld patch specimens before and after heat treatment, and on a random number of the as-welded panels.

Quartz lamps provided the heating which was disposed in the manner shown in Fig. 2. The heating rate was calibrated to reach the desired test temperature within 2 min. Specimens were held at temperature for an additional 8 min before the load was applied.

Testing of T-joint specimens was

performed in a Baldwin machine. Each side of the horizontal member was clamped to one head of the machine and the vertical end held in standard tensile grips. The specimen was then loaded to failure.

Metallographic Inspection

Areas of material selected for microscopic examination were mounted in Buehler Castolite resin. Specimens were polished then etched with one of the following etchants: (a) glyceregia for 3 min., (b) electrolytically in chromic acid, at 2 V for 2 s. Macrographs (5X) were taken to show the overall weld area followed by micrographs (100X) to show weld, heat-affected zone, and base metal microstructure.

A series of Knoop hardness numbers was taken across several butt welded specimens. Hardnesses were determined under a 500 gram load at 0.020 in. (0.5 mm) intervals across the weld, through the heat-affected zone, and into the base metal.

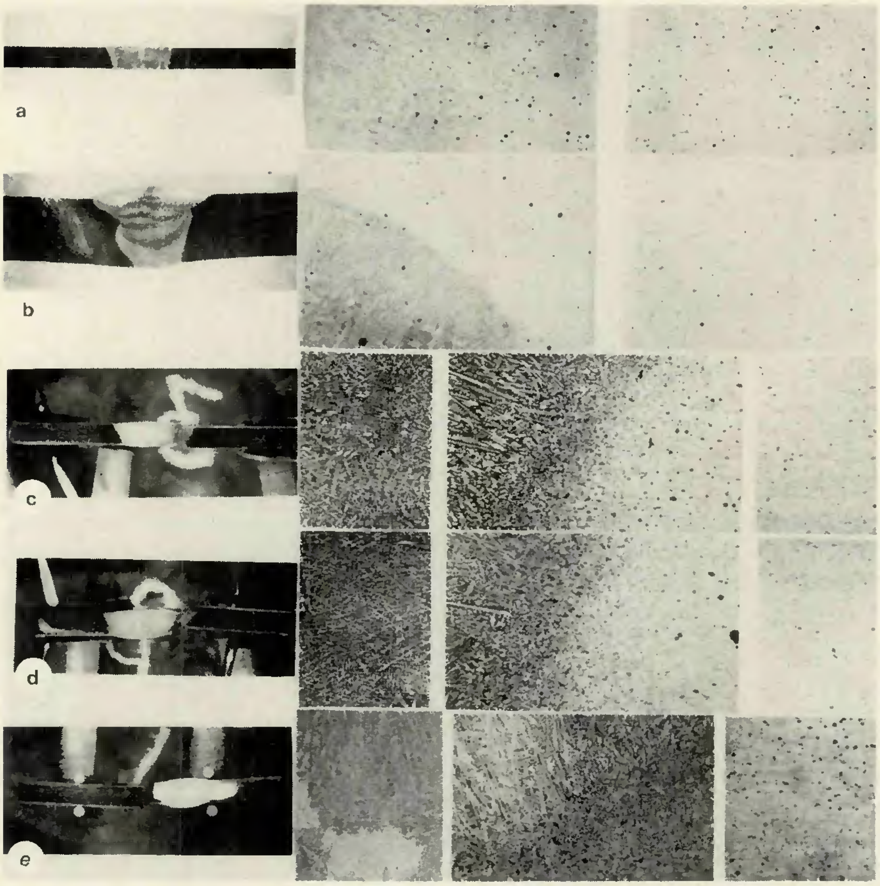

Fig. 6 — Microstructures of typical butt welds. Weld cross section is shown at left (5X) with the weld zone, weld/base metal interface and base metal microstructures shown at right (100X). From top to bottom: (a) as-welded Inconel 706 (glyceregia etch); (b) aged Inconel 718 (glyceregia etch); (c) aged Inconel 718 tested at room temperature (electrolytic etch); (d) aged Inconel 718 tested at 1200 F (649 C) (electrolytic etch); (e) aged Inconel 718 tested at 1400 F (760 C) (electrolytic etch). All photos reduced 40%

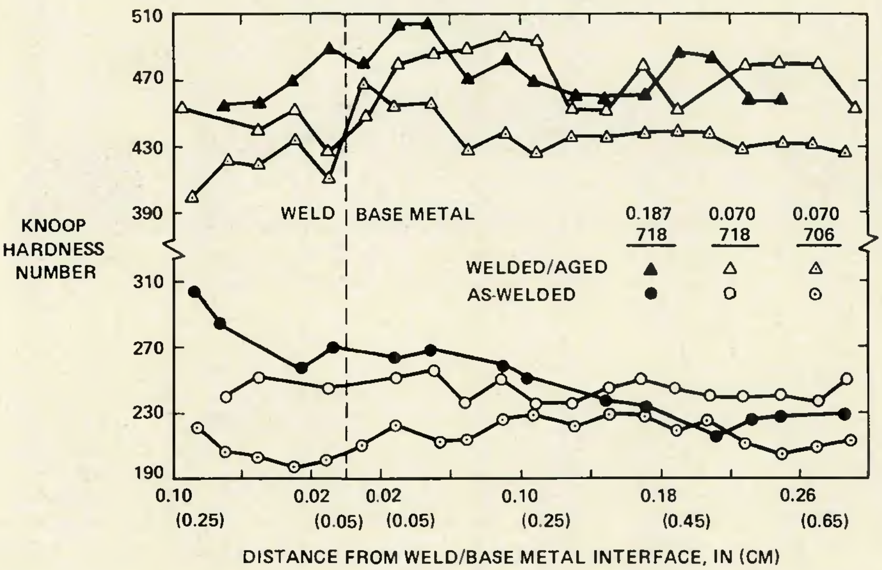

Fig. 7 — Hardness surveys on Inconel 718 and 706 weldments

Experimental Observations

All of the 0.070 in. (1.78 mm) thick as-welded specimens were bent to the maximum (180 deg) about a 2T radius without failure, whereas the aged specimens broke after a maximum 20 deg bend. Similar relative results were observed with the single fillet bend tests. Typical examples are shown in Fig. 3. The soundness of all welds was found to be acceptable since no internal defects were observed upon close examination of the fracture surfaces.

A graphical summary of tensile testing results is shown in Fig. 4. These results show that:

1. Room temperature ultimate strength of aged Inconel 718 welds is within 90% of aged base metal, and in most cases exceeds the 180 ksi (1241 MPa) minimum level specified by AMS 5596 and MIL-Hdbk-5B for aged Inconel 718 wrought sheet. The same is true for 0.2% offset yield strength, for which the minimum specified value is 150 ksi (1034 MPa). Similar relative results were obtained from Inconel 706, although as expected, strength values are lower than those of 718.

2. The 1200 F (649 C) and 1400 F (750 C) ultimate and 0.2% offset yield strength values of aged Inconel 718 were always above those shown in MIL-Hdbk-5B for base metal at similar temperatures.

3. A trend of lower tensile values was evident for those specimens that underwent a re-solution treatment after welding.

4. Acceptable compatibility was shown when welding Inconel 718 to 706. Fracture always occurred along the weaker member (706), but strength values do not deviate excessively from comparative 718 to 718 welds.

It should be noted that the 1200 F (649 C) and 1400 F (750 C) strength values of as-received (solution treated) base metal and as-welded (unaged) specimens are not reported. This is because the specimens in this condition yielded repeatedly as the load was applied, thus precluding a smooth, uniform load-elongation curve. The phenomenon of repeated yielding or serrations (Portevin-LeChatelier effect) has been found in many other alloys including aluminum, titanium, and steels. There are many theories dealing with the cause of these serrations, but these are beyond the scope of this work.

The appearance of as-welded Inconel 718 tensile specimens before and after testing is depicted in Fig. 5. The amount of elongation that has taken place during testing is clearly visible in the photographs. This tensile elongation averaged 35 and 25% for 0.070 and 0.187 in. (1.78 and 4.75 mm) thick specimens, respectively. The fracture zone was generally the weld/base metal interface for the 0.070 in. thick specimens, and the base metal for the 0.187 in. specimens. However, the thicker specimens also had bulkier, more reinforced welds.

The cross section and corresponding microstructures of a number of typical Inconel 706 and 718 welds are shown in Fig. 6. The multipass weld seen in 0.187 in. thick material, Fig. 6b, is definitely bulkier than single pass welds. The strength of the specimens showing fracture through the weld is still within 90% of base metal, as previously observed. The microstructural features of these welds do not show any abnormalities (the dark spots are etching pits produced during polishing and etching operations). The welds are clean and free of cracks and porosity. The grain growth in the heat-affected zone is not as apparent in the as-welded Inconel 706 specimen as it is in the aged Inconel 718 welds. The fractures are all observed to have occurred through these areas.

Results of hardness surveys taken across the weld, heat-affected zone, and base metals of various welds are shown in Fig. 7. The hardness of Inconel 718 averages 40 HK higher than Inconel 706. There are no basic differences in hardness between the 0.070 and 0.187 in. (1.78 and 4.75 mm) thick Inconel 718 specimens in the aged condition. In the as-welded condition, however, the weld zone in the 0.187 in. thick specimen shows a hardness increase of approximately 40 HK over the corresponding zone in the 0.070 in. specimen. The values become similar in the base metal away from the heat-affected zone.

The data obtained from testing plug and double fillet welds are presented in Fig. 8. These welds were tested as T-joint specimens and pulled in tension. Yield strength values were not recorded as the specimen size, geometry, and fixtures did not allow this to be conveniently done. The plug weld ultimate strength values in the as-welded condition were approximately the same as base metal, whereas the welded and aged specimens averaged 70% of that base. A large discrepancy was observed in the re-solutioned and aged specimens where strength values were even lower than the as-welded specimens. Specimens before and after testing, a typical plug weld cross section, and corresponding microstructure are shown in Fig. 9. Fracture occurred through the weld, parallel to the thin member in one instance and perpendicular to it in another.

The double fillet welds were never broken as fracture always occurred in the base metal. Specimens, cross section, and microstructures of these welds are shown in Fig. 10. The unfused root area under the welds had no effect on the effective strength of the joint.

The restrained weld patch specimens showed excellent quality as no cracking and/or distortion was observed in the as-welded and in the aged conditions. A weld patch specimen before and after aging is shown in Fig. 11. The inside circular weld was done after aging and did not show any cracking and/or distortion.

Discussion of Results

The results obtained corroborate the reported excellent weldability of Inconel 718 and 706. There was a complete lack of welding defects such as cracks, inclusions, and porosity. In

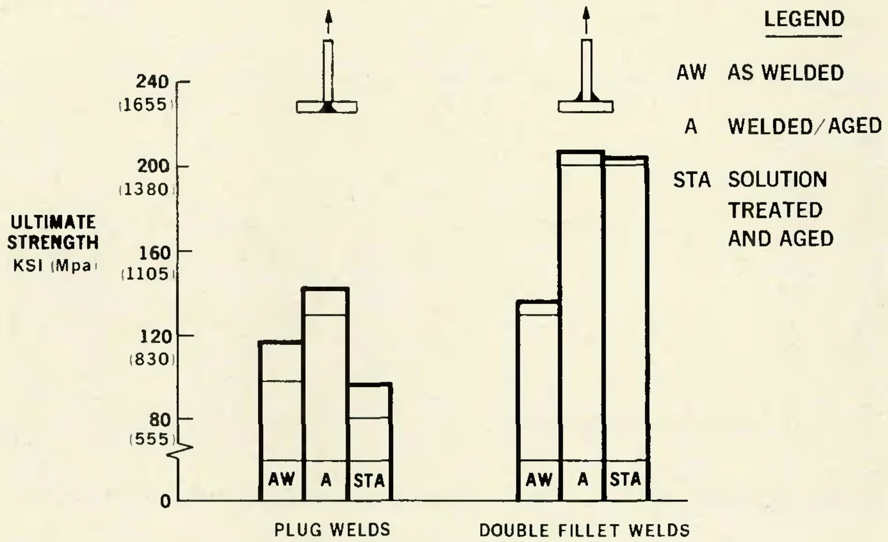

Fig. 8 — Ultimate tensile strength of plug and double fillet welds

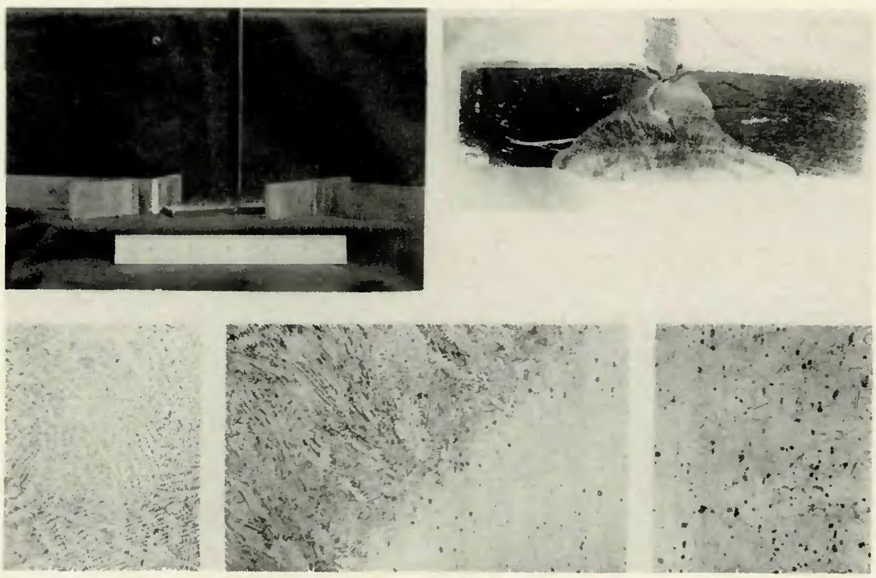

Fig. 9 — Aged plug weld T-joints before and after tensile testing. Fracture has occurred mainly through HAZ as seen in cross section. Microstructures of weld zone, weld/base metal interface and base metal are shown from left to right (X100, reduced 52%)

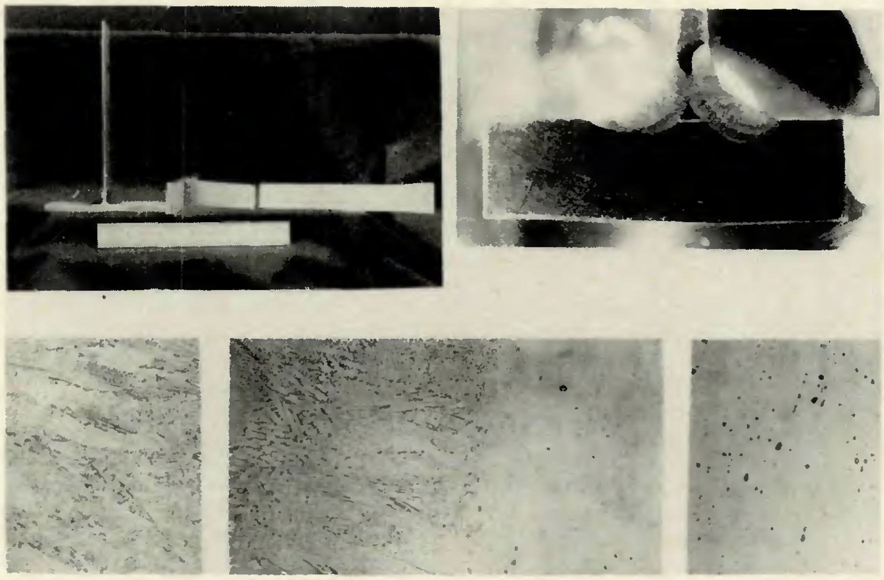

Fig. 10 — Aged double fillet weld T-joints before and after tensile testing. Fracture has occurred in base metal. Microstructures of weld zone, weld/base metal interface and base metal are shown from left to right (electrolytic etch, X100, reduced 52%)

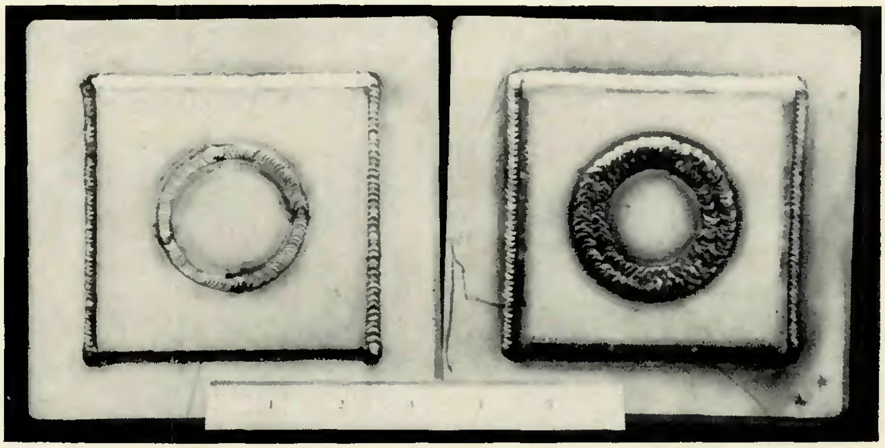

Fig. 11 — Restrained weld patch specimens, 0.070 in. (1.78 mm) and 0.187 in. (4.75 mm) thick are shown at left and right, respectively

addition, bend test results proved the soundness and ductility inherent in the as-welded structures, which did not break after being bent about a sharp radius (1T and 2T) to angles up to 180 deg. The aged specimens did not show as good ductility, as expected, especially as the thickness of the material increased.

Considering the ratio of ultimate load sustained in the aged specimens to that in the as-welded specimens, it is observed that this ratio is approximately 2 to 1 for tensile tests regardless of thickness. This ratio was also approximately 2 to 1 in the bend tests of 0.070 in. (1.78 mm) thick butt welded specimens, but has decreased to almost 1 to 1 in the 0.187 in. (4.75 mm) thick specimens.

The significance of these results lies mainly in the method employed in analyzing the welded structure. The results suggest that crack propagation resistance criteria (fracture toughness) should also be used in addition to straight tensile data to determine or assess the actual strength of a welded joint. The tensile test results have nevertheless provided a high degree of confidence in the strength of the welded structure at room and elevated temperatures, provided that quality standards are met. The values obtained in these tests are not welding allowables as such, since the number of tests is not statistically large, but a confident welding efficiency number was established.

Microstructures of the as-welded and aged specimen did not show any abnormal conditions, and the uniform hardness distribution observed is indicative of excellent aging response. The increase in hardness observed (Fig. 7) in the multipass 0.187 in. (4.75 mm) thick butt weld shown in Fig. 6b indicates that limited aging took place due to heat accumulation during the welding operation. In other words, exposure to multipass welding maintained the temperature in the surrounding zones long enough in the 1150-1400 F (620-760 C) range to promote limited aging. This limited strengthening contributed to the observation that the 0.187 in. thick Inconel 718 tensile specimens broke in the base metal rather than the heat-affected zone.

The double fillet welds did not show any unexpected results. The smooth, uniform fillets on both sides of the joint do not foster the presence of stress concentrations and/or cracks and thus; fracture should only be expected to occur in the perpendicular member of the joint away from the weld.

Plug weld results, however, point out again the need for crack propagation criteria in the analysis of the structure. The as-welded plug specimens exhibited approximately the same strength values of not aged base metal, but only 70% in the aged condition for corresponding aged base metal. The aged structure has a lower crack resistance (fracture toughness). As shown in Fig. 9, the plug weld specimen is likely to have some unfused area at the root of the vertical member which, in effect, constitutes an incipient crack. This occurs because the plug weld is only accessible from one side and complete fusion with a smooth radius on the inside is almost impossible to achieve. Due to lower crack propagation resistance in the aged specimen, it is relatively easier for the crack to move. Fracture, therefore, results at a lower strength than expected from tensile data.

Restrained weld patch tests results produced additional proof of the good weldability features of this alloy as no cracking was found even after welding in the aged condition.

Conclusions

The welding program demonstrated excellent weldability of Inconel 718. Radiographic and metallographic results showed excellent quality and lack of weld defects; hardness values showed structural uniformity and good aging response; weld patch tests showed minimum distortion and lack of cracking even in the age-hardened condition; and bend tests showed fully sound and ductile welds.

Weldment efficiency of Inconel 718 weldments at room temperature is above 90%, i.e., ultimate tensile strength of aged Inconel 718 welds is within 90% of base metal and, in most cases exceeded the 180 ksi (1241 MPa) minimum level specified by

AMS 5596 and MIL-Hdbk-5B for aged Inconel 718 wrought sheet. The same is true for 0.2% offset yield strength, for which the minimum specified value is 150 ksi (1034 MPa).

Similar relative results were obtained from Inconel 706, although as expected, strength values are approximately 15% lower than those of Inconel 718.

The 1200 F (649 C) and 1400 F (750 C) ultimate and 0.2% offset yield strength values of aged Inconel 718 were always above those shown in MIL-Hdbk-5B for base metal at similar temperatures. There is acceptable compatibility in welding Inconel 718 to 706.

Double fillet T-joints exhibited strength equal to base metal both in the as-welded (not aged) and aged conditions. This is due to smooth fillets on both sides without the presence of stress concentrations.

The plug weld strength values in the as-welded condition are approximately the same as base metal, whereas in the aged condition, corresponding values are 70% of base metal. This joint has limited accessibility and is conducive to incomplete fusion. Thus, unfused and stress concentration areas are present which eventually result in cracks. The results also suggest that crack growth rate rather than yield or ultimate values dictate the strength of the plug weld joint.

Age hardening treatment following welding was found to be more than adequate, without a need for a resolution treatment. Some anomalies were observed in specimens that were re-solutioned, the cause of which was not resolved during the course of this investigation.

Acknowledgments

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