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The Influence of Brazing Conditions on the Impact Strength of High-Temperature Brazed Joints

Deformation behavior is strongly influenced by operating temperature

BY E. LUGSCHEIDER AND H. KRAPPITZ

ABSTRACT. Notch impact bending tests and supplementary investigations on six representative, high-temperature, brazing combinations show the relationship between the operating temperature and the ductility properties, as well as the correlation between the brazed joint microstructure and fracture behavior. A strong dependence of the toughness qualities on temperature was established. The origin of fracture formation and propagation mechanisms could further be interpreted as a result of microstructural inhomogeneities.

It became apparent that a prerequisite for ductile joint behavior is freedom from related hard phase bands in the brazed joint and a matching of elastic/plastic behavior in the brazed joint and base material. It thus follows that not only is the optimal structural development required for a joint capable of deformation, but also the elastic/plastic behavior of the whole system of filler metal and base metal must be considered. This leads to the demand for brazing alloys whose brazed joints match the properties of the base materials with regard to the elastic moduli, plastic deformation behavior and increased strength features.

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E. LUGSCHEIDER and H. KRAPPITZ are with the Technical University of Aachen, Aachen, West Germany.

Introduction

The application of high-temperature brazed joints in both highly specialized and conventional industrial areas frequently requires not only high strength in static load, but also ductile behavior, to achieve high strength in dynamic load. Precious metal alloys, as well as nickel based alloys, are commonly used as filler metals.

While the strength and ductility characteristics of the brazing alloys containing precious metals cannot generally be faulted, their high cost means that they are sometimes rejected in favor of nickel based brazing alloys when the application allows. In order to improve the flow behavior and to lower the melting temperature of the base element nickel, boron, silicon or phosphorus is added. The resulting formation of extremely hard phases, *i.e.*, borides and silicides, may have an adverse effect on the ductility of the joint.

Through recent systematic optimization of various high-temperature brazing combinations (Refs. 1–3), it is possible to obtain joints which are generally free of embrittling secondary phases when the optimized brazing variables (brazing time, temperature, gap width) are observed. Having established the strength properties of these brazed joints, the next step in this study was to investigate their ductility behavior.

Experimental Work

Filler and Base Metals

To investigate the ductility characteristics of high-temperature brazed joints, representative alloys were chosen from

Table 1—Chemical Composition and Characteristic Temperatures of the Investigated Filler Metals

Brazing Alloy	Au %	Cr %	Fe %	Si %	B %	Ni %	Solid Temperature °C (°F)	Liquid Temperature °C (°F)
	Chemical Composition							
BNi-2	–	7	3.0	4.5	3.1	rest	970 (1778)	1000 (1832)
BNi-5	–	19	–	10	–	rest	1080 (1976)	1135 (2075)
Au-6	20.5	5.6	2.3	3.4	2.3	rest	947 (1737)	969 (1776)

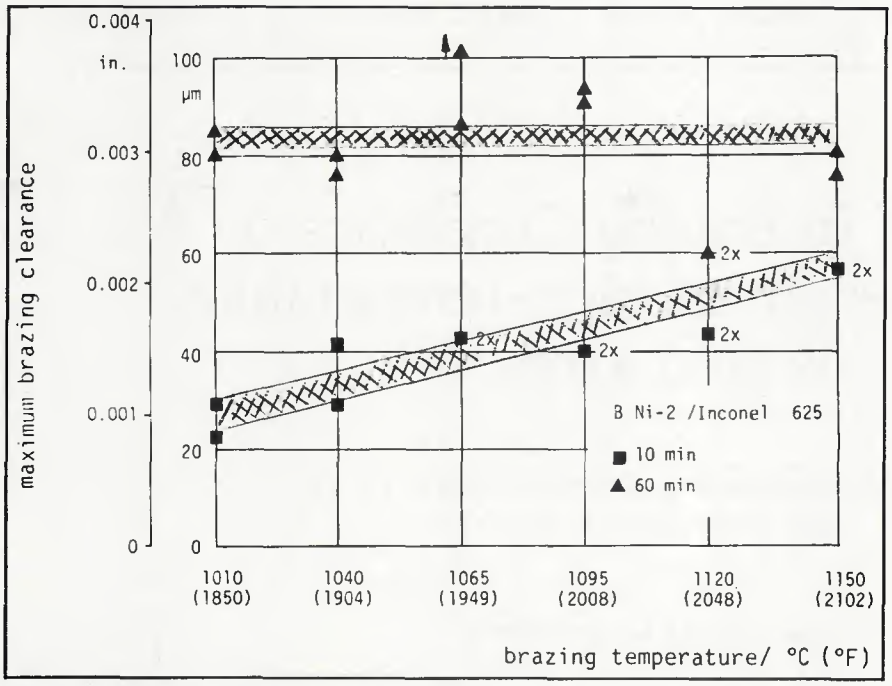

Fig. 1—Dependence of maximum brazing joint clearance on brazing temperature and holding time for the BNi-2/Inconel 625 brazing system

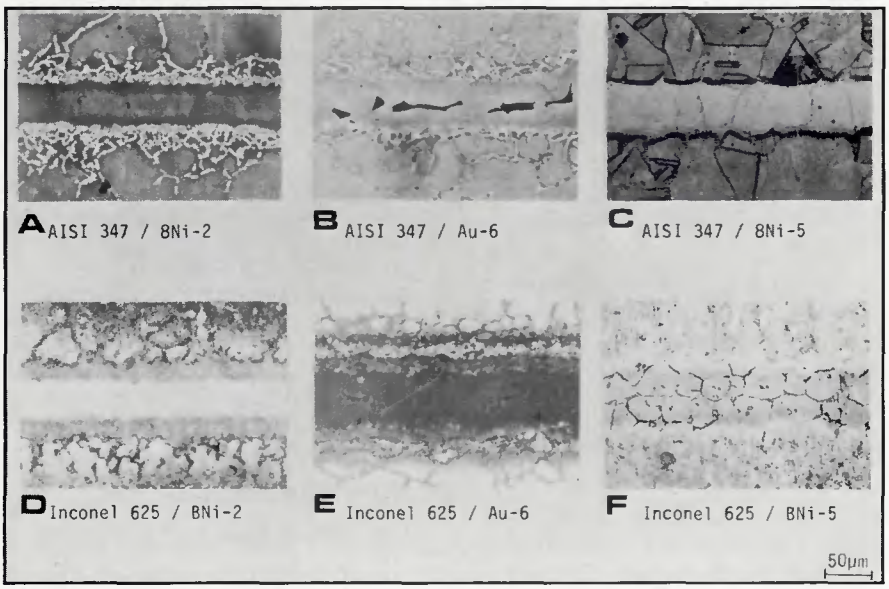

Fig. 2—Structures of the examined brazed joints made with the brazing and heat treatment conditions shown in Table 2

the groups of boron-containing, boron-free and low-precious-metal-content nickel base filler metals, respectively. Thus, the AWS standardized filler metals BNi-2 and BNi-5 and the nonstandardized, gold-containing filler metal Au-6 (Ref. 4) were used. Table 1 shows the chemical composition of the investigated filler metals and their characteristic temperatures. The filler metals were applied in powder form without a binder.

For the base metal, austenitic stainless steel AISI 347 and Inconel 625 material were chosen. The niobium-stabilized AISI 347 stainless steel is used for numerous parts in the building of chemical apparatus, as well as in the food industry. The nickel base alloy Inconel 625, due to its high resistance to oxidizing and reducing medium, is widely used in the area of chemical process technology and in the aerospace and space industries.

Brazing Conditions

The dependence between microstructure and brazing conditions of brazed joints was shown by the metallographic evaluation of specimens as described by Ref. 5. From the geometry of a wedge-shaped joint clearance, the influence of root opening width on the formation of hard phases was established. These specimens were brazed at various temperatures and holding times. The metallurgical behavior of the brazed joint was ascertained from an evaluation of the specimens by metallographic methods, and by combining the individual evaluations into a filler metal/base metal characteristic. Figure 1 shows an example of a filler metal/base metal characteristic with regard to the brazing combination of Inconel 625 and BNi-2. At brazing joint clearances wider than the determined maximum brazing joint clearance, brittle phases occur. The maximum brazing joint clearance depends on brazing temperature and holding time. In a similar way, the dependence of the maximum brazing joint clearance on the heat treatment applied can be shown.

To obtain joints free of bands of connected hard phases, brazing cycles were found (Table 2) from an evaluation of filler metal/base metal characteristics. Brazing specimens were produced using optimum brazing variables obtained in this evaluation. Brazing was carried out in a resistance heated vacuum furnace at a pressure of 1.3×10^{-4} mbar (9.75×10^{-5} torr).

Brazed Joint Structures

To examine the structure and phase composition of the joints, microsections were evaluated. Figure 2 shows typical structures of the examined brazed joints.

The transition zones of joints brazed with BNi-2 and Au-6 show boride precipitations, the intensity of which depends on the boron content of the filler metal and on the conditions of diffusion of this element in the base metal.

Due to the lack of miscibility in the solid state of the nickel/gold system, a solid solution rich in gold appears in the nickel solid solution of the gold-containing brazed joint. This can be seen as a darker area in the brazed joint—Figs. 2B, E. The microhardness of this phase is in the same scale as that of the nickel solid solution.

The joints of the austenitic base metal brazed with BNi-5 (Fig. 2C), however, show a light microscopic homogeneous structure in the brazed zone. Crystals grew out of the base metal into the brazed zone. With the established brazing conditions, a structure free of embrittling hard phases formed.

The structure of the nickel base alloy Inconel 625, brazed with the filler metal BNi-5, has a completely different appearance. The grain boundaries of the brazed seam are covered throughout with silicides, resulting in brittle behavior of the joint—Fig. 2F. At the observed brazing temperatures and holding times, it was not possible to completely eliminate the silicides.

The brazed zone may have a metallurgical notch effect on the joint. This causes, depending on different elastic and plastic properties, a more or less acute, multi-axial state of stress, which has an embrittling effect (Ref. 6).

As one method of estimating the notch effect of the brazed zone, hardness patterns were measured through the brazed joint as shown in Fig. 3. The microhardness was measured according to Vickers scale at a load of 0.5 N (HV 0.05). The boron-containing filler metals, BNi-2 and Au-6, showed an obvious increase in hardness in the transition zone, due to the inter- and transcristalline boride precipitations. The hardness of these zones reach 1.8 times the hardness of the base metal.

Brazed joints of the combination BNi-5/AISI 347 show regular hardness results through the joint. As well as the homogeneous structure, the small differences in hardness results indicate matching elastic and plastic behavior on the part of the elements making up the brazing combination.

The hardness measured in the brazed joints of BNi-5 and Inconel 625 also shows few differences, although the silicides occurring at the grain boundaries are, in this systematic graph, not taken into account because of their small size and irregular distribution through the cross-section of the brazed joint. Their hardness amounts to approximately 800 HV 0.05, as determined by further mea-

Table 2—Brazing Cycles Resulting from the Filler Metal/Base Metal Characteristics

Base Material	Brazing Alloy	Brazing Temperature °C (°F)	Holding Time, min	Heat Treatment Temperature °C (°F)	Duration of Heat Treatment, min
AISI 347	BNi-2	1065 (1949)	10	1000 (1832)	60
	BNi-5	1190 (2174)	10	1100 (2012)	60
	Au-6	1020 (1868)	60	–	–
Inconel 625	BNi-2	1065 (1949)	10	1000 (1832)	60
	BNi-5	1150 (2102)	10	1100 (2012)	60
	Au-6	1060 (1940)	60	–	–

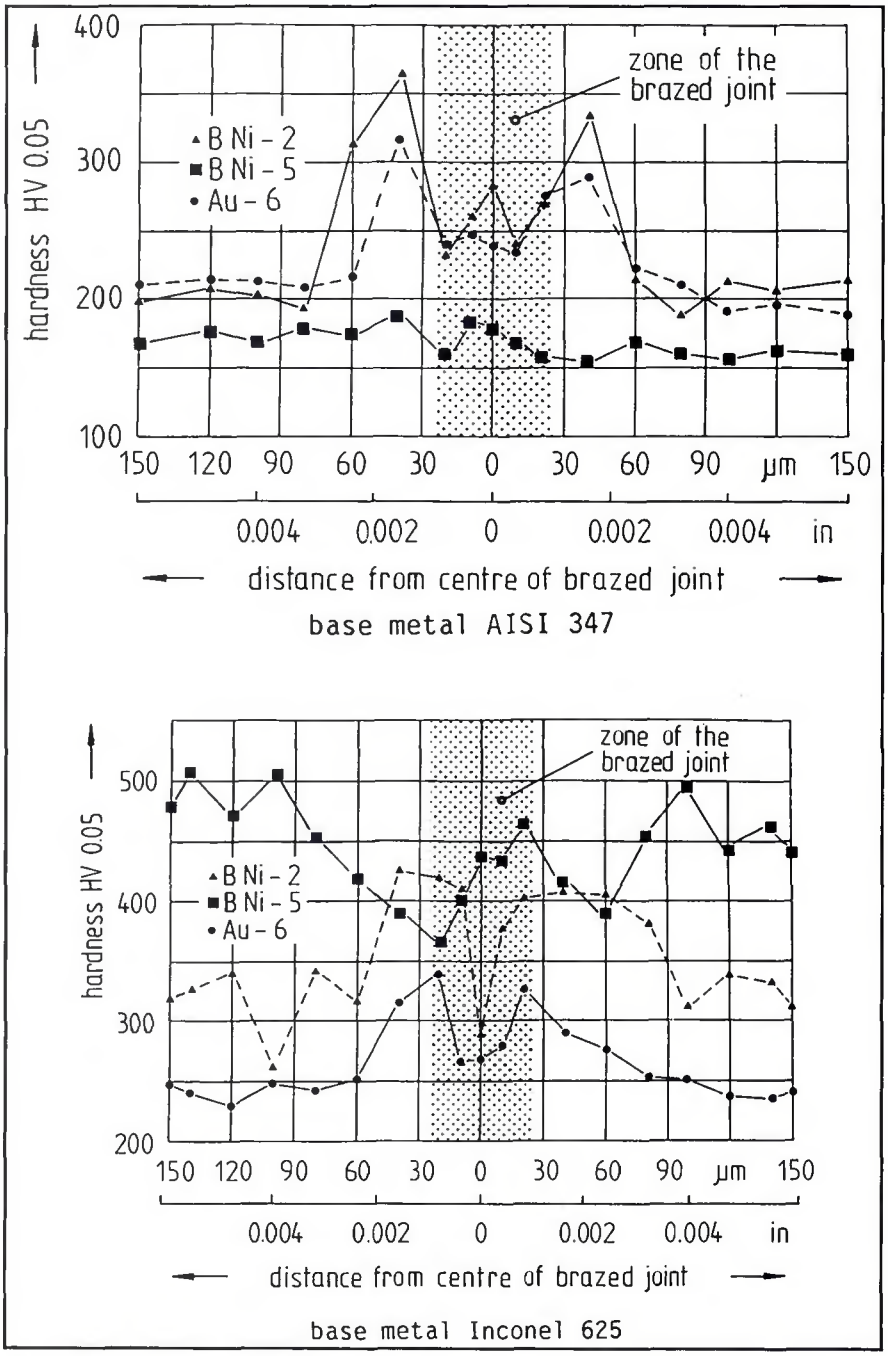

Fig. 3—Hardness patterns of the brazed joints examined

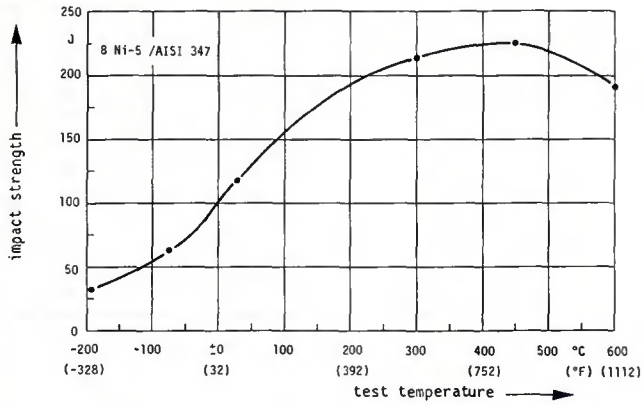

Fig. 4 — Notch impact work/temperature graph for joints brazed with BNi-5 (DVM specimens)

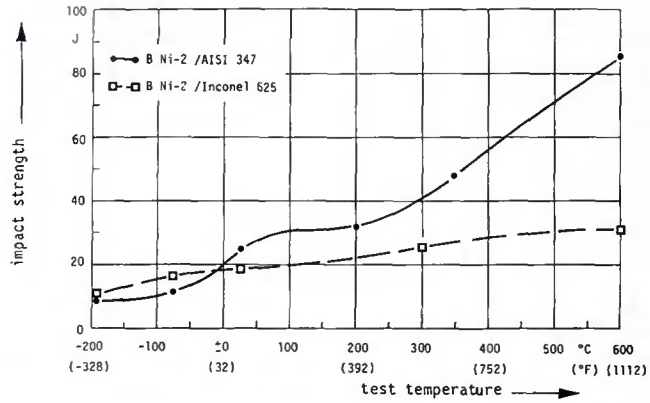

Fig. 5 — Notch impact work/temperature graph for joints brazed with BNi-2 (DVM specimens)

surement of specimens of this brazing combination.

In the joints BNi-5 and Inconel 625, the high hardness values of the base metal after completion of the brazing cycle are notable. This increase in hardness, that was always found in specimens which were brazed at high temperature, may be due to a beginning precipitation of the gamma-prime-phase Ni_3Nb when passing through the 640°C (1183°F) range during the cooling of the furnace. In addition to the formation of silicides, the increase in hardness of the base metal has a negative effect on the ductility of the joint.

The ductility properties were judged with the help of notch bend impact tests in connection with fractographic analysis of the fracture surfaces, as well as an examination of microtensile tests (using special tensile test equipment) in a scanning electron microscope.

Notch Bend Impact Tests

Influence of the Test Temperature

Notch bend impact tests were conducted using a semicircular notch (DVM specimen). This type of notch had been found in earlier investigations (Ref. 7) to be the most suitable in evaluating the ductility of brazed joints.

The dependence of ductility properties on the test temperature was established by notch impact energy/temperature graphs — Figs. 4-6. Each of the shown values is based on the evaluation of three to five samples. The notch impact test pieces which had a brazing clearance of 25 μm (approx. 0.001 in.) were tested in a temperature range of −196°C (−320°F) to +600°C (1112°F) using an impact testing machine with a maximum working capacity of 300 J (221 ft-lb).

Samples of the two investigated base metals showed completely different behavior. While the toughness of the joints in austenitic stainless steel AISI 347 has a strong dependence on the test temperature, this dependence was less severe in joints of the base metal Inconel 625, and particularly in the Au-6/Inconel 625 brazements. In the range between −79°C (−110°F) and +600°C (1112°F), impact energy increased with the increasing temperature. With lower test temperatures, a further decrease of notch impact energy was established.

Joints made with the combination BNi-5/Inconel 625 were brittle at all tested temperatures, therefore, the notch impact energy/temperature graph is not given. The silicides seen in the metallographical sample of the joint (Fig. 2F) lead to a notch impact energy of approximately 3 J (2.2 ft-lb) throughout the whole temperature range, thereby indicating the dominant influence of hard phases on the embrittlement of the joint.

Joints of the base metal AISI 347 brazed with BNi-5 which show a structure free of hard phases have high values of notch impact energy in the entire temperature range. The temperature dependence of the test results was clearly revealed — Fig. 4. With test temperatures above room temperature, the joints are very ductile. The measured values reach the notch impact energy of unbrazed metal specimens, which range from 180 to 230 J (133 to 170 ft-lb). Test temperatures above 450°C (842°F) show a slight decrease of notch impact energy. This may be attributed to a decline in the deformation resistance of the base material as the temperature increased. Below

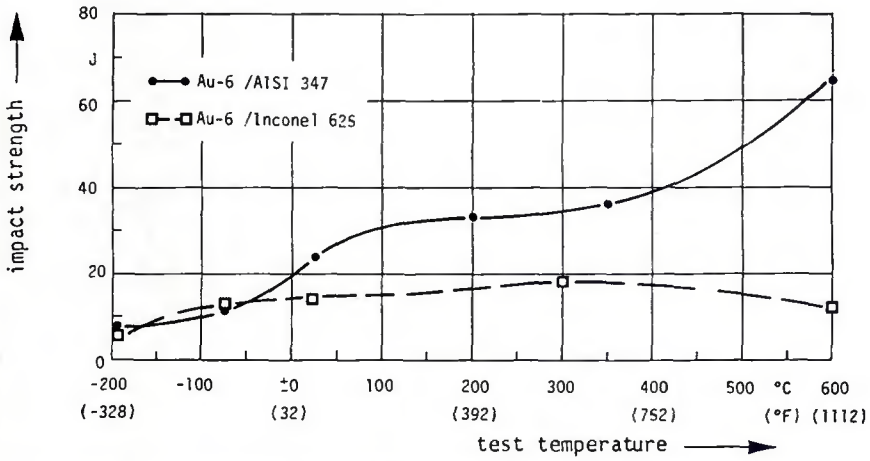

Fig. 6 — Notch impact work/temperature graph for joints brazed with Au-6 (DVM specimens)

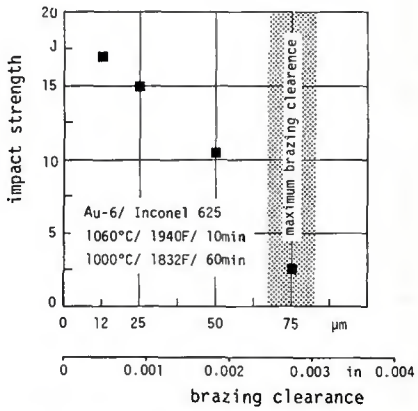

Fig. 7 — Dependence of impact strength on brazing joint clearance for the Au-6/Inconel 625 brazing system

room temperature, the notch impact energy graph shows an obvious decrease. The fracture surface of tested specimens, however, even at these low temperatures, shows a considerably deformed honeycombed microstructure. An embrittlement of the nickel solid solution caused by the temperature could not be found as expected, considering the cubic face centered lattice structure. The reduction in the notch impact energy at low testing temperatures is to be attributed to the reciprocal influence of brazing joint and base material and the thereby intensified multi-axial state of stress. Considering the notch impact work of more than 30 J (22 ft-lb), the fracture behavior of the joint, even at low temperatures, cannot be designated as brittle.

Samples of the combination BNi-2/AISI 347 generally show lower toughness than the corresponding joints brazed with BNi-5—Fig. 5. A strong dependence of the testing results on the temperature can also be seen in this brazing combination. While the joint considerably deforms at high temperatures and some samples were drawn through the support of the pendulum impact tester without fracturing, extremely low tempertures cause a macroscopic, brittle-appearing failure of the joint with poor deformation. Microscopic, ductile areas can be seen on the fracture surface. Fracture primarily occurs in the zone of the inter- and transcrystalline boride precipitations.

Joints of the nickel base alloy Inconel 625 brazed with the filler metal BNi-2 show considerably less temperature dependence than the above-mentioned brazing combination. While at room and lower temperatures, the values are almost equal for both base metals, and the toughness of the joint at high temperatures is far below that of the steel.

Similar results are found in the brazing combinations AISI 347/Au-6 and Inconel 625/Au-6—Fig. 6. It can be seen that the gold content makes no contribution to the ductility of the joint. The transition zone of the boride precipitations, where fracture primarily occurs, is hardly affected by the precious metal content.

With regard to the precious metal content, it is worth mentioning that the low scatter exhibited by the values shows very small differences in the joint properties. These results were also found for the notch impact and tensile test specimens, where the tensile strength of brazed butt joints reaches that of the base metal.

The dependence of notch impact energy on the brazing joint clearance was established at constant temperature. The joints of all investigated brazing combinations showed broadly similar behavior. This is shown for the brazing combination Inconel 625/Au-6—Fig. 7. The notch impact energy reaches the highest values at a brazing joint clearance of 12 μm (approx. 0.0005 in.). With increasing brazing joint clearance, the notch impact energy clearly decreases. Above the maximum joint clearance, at which a closed band of brittle phases occurs, low values are realized, indicating very brittle behavior. These results were confirmed in previous research (Refs. 8, 9).

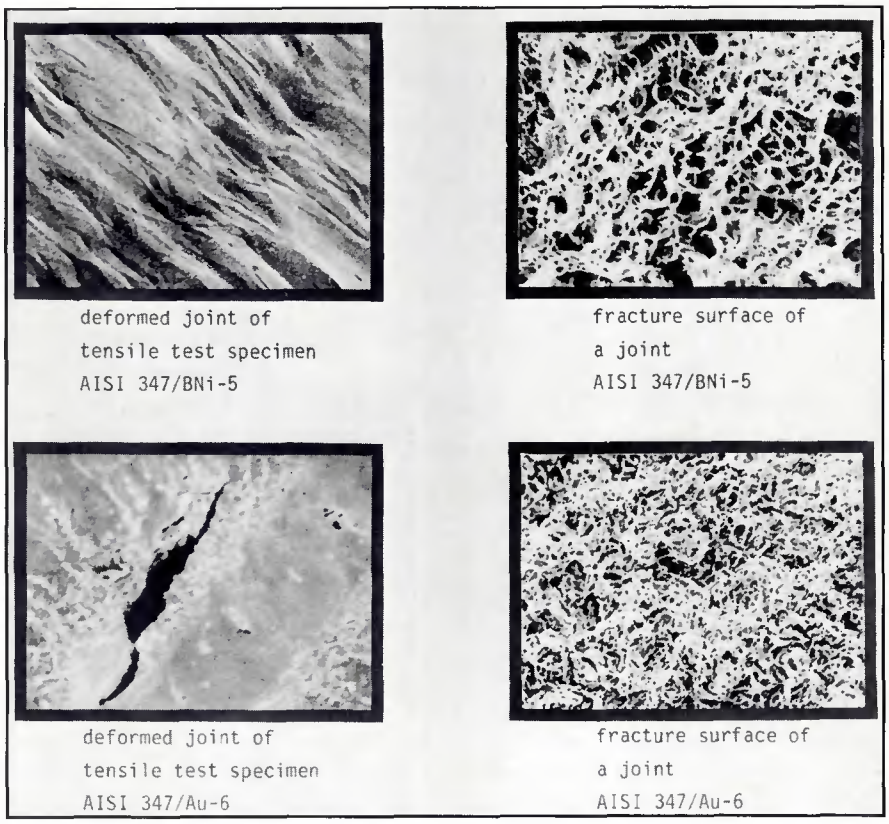

Fig. 8—Deformed joints and fracture surfaces of brazed specimens

With the least joint clearances, the wetting and flowing behavior of the filler metal must be taken into account. At brazing joint clearances of 12 μm (0.0005 in.) and less, large areas of wetting failure frequently occurred, which lead to less strength in the joint. Such a small joint clearance can seldom be achieved in production. At a more readily achievable brazing joint clearance of 25 μm (approx. 0.001 in.) and more, wetting failure seldom occurred.

Micro-Tensile Tests

The failure of brazed joints is largely influenced by the properties of the base metal and the braze, as well as by the type of load (static, dynamic, impact) and the resulting mechanisms of crack formation and propagation. In order to establish the deformation behavior of the brazed joints of the tested combinations, they were observed under load. For this purpose, adapted tensile test equipment attached to a scanning electron microscope was used. Butt joint brazed flat tensile test specimens, which were previously polished and etched to develop the microstructure, were used as samples.

Investigations show that in joints which contain a closed band of hard phases, a brittle failure of the joint already occurs at light load, as is the case in the brazing combination BNi-5/Inconel 625.

The micro-cracks which developed in the hard phases during the preparation of the samples spread spontaneously, and the work necessary for crack propagation was low. This influence of hard phases, however, is already known and has been described by various authors.

Another influence on the fracture behavior of high-temperature brazed joints was found in brazed samples which were free of hard phases. Here, the elastic and plastic deformation properties are of essential importance. As the brazed zone and the base metal show matching elastic and plastic behavior, a strong microscopic and macroscopic deformation of the joint was observed. Figure 8 (top) shows an example of a brazed joint of the filler metal/base metal combination BNi-5/AISI 347. Both the grains in the brazed zone and those of the base metal stretched considerably. Due to the high plastic deformation, the surface of the previously polished specimen formed a considerable relief. The

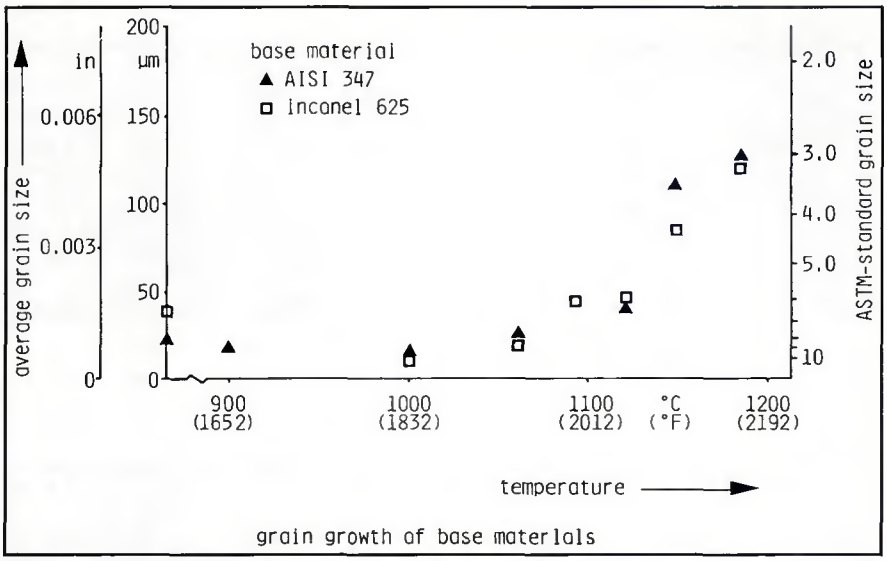

Fig. 9—Influence of brazing temperature on the average grain size for the investigated base metals

fracture in this sample occurred approximately 15 mm (0.6 in.) next to the brazed zone in the base metal. Fractures occurred in the brazed zone in further tests with this brazing combination. The fracture surface of these samples shows an acute, deformed, honeycombed structure that indicates high plastic deformation in advance of fracture.

Isolated hard phases in the brazed zone do not cause embrittlement of the joint. Cracks, which already occur at light load, in these phases are stopped at the interfacial zone of the nickel solid solution by high plastic deformation. The originally sharp base of the crack widens in the matrix and forms a large notch radius. In this way the concentration of stress at the base of a notch is reduced, and further propagation of the crack is obstructed.

The joints brazed with boron-containing filler metals show preferential formation and propagation of cracks in the zone of the inter- and transcrystalline precipitations—Fig. 8 (bottom). Cracks are formed in these areas at low deformation due to their hardness. These zones, however, do not cover large closed areas but are formed by discrete precipitated boride needles. Crack propagation is obstructed at the phase-boundaries between boride needles and base metal by plastic deformation of the base metal, which causes a more ductile behavior of these zones, compared with that of the hard phases.

Tested samples of these combinations show a finely structured fracture surface due to the boride precipitations. Besides ductile zones in the fracture surface, cracks can be found. Typical for the fracture surfaces of the tested boron-containing filler metals is the development of cracks on two levels, corresponding to the transition zone, which may be seen with the naked eye.

The influence of the braze interface structure on the ductility properties of joints brazed with Au-6 was investigated in the brazing combination AISI 347/Au-6. The formation of cracks caused by phased detachment of the interface of the dual phase crystal structure was not established. The deformation behavior of nickel-rich and gold-rich solid solutions is matched. Fracture occurs in the boride precipitations of the transition zone.

With regard to the interpretation of the above results, it should be noted that the mechanisms of fracture formation and propagation which are explained were found in a tensile test under static load. Although the obstruction of contraction across the joint produced a microscopic multi-axial state of stress, macroscopically, a uni-axial state of stress occurs. The deformation behavior of these joints, therefore, cannot be transferred to complex parts. This investigation, however, gives information on the formation and propagation of cracks.

Influence of the Brazing Cycle

Besides the above-mentioned influence of the cooling conditions on the material properties of precipitation-hardening alloys, the heat treatment applied by the brazing cycle leads to rapid grain growth in the base metal above a maximum temperature. With the tested base metals AISI 347 and Inconel 625, this rapid grain growth starts at temperatures above 1060°C (1940°F)—Fig. 9. In particular, the high temperatures needed to braze BNi-5 lead to coarse grain growth in both base metals. The ASTM average grain size increased from 8, in their delivered state, to grain size 3, after completion of a brazing cycle. In this investigation, the time the base metals are exposed to the brazing temperatures is of less significance than temperatures themselves. Tests show, however, little influence of the grain size on the ductility properties of austenitic materials.

Conclusions

The investigations conducted showed that a systematic optimization of the brazing variables leads to joints which are free of embrittling hard phases. This is an essential condition in order to achieve ductile behavior of brazed joints. The absence of embrittling hard phases leads to joints which can withstand high plastic deformation if the elastic and plastic properties of the brazed joint and base metal are well matched. This leads to the demand for filler metals whose mechanical properties in the joint are well matched to those of the base metals. The development of precipitation-hardening filler metals to join high-strength steels could be considered. The specific influence of the brazing process, for example, the control of cooling conditions, as suggested in Ref. 10, could also contribute to this.

Samples of joints with mechanically matched filler metal/base metal combinations tested at various temperatures showed a strong dependence of the deformation behavior on the test temperature. The temperature dependence of impact energy was low when the different behavior of the base metal/filler metal leads to the obstruction of contraction across the joint, causing embrittlement.

By *in situ* observations of brazed butt joint tensile test specimens under load, the failure procedure of brazed joints with various microstructures could be determined. Different mechanisms of failure occurred, depending on various brazing combinations.

Considering the mechanisms of fracture in high-temperature brazed joints, an assessment of the notch impact test can be made. As high values of notch impact energy are obtained, the proof of ductile behavior of the joints is furnished. However, when the values of notch impact energy achieved are low, it may not be attributed to brittle behavior of the joint. For an assessment of the ductility behavior, further investigations are required. For additional information, the fracture surface of tested specimens may be evaluated. In combination with a metallographical examination, it can be evaluated if the brittle-appearing behavior in notch impact tests are caused by hard phases or brazing defects or by a mismatch of the elastic and plastic deforma-

tion behavior of the brazed joint and the base metal. In this case, the joint may show microscopic ductile behavior. An assessment of the ductility then requires further investigations, for example, fracture mechanic evaluations.

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Call for Papers

Applications of Electron and Laser Beam Welding

Papers are being solicited for an AWS/AWI-sponsored international conference, "Applications of Electron and Laser Beam Welding," to be held in Hartford, Conn., September 16-17, 1987. The conference will cover present and potential production applications and laboratory innovations of both of these forms of energy beam technology. Specific topics will include heat treatment, thin material welding and cutting, dissimilar metal joining, and out-of-vacuum electron beam processing, among others. Application areas include shipbuilding, nuclear, transportation and consumer products. Conference proceedings will be published. Submit abstracts of 200–250 words by November 30, 1986, to Dr. H. G. Ziegenfuss, Technical Director, American Welding Society, 550 N. W. LeJeune Rd., P. O. Box 351040, Miami, FL 33135. Full papers for those abstracts selected will be required by March 1, 1987.

WRC Bulletin 315
June 1986

Stress Rupture Behavior of Postweld Heat Treated 2¼ Cr-1Mo Steel Weld Metal
By C. D. Lundin, S. C. Kelley, R. Menon and B. J. Kruse

WRC Bulletin 315 complements Bulletin 277, issued in May 1982. Together, these bulletins address the creep properties of 2¼Cr-1Mo steel weld metal deposited with several different welding processes. They contain data obtained from the literature as well as from the many tests conducted on this program. The experimental data, in both reports, are for weld metal of several different carbon contents, postweld heat treated at either of two commonly used postweld heat treating temperatures.

Publication of this report was sponsored by the Subcommittee on Weld Metals and Welding Procedures of the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 315 is $18.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Ste. 1301, 345 E. 47th St., New York, NY 10017.