

# Brazing Filler Metal Evaluation for an Aircraft Gas Turbine Engine Application

Silver, copper and nickel base brazing filler metals were investigated as replacements for an Au-18 Ni brazing filler metal for vane-and-shroud compressor stator assemblies

BY R. P. SCHAEFER, J. E. FLYNN AND J. R. DOYLE

**ABSTRACT.** The basic characteristics of some silver, copper and nickel base brazing filler metals were investigated for application as possible cost-effective replacements for the Au-18Ni filler metal in an aircraft gas turbine engine component. A metallographic examination was conducted on brazed AISI 410 tee-joint specimens to evaluate braze flow, joint microstructure, and interaction between the filler metal and the base metal. Oxidation and tensile shear strength testing of each filler metal was conducted up to 1200°F, followed by room temperature fatigue strength testing of selected brazing filler metals.

Actual vane-and-shroud compressor stator assemblies were brazed with selected filler metals under normal production conditions for engine testing to evaluate their reliability under actual service conditions.

It is shown that the ductility and strength of the filler metals investigated are related to the joint microstructure. Filler metals of Au-Ni and Cu-Mn-Co which are predominantly solid solution possessed excellent ductility and strength, whereas the properties of the filler metals of Ag-Cu-Pd and Ni-Cr-Si-B with intermetallic and/or eutectic phases were considerably lower at gap width tested. The silver and copper base brazing filler metals were shown to be limited by their oxidation resistance, although high temperature strength was adequate. Brazing filler metals 706 and 9217 satisfied the established goals of this program for service applications to 800°F and 1000°F, respectively.

## Introduction

Brazing processes have established a long history of dependable, aircraft quality joints in the assembly of gas turbine engine components. Over a period of years, one specific filler

The authors are affiliated with the Materials Engineering and Research Laboratory, Pratt & Whitney Aircraft Div., United Aircraft Corp., East Hartford, Conn.

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metal system (82 w/o Au-18 w/o Ni) has found wide usage in the aerospace industry based on a series of enviable joint properties. As observed in Fig. 1, the Au-18Ni composition lies at the minimum point in the Au-Ni phase diagram and solidifies completely at 1742°F; it exists as a mixture of solid solutions below 1400°F.<sup>1</sup> This sharp solid/liquid transition coincides with the austenitizing temperature for martensitic stainless steels, eliminating the necessity of an additional and costly heat treatment after brazing. The absence of brittle eutectic and/or intermetallic phases within the filler metal yields a ductile joint, characteristic of solid solutions. The relative insensitivity of the filler metal to joint clearance variations eliminates the need and cost of precise clearance control during assembly fabrication. Excellent strength and oxidation resistance, coupled with extensive reliability under service conditions, have established the Au-18Ni filler metal as the quality brazing filler metal of the industry with regard to manufacturing and service considerations.

The Au base filler metals, however, imply high cost, especially with the appreciable volume utilized in the construction of gas turbine com-

ponents. The Au-Ni filler metal is widely used, with the greatest volume committed to compressor stator vane and shroud assemblies (Fig. 2). This application offers a particular challenge for brazing filler metals because of the criticality of the component and the wide service temperature range over which it operates. The high cost of Au-Ni has been traditionally justified on the basis of its unique ability to fulfill this application requirement.

In an attempt to increase cost effectiveness, a continuing effort has been maintained to locate alternative, low cost filler metals with properties approaching those of Au-18Ni. Ag, Cu and Ni base filler metal systems and filler metals with reduced Au levels were therefore investigated for stator assembly applications. It was acknowledged from earlier data on these systems that a reduction in some of the desired properties would be inevitable; however, it appeared that a customized filler metal selection for specific service conditions could effect a significant filler metal cost reduction. With this in mind, various filler metal compositions were selected and evaluated with consideration given to the following goals:

1. Cost less than 50% that of Au-18Ni.
2. A narrow melting range and a brazing temperature compatible with the hardening heat treatment of martensitic stainless steels (i.e., 1800 to 1900°F).
3. Adequate flow characteristics on martensitic stainless steel for varying joint clearance situations without excessive flashing.
4. Useful tensile shear strength (i.e., 15 ksi at maximum service temperatures), oxidation resistance (e.g., less than 0.005 in. after 1000 hr/1000°F exposure) and ductility at elevated temperatures.

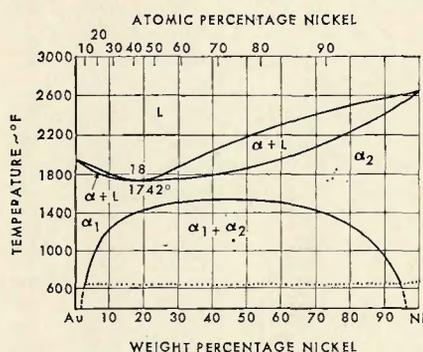


Fig. 1—Au-Ni constitutional phase diagram

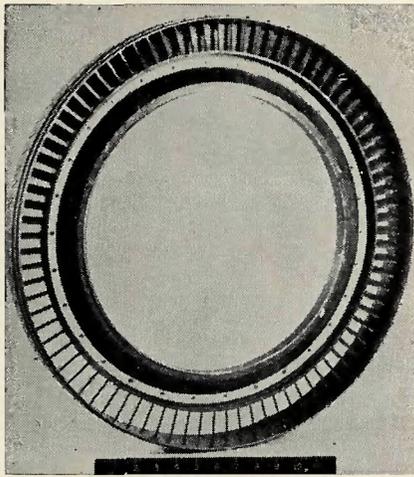


Fig. 2—Typical brazed compressor stator assembly for aircraft gas turbine engine application

5. Fatigue strength comparable to that of Au-18Ni.

### Materials

Variations of Cu and Ag brazing filler metal systems were investigated and thereupon compared to the standard Au-18Ni filler metal. In addition, data were generated on some of the commercially available Ni base filler metals. A tabulation of the nominal chemical analysis, liquidus temperatures, and relative cost of all filler metals investigated is given in Table 1.

The Ag and Au filler metals were prepared by commercial sources using conventional vacuum induction melting equipment. These filler metals were single melted and cast into ingots at vacuum levels below  $10^{-4}$  mm Hg pressure. After spectrographic analysis to verify alloy content, the ingots were converted into 0.028 in. thick foil by a precision cold rolling process, and further reduced as specified. Cu systems containing Mn required an argon partial pressure during melting to prevent loss of Mn and intermittent bright annealing treatments in exothermic gas during the foil conversion to reduce cold working tendencies. Since the Ni base brazing filler metals are basically brittle in the as-cast condition and consequently unfabricable into wire or sheet, -140 mesh powder was produced by melting and atomization in an inert gas atmosphere.

The filler metals investigated were intended for applications on vane-and-shroud compressor stator assemblies since the greatest volume of the Au-18Ni filler metal is utilized in the construction of these components. Martensitic stainless steels, capable of retaining adequate strength through 800°F service conditions, are common materials for these stator assemblies. AISI Type 410 stainless steel (AMS

Table 1—Tabulation of Brazing Filler Metals and Brazing Temperatures

Alloy system designation	Filler metal designation	Nominal composition wt-%	Approximate liquidus, °F	Brazing temperature, °F	Relative cost
Au	698	82Au-18Ni	1742	1825	100%
	712	18Au-45Cu-27Ni-10In	1800	1850	30
Ag	706	54Ag-25Pd-21Cu	1742	1800	40
Cu	9217	58.5Cu-31.5Mn-10Co	1730	1825 <sup>a</sup>	5
Ni	4777	83Ni-7Cr-4Si-3B-3Fe	1830	1900	2
	4778	92.6Ni-4.5Si-2.9B	1900	1900	2

<sup>a</sup> Higher temperatures may be required in hydrogen atmospheres of marginal dew point.

5504) and Greek Ascoloy (AMS 5508) were therefore chosen as base metal alloys for this brazing program. Compositions of these alloys are Fe-12.5Cr-0.15C and Fe-13Cr-3W-2Ni-0.175C, respectively; standard heat treatments for both alloys consist of austenitizing above 1550°F with a rapid cool followed by tempering at 1020-1075°F to attain a balance between strength and toughness. Initial brazing studies were conducted on simple sheet metal assemblies, while final evaluations were conducted with actual vane-and-shroud compressor stator assemblies.

### Brazing Equipment

The preliminary brazing filler metal investigation was conducted in a resistance heated mullite-tube laboratory furnace under purged dry hydrogen of -80°F dew point.

Subsequent brazing of tensile shear strength specimens and actual vane-and-shroud stator assemblies was performed in production brazing facilities, as shown in Fig. 3. This Lindberg continuous roller hearth furnace is 78 ft long, and has a 63 in. wide by 23 in. high brick-lined chamber with internal resistance heating elements. Dry hydrogen (-60°F dew point) is introduced into the center of the chamber with appropriate flame curtains at each end. The furnace chamber is divided into six separate compartments with overhead doors between each to permit sequential brazing operations as a component progresses through the furnace.

A typical stator assembly furnace brazing operation requires  $4\frac{1}{6}$  hr

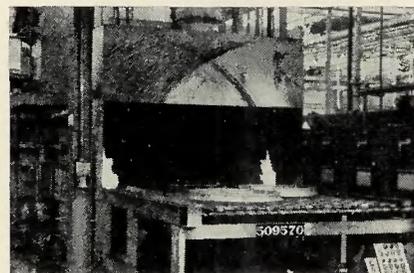


Fig. 3—Continuous roller-hearth brazing furnace utilized in the production of stator assemblies

from introduction to exit at the opposite end. The first zone (65 minutes duration) is an unheated, hydrogen purging station, to assure that clean, dry hydrogen will be attained through subsequent zones. Preheating to 1650-1700°F is conducted in the second zone (70 minutes) to uniformly raise the assembly temperature just below the filler metal solidus temperature and to reduce any surface oxides before brazing. Brazing takes place in the third zone (10 minutes) between 1800°F and 1900°F depending on the filler metal being used followed by a 25 minute furnace cool. The braze solidifies and is allowed to set in the 1650°F fourth zone (20 minutes) while quenching from the austenite region is carried out in the fifth zone (50 minutes). This unheated fifth zone is water jacketed to effect rapid cooling. The sixth and final zone (10 minutes) consists of an unheated gas dispurge with a flame curtain at the exit door. Cycle times and temperatures may vary depending on the alloy being brazed.

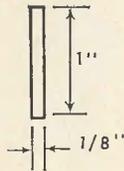
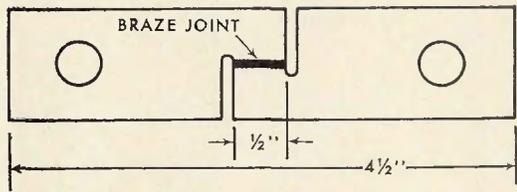
After visual joint inspection and verification of shroud hardness levels, stator assemblies are tempered at 1020-1075°F in an electric resistance heated Lindberg pit furnace under a purged nitrogen atmosphere, and then fan cooled.

### Experimental Procedure

All experimental testing was conducted on AISI Type 410 stainless steel to simulate actual stator brazing conditions. Sheet metal specimens were vapor degreased and cleaned with acetone prior to application of the brazing filler metal. Since aluminum and titanium are not present in the base metals under consideration, special preparation (such as nickel plating) of the mating surfaces was unnecessary. Grit blasting of the base metal with silicon carbide particles was found to have an insignificant effect on braze wettability and was not employed in this investigation. Vacuum brazing specimens were cleaned as above and precycled in hydrogen at 1825°F for 10-15 minutes.

Preliminary alloy screening was

MILLER-PEASLEE SPECIMEN



SINGLE-LAP SHEAR SPECIMEN

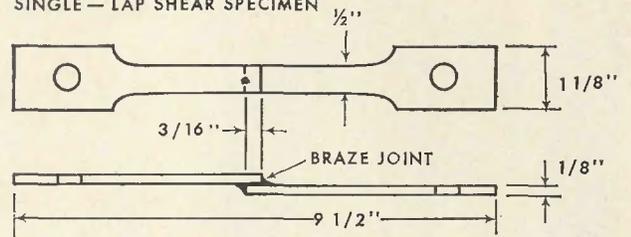


Fig. 4—Braze joint tensile shear strength specimens

performed on 0.042 in. thick sheet metal tee-joint specimens with a nominal joint clearance of 0.003 in. held by a tack weld on either side of the 4 in. length. The filler metals were applied in various forms along the entire length of one side of the specimen; alloys in wire and sheet form were tacked close to the joint by a capacitor discharge unit, while an acrylic vehicle was used with those filler metals in powder form. Each filler metal was brazed at several temperatures in a laboratory furnace to determine optimum brazing conditions, and subsequently examined metallographically. The Mn bearing compositions were also brazed in the roller hearth furnace described earlier to determine their suitability under production brazing conditions. Selected alloys were also brazed in vacuum. An electron microprobe traverse was conducted on a braze joint of one filler metal (alloy 712) to identify elemental segregation.

Tee-joint specimens were then brazed under optimum conditions and exposed to 600°F, 800°F, 1000°F and 1200°F in still air to determine the oxidation resistance of each of the filler metals. Specimens were nickel plated to retain the oxide during subsequent metallographic preparation. The depth of oxide penetration was

measured metallographically after 500 and 1000 hours exposure. The presence of thermal instabilities was evaluated by the comparison of bend ductility taken in the as-brazed condition and after the elevated temperature air exposure. The single leg of the tee was bent in a vise, with subsequent observation of the location of failure and the angle of bend at the onset of failure.

Two types of sheet metal specimens (shown in Fig. 4) with a nominal joint clearance of 0.003 in. were utilized to determine braze joint tensile shear strength.<sup>2</sup> All brazing was accomplished in a roller hearth furnace at the predetermined optimum conditions. After final machining, tensile shear strength testing was conducted in the as-brazed condition on an Instron testing machine at room temperature, 800°F, 1000°F and 1200°F.

Upon completion of the initial laboratory testing, an actual aircraft engine 10th stage high pressure compressor stator assembly (Fig. 2) with AISI Type 410 stainless steel shrouds and Greek Ascoloy strip stock vanes was chosen for fatigue testing and investigation of selected filler metals on actual engine components. The slots in annealed shrouds were produced by a piercing operation using prehardened vanes as the die punch.

The assembly was partitioned into 120 deg arc segments of 28 vanes per segment for comparison of properties. The brazing filler metal was applied in the form of 0.012 in. thick airfoil-shaped preforms stamped out of cold rolled sheet. The assembly was brazed and austenitized simultaneously to a hardness of RC 35-40 and then tempered to a hardness of RC 30-38. All of the braze joints were visually and fluorescent penetrant inspected for residual strain cracking caused by differential cooling between the inner and outer shrouds.

Fatigue data on these brazed stator joints were obtained at room temperature in a high-cycle fatigue testing rig. The inner shroud was removed from the stator assembly segments to permit electromagnetic excitation of individual vanes, causing an alternating fatigue load in the vane-to-shroud braze fillets (see Fig. 5). Vanes were excited at their natural resonant frequency, with the flutter amplitude related to fillet fatigue stress via initial strain gauge readings. The maximum applied stress of  $10^7$  cycle fatigue endurance was generated by incremental fatigue loading and determination of the vane life before failure. Fatigue failures were indicated by a reduced flutter amplitude and were detected with an oscillator/oscilloscope monitor as well as being obvious visually.

Finally, selected filler metals were used to braze full stator assemblies under normal production conditions for engine testing to evaluate their

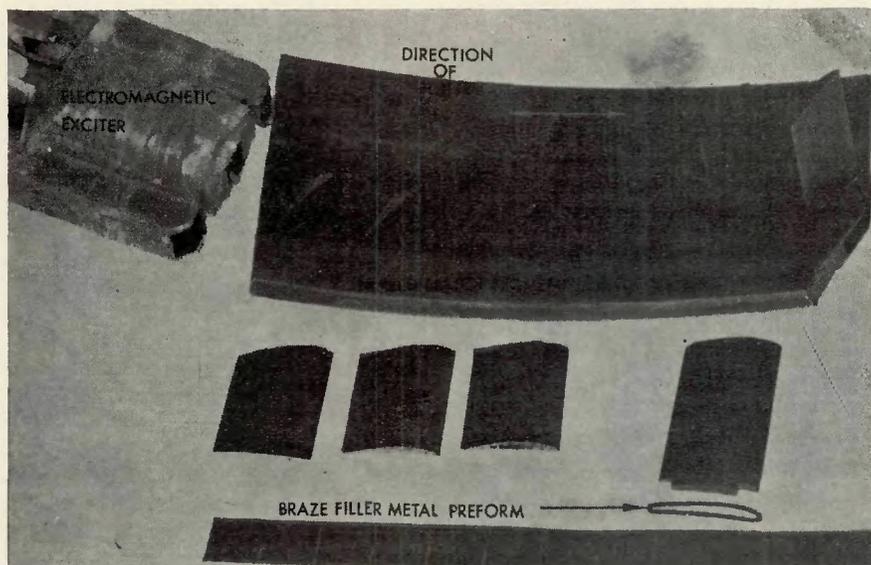


Fig. 5—Fatigue tested brazed vane and shroud stator segment



Fig. 6—Typical as-brazed fillet microstructure, Au-based filler metal 698; tee-joint. Vilella's reagent + 50% acetic acid + 50% HNO<sub>3</sub> etch.  $\times 75$  (reduced 50% on reproduction)

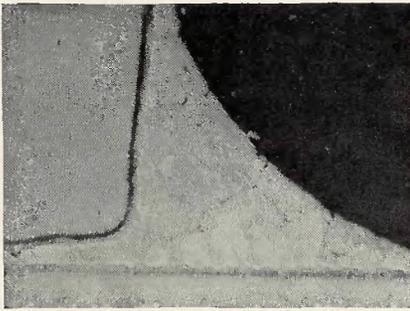


Fig. 7—Typical as-brazed fillet microstructure, Ag-base filler metal 706; tee-joint. Vilella's reagent + Palmerton's reagent.  $\times 75$  (reduced 50% on reproduction)

reliability under actual service conditions.

## Discussion

Before proceeding with the discussion of results, it must be noted that the brazing filler metals listed in Table 1 were not all evaluated simultaneously. Filler metal 706 (Ag-Pd-Cu) was initially considered and it has already replaced Au-18Ni on many components up to 800°F service temperatures. A second program investigated filler metal 712 (Au-Cu-Ni-In) in an attempt to extend the range of Au-18Ni replacement, and finally the Cu and Ni base filler metals were evaluated to pursue more cost-effective systems (Table 1). For clarity, however, all of these filler metals will be discussed simultaneously with respect to their application to stator assemblies.

## Brazing Characteristics

Tee-joint specimens furnace brazed in hydrogen at temperatures ranging from 1775°F to 1925°F were visually and metallographically examined to determine the optimum brazing temperature and conditions for each filler metal. Specific attention was given to wettability, flow, microstructure and interaction with the base metal. The optimum brazing temperature was chosen as that temperature within the normal heat treating range of AISI 410 stainless steel and Greek Ascoloy (1800-1900°F) which yielded uniform fillets on both sides of the joint without excessive base metal erosion. The recommended brazing temperatures are listed in Table 1. At these temperatures the AISI 410 stainless steel was readily wet by all of the alloys under consideration; individual alloy temperature restrictions will be discussed later.

### Filler Metal 698 (Au-Ni)

Although filler metal 698 readily flowed above 1775°F, an optimum brazing temperature of 1825°F was chosen in consideration of temperature

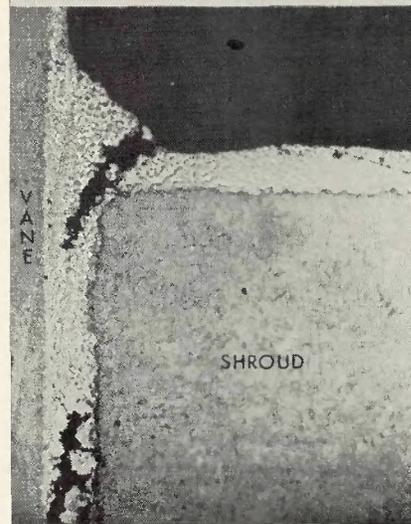
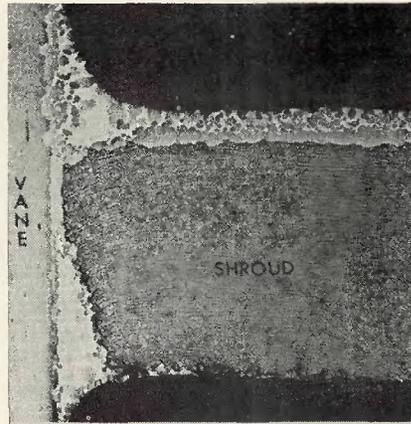


Fig. 8—Typical as-brazed Au-base filler metal 712 microstructure (top) unrestrained vane and shroud joint; (bottom) hot cracking of restrained compressor stator assembly fillet. Vilella's reagent.  $\times 50$  (reduced 28% on reproduction)

tolerances of large production furnaces. At temperatures above 1850°F, base metal erosion became evident with up to 0.005 in. penetration observed at 1925°F in the area of the braze fillet. The extent of erosion is an important factor, especially at the thin trailing edge of the vane where a buildup of filler metal due to gravity is common. Erosion occurs by dissolution of the base metal in the molten filler metal; consequently, excessive filler metal will allow a greater volume of base metal to be dissolved. Above 1850°F, filler metal 698 may erode completely through the vane trailing edge, detracting from the structural integrity of the brazed assembly. A typical filler metal 698 fillet is shown in Fig. 6. Etching with 50% acetic acid and 50% HNO<sub>3</sub> delineates the Au and Ni rich solid solutions present in Au-18Ni.

### Filler Metal 706 (Ag-Pd-Cu)

The flow characteristics of filler

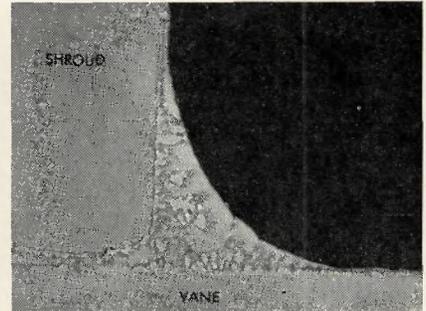


Fig. 9—Typical as-brazed fillet microstructure, Cu-base filler metal 9217; vane to shroud joint. Vilella's reagent.  $\times 75$  (reduced 50% on reproduction)

metal 706 were similar to those of filler metal 698. At the higher temperatures there was no evidence of base metal erosion; however, flashing away from the joint was extensive with filler metal 706. This condition appeared to be time and temperature dependent and consequently the brazing temperature was limited to 1800°F; shortening of the time at temperature would be impractical for production conditions. The structure of an filler metal 706 fillet, as shown in Fig. 7, consists of islands of Pd-rich solid solution in a eutectic matrix (Ag-Cu). Minor shrinkage cracking was occasionally observed within this eutectic phase, which indicates lower ductility. Conversely, brazing filler metals with a solid solution matrix normally do not exhibit this reduced ductility characteristic.

### Filler Metal 712 (Au-Cu-Ni-In)

A typical brazing filler metal 712 vane-to-shroud braze joint is illustrated in Fig. 8 (top). As seen at the top of the horizontal member, a skull of filler metal is evident at the area of alloy preplacement. It is apparent that alloying with the base metal has occurred during heatup through the alloy's wide solid/liquid transition, leaving an unmelted phase at the braze base metal interface at brazing temperature. This solid phase at the interface has restricted complete flow into the joint; however, sufficient molten material was available to create ample fillets on both sides of the joint. As expected, this effect was more pronounced on those joints brazed in a roller hearth furnace, where partial melting may have existed during the 70 minute preheating cycle. As is typical of Cu bearing filler metals, extensive flashing was observed; however, the thickness of the layer was on the order of 0.0001 in. and was considered insignificant.

Three separate phases are discernible in the top photomicrograph of Figure 8. An electron microprobe traverse was conducted across a typi-

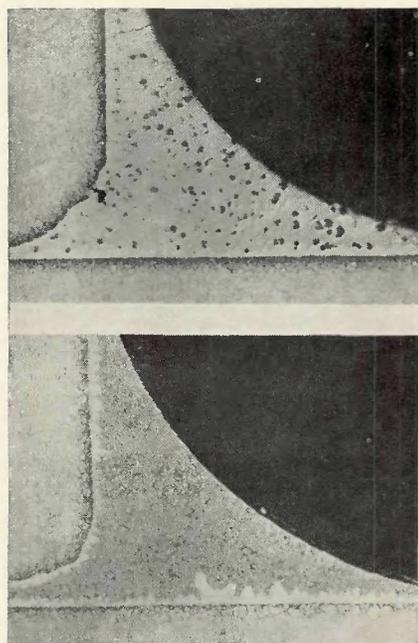


Fig. 10—Typical as-brazed fillet microstructure (top) Ni-base filler metal 4777, tee-joint; (bottom) Ni-base filler metal 4778, tee-joint. Vilella's reagent + 50% acetic acid-50% HNO<sub>3</sub> etch.  $\times 75$  (reduced 50% on reproduction)

cal filler metal 712 braze joint to determine the elemental composition of each of these phases. The dark phase found primarily near the braze/base metal interface was found to be rich in Ni and deficient in In, with significant levels of Fe and Cr resulting from diffusion with the base metal. These data suggest that this phase is completely solidified at the brazing temperature as discussed earlier. The matrix of the braze joint is separated into two distinct phases; the darker phase was predominantly Cu and Au, while the lighter phase was rich in Au with up to 25% In. The white area appeared to be the last portion to freeze upon cooling due to its high concentration of the melting point depressant indium. Brittleness of this phase was evidenced on subsequent bend testing (discussed later) and further supported by examination of an experimental brazed stator assembly, where cracking occurred at the trailing edge fillet of every vane at the inner shroud location (Fig. 8, bottom). This cracking was caused by restraint stresses developed by unequal cooling of the unequal mass shrouds. Either inadequate hot tensile strength or the presence of the In-rich phase as a liquid (at 1650°F quench) could have caused this cracking.

#### Filler Metal 9217 (Cu-Mn-Co)

Brazing filler metal 9217 flowed readily at 1825°F under laboratory

Table 2—Oxidation Resistance of Brazed Joints

Filler metal <sup>a</sup>	Oxidation in static air <sup>b</sup>					
	600° F 1000 hr	800° F 500 hr	800° F 1000 hr	1000° F 500 hr	1000° F 1000 hr	1200° F 500 hr
4777	A	A	A	A	A	A
4778	A	A	A	A	A	A
698	A	A	A	A	A	A
712	A	A	A	A	A	B
9217	A	A	A	C	C	D
706	A	B	B	D	E	E

<sup>a</sup> Filler metals are listed in order of decreasing oxidation resistance.  
<sup>b</sup> A = < 0.001 inch penetration; B = 0.001–0.002 inch penetration; C = 0.002–0.005 inch penetration; D = > 0.005 inch penetration; E = fillet completely oxidized.

conditions as shown in Figure 9. The Cu-Mn phase diagram is similar to that of Au-Ni with congruent melting at 1598°F and 35% Mn. Brazing filler metal 9217 consists of this minimum melting point composition with 10% Co added to improve the oxidation resistance of the filler metal. Similar to Au-18Ni, it consists basically of a mixture of solid solutions which tend to be ductile and insensitive to varying joint clearances.

Tee-joint specimens brazed at 1825°F in a roller hearth furnace under production conditions exhibited a greenish-grey oxide on the fillet surface and also a skull of oxide where the filler metal wire or sheet was preplaced on the specimen. Although braze flow was observed through the oxide shell, a poor quality joint resulted with shrinkage cavities, voids and oxide contamination. This oxide case would make repair rebrazing impossible. When the filler metal was applied in powder form and brazed at 1825°F, braze flow was negligible. Oxidation during heatup was more severe in this case due to the greater surface area of the powder compared to the wire or sheet and consequently powder is not recommended where atmospheres are marginal.

While the hydrogen dew point of the laboratory furnace was generally –80°F, the dew point in the roller hearth furnace averaged –60°F, due to its size and to back leakage from the open ends of the furnace. This increase in water vapor allowed oxidation of the Mn to occur by the reaction  $Mn + H_2O \rightarrow MnO + H_2$ , while reduction took place with the dew point of –80°F. This sensitivity of Mn to water vapor may be diminished by increasing the brazing temperature and consequently raising the free energy of MnO to a level where reduction occurs under the same –60°F dew point. It was found that brazing of filler metal 9217 at 1875°F or higher in the –60°F dew point hydrogen roller hearth furnace consistently resulted in a clean oxide-free joint. Although some fillet shrinkage

occurred at the 1875°F brazing temperature, it was considered insignificant. Higher brazing temperatures (e.g., 1900°F), capable of correcting this shrinkage condition, were therefore not employed.

Special conditions were required for vacuum brazing filler metal 9217 due to its high Mn content. Mn has a high vapor pressure (approximately 25 microns Hg at 1850°F) and requires a rapid heating rate and short time at temperature to prevent excessive vaporization with resulting variance in alloy composition. This type of a furnace cycle, however, is impractical for large production vacuum furnaces, making necessary a partial pressure backfill of a dry inert gas such as argon to prevent vaporization.

#### Filler Metals 4777 (Ni-Cr-Si-B-Fe) and 4778 (Ni-Si-B)

Filler metals 4777 and 4778 flowed readily at 1900°F with no base metal erosion as shown in Figure 10 (top and bottom, respectively). The unalloyed fillets in these joints generally consist of B and Si lean solid solution dendrites in a matrix of eutectics and intermetallic compounds (borides and silicides). A layer of complex solid solution exists at the braze/base metal interface due to rapid diffusion of B and Si from this region into the AISI 410 stainless steel grain boundaries.<sup>3</sup> For joint clearances less than 0.002 in., this more ductile solid solution phase was observed completely across the joint; at joints of wider gaps, a brittle eutectic structure was observed between the two base-metal members.

It was observed that long diffusion cycles near the brazing temperature greatly increased the extent of the desirable interfacial solid solutions; however, the depth of intergranular penetration of B correspondingly increased. Due to the low ductility of the borides, the effective thickness of the base metal can be significantly lowered by this intergranular type of diffusion, especially with the thin sheet metal vanes and shrouds of stator assemblies. Joint ductility may also be improved by increasing the brazing

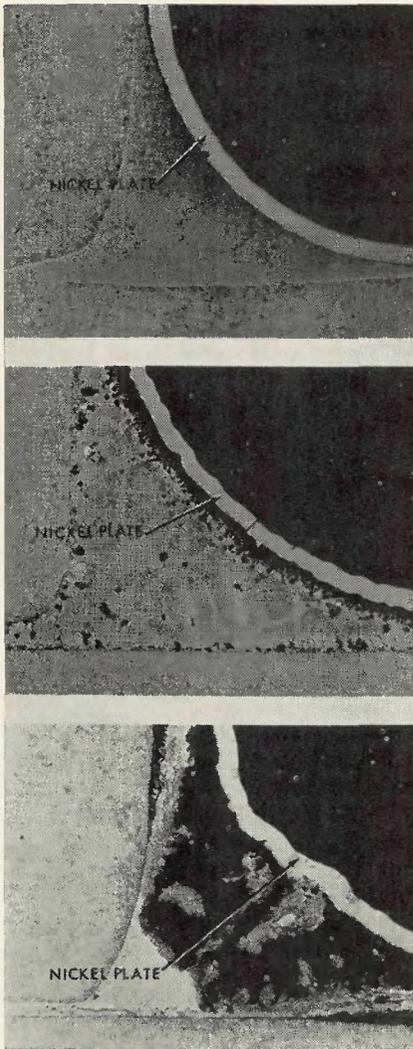


Fig. 11—Typical fillet microstructures after 1000° F air exposure: (top) Au-base filler metal 698, 1000 hr; (center) Cu-base filler metal 9217, 1000 hr; (bottom) Ag-base filler metal 706, 500 hr. Vilella's reagent.  $\times 75$  (reduced 43% on reproduction)

temperature; however, base metal grain growth occurs above 1900°F, resulting in reduced fatigue properties. Reaustenitizing of the assembly between 1800°F and 1900°F to regain the desired properties would also add additional cost to the assembly.

### Oxidation Resistance

The results of air exposure at temperatures between 600°F and 1200°F are given in Table 2 in order of decreasing oxidation resistance. Brazing filler metals 4777, 4778, and 698 showed negligible oxidation through 1200°F, while the other filler metals, with the exception of 706, exhibited primarily diffusion-controlled surface oxidation. Typical microphotographs of varying levels of oxidation as a function of brazing filler metal alloy composition are shown in Fig. 11.

Because the oxide is intact on the fillet surface as a solid layer, the rate

Table 3—Tensile Shear Strength of AISI 410 Braze Joints

Filler metal	Average tensile shear strength, ksi			
	Room temperature	800° F	1000° F	1200° F
698	63.9	40.1	31.5	21.7
712	42.0	31.0	11.5	—
706	43.2	30.2	20.5	14.5
9217	60.2	45.9	32.0	15.1
4777	28.5	31.5	—	23.7*
4778	31.9	30.6	—	27.8*

\* Base metal failure.

of oxidation is controlled by the diffusion of  $O_2$  through this layer to the unoxidized brazing filler metal and is therefore inversely proportional to the oxide thickness. Consequently, the depth of oxidation may be given by the expression  $l = \sqrt{2kt}$  where  $l$  is the depth of oxidation,  $t$  is the time of exposure and  $k$  is a constant which is a function of temperature. The oxidation rate decreases with time, and most of the oxidation will occur within the first 1000 hours as long as the oxide does not separate from the fillet due to thermal shock. Most of the filler metals examined appeared to follow this trend.

In the case of filler metal 706, however, the oxide layer is very porous. The rate of oxidation is consequently surface controlled instead of diffusion controlled and does not follow the above relationship. It was observed that the oxidation rate of filler metal 706 above 800°F actually increased with respect to time, and oxidation proceeded catastrophically. Interfacial attack was also observed on filler metal 706 fillets as shown in Fig. 11 (bottom).

As a result of the oxidation data in Table 2, filler metal 706 must be restricted to a maximum service temperature of 800°F, while filler metal 9217 may be operated to 1000°F. The remaining filler metals may be operated through 1200°F service temperatures, which includes all present-day compressor components.

### Bend Testing

Bend testing was conducted on brazed tee-joint specimens in the as-brazed condition and after long-time air exposure at elevated temperatures to detect possible alloy instabilities. No significant differences in the ultimate bend angles were observed between the two conditions except where oxidation consumed a substantial volume of the fillet. Moderate improvement in the bend ductility of filler metal 712 was apparent due to homogenization within the matrix phase, while filler metal 698 homogenization produced no detectable variance in bend ductility.

Specimens brazed with filler metals 698, 9217, and 4778 all failed in the base metal, while braze joint failures occurred with the remaining filler metals (706, 712, 4777). Secondary cracking was observed within the filler metal 4778 matrix and also in the boron-rich grain boundaries just below the braze/base metal interface. As anticipated from previous metallographic analyses, failure with filler metals 706, 712, and 4777 occurred through the hard, brittle phases. Filler metals 706 and 4777 exhibited cracking in their eutectic matrices, while the In-rich network cracked in filler metal 712.

### Tensile Shear Strength Testing

The results of tensile shear strength testing are listed in Table 3. After testing, the area of braze coverage was determined for each specimen and all specimens with less than 80% coverage were neglected. The full mating area on those specimens with greater than 80% coverage was used for the calculations of the shear stress without regard to percentage of area actually covered by the brazing filler metal. It was observed that the data generated by both of the specimens (Fig. 4) were comparable and consequently the results from both types of specimens were averaged together.

All of the filler metals investigated, with the exception of 712, exhibited adequate tensile shear strength for service operation up to 1200°F; filler metal 712 showed limited strength even at 1000°F. Although filler metals 706 and 9217 have adequate tensile shear strength at 1200°F, they are restricted by their resistance to oxidation as discussed earlier. The lower strength levels of filler metals 4777 and 4778 are attributed to the wide joint clearances (0.003 in. nominal) employed on these specimens. It has been reported earlier that the strength of similar Ni-Sr-Si-B filler metals is greatly dependent on the joint gap. It was demonstrated that with a "zero" gap, Au-18Ni and the Ni-Cr-Si-B filler metals had comparable strengths but that the strength of the latter dropped off drastically as the joint

clearance was increased, while the strength of the Au-18Ni alloy was gap-independent due to its solid solution nature.<sup>4</sup> The narrow joint clearances required for filler metals 4777 and 4778 would be impractical using the present fabrication techniques.

### High Cycle Fatigue Testing

Fatigue strength of filler metals 698, 706 and 9217 was evaluated by individual high frequency excitation of vanes in stator assembly segments brazed with the respective filler metals. Results of fatigue tests are given in Table 4. Fatigue strengths ( $10^7$  cycles endurance) of 30, 25 and 25 ksi reported for filler metals 698, 706 and 9217, respectively, were based on a criteria of the highest stress at which no failures occurred. The geometry of the test specimen encouraged failure of the cantilevered vane at its base where the constant section vane interfaced with the braze fillet reinforced vane section. Stress measurements were determined at this location. Failure below this location implied a braze joint fatigue strength inferior to that of the base metal vane. Post failure metallographic investigation indicated that all filler metal 698 brazed vanes incurred base metal vane failures. All but one filler metal 9217 brazed vane failed in the same manner. Failure of one vane was attributed to an external shrinkage void thus effecting a notch in the fillet. The presence of a few small internal fillet shrinkage voids did not have a detrimental effect on the other filler metal 9217 brazed vanes. A consideration of the data for smooth fillet filler metal 9217 brazed vanes indicated a fatigue strength (30 ksi) equal to that of alloy 698. Exposed fillet shrinkage would normally be blended out on production components. All filler metal 706 vanes incurred base metal failures. The slightly lower fatigue strength (25 ksi) of filler metal 706 relative to filler metal 698 was essentially determined by one vane failure at 30 ksi. In view of the base metal failure location of this vane, it was concluded that base met-

**Table 4—Room Temperature Fatigue Endurance ( $10^7$  Cycles) Data**

Summary of Data			
Filler metal		Fatigue strength psi	
698		30,000	
706		25,000	
9217		25,000	

Test Data			
Filler metal	Vane no.	Stress level psi	Results
698	1	40,000	Failure
	2	35,000	Failure
	3-12	30,000	No failure
706	1	60,000	Failure
	2	50,000	Failure
	3	40,000	Failure
	4	30,000	No failure
	5	30,000	Failure
9217	6-9	25,000	No failure
	1	40,000	Failure
	2	35,000	Failure
	3-4	30,000	No failure
	5	30,000	Failure*
	6-13	25,000	No failure

\* Failed from shrinkage notch in fillet.

al scatter rather than inferior braze joint strength accounts for the slightly lower reported filler metal 706 fatigue strength.

### Stator Assembly Brazing

Upon consideration of brazing filler metal properties and cost effectiveness, two filler metals, 706 and 9217, were selected for qualification in actual stator assemblies. Assemblies were brazed in production facilities and carefully inspected following brazing. Stators were determined to be sound and were therefore committed to engine endurance tests. Post engine test visual and fluorescent penetrant inspection detected no braze cracking.

### Summary and Conclusions

Filler metal 706 (Ag-Pd-Cu) has been qualified for engine service as described above and has already replaced Au-18Ni on many assemblies up to 800°F service temperature. Production problems which have been

encountered with filler metal 706 include excessive filler metal flow, requiring a costly hand application of stop-off, and occasional fillet cracking, requiring a repair operation.

Filler metal 9217 (Cu-Mn-Co) has recently been similarly qualified for engine service and committed to a production application. The reduced cost, increased temperature capability, and minimized process problems of filler metal 9217 make it an effective replacement for filler metal 706 and Au-18Ni for service temperatures to 1000°F. Au-18Ni alloy continues to be uniquely suitable for stator applications exceeding 1000°F service temperature.

The conclusions that may be drawn as a result of this study are:

1. Filler metal 9217 satisfies the stated program goals and is a suitable substitute for Au-18Ni in stator assembly applications for service temperatures to 1000°F.
2. Filler metal 9217 may be successfully brazed at 1875°F in a -60°F dew point hydrogen roller hearth furnace.
3. Filler metal 706 meets program goals when limited to a service temperature of 800°F but is less attractive than filler metal 9217 from a cost-effectiveness standpoint.
4. The serviceability of filler metals 9217 and 706 was demonstrated by engine endurance tests.
5. Filler metals 712, 4777 and 4778 are not suitable substitutes for Au-18Ni in this stator assembly application because of reduced ductility associated with wide gaps.

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