# Microstructure and Strength Properties of Austenitic and Ferritic Stainless Steels When Brazed with Ni-Cr-P Amorphous Brazing Foils

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#### Abstract

Austenitic and ferritic stainless steel are important alloys used in the manufacturing of heat exchangers. These alloys are used in heat exchangers in automotive industry applications such as exhaust gas re-circulator and heat recovery units. They are also used in heat exchangers in the power generation industry and oil and gas industry. The following paper describes the microstructure and single-lap shear strength results of both types of stainless steel alloys when joined with Ni-Cr-P amorphous brazing foils.

#### Introduction

Austenitic stainless steel (SS316) and ferritic stainless steel (SS444) are important alloys used in the manufacturing of heat exchangers. These alloys are used in heat exchangers in automotive industry applications such as exhaust gas recirculator and heat recovery units. They are also used in heat exchangers in the power generation industry and oil and gas industry. Further details on automotive applications for braze foils can be found elsewhere [1]. High corrosion resistance is often required for heat exchangers and previous studies have focused on the role of high Cr containing foils for preventing corrosion [2, 3, 4]. It has been shown that the corrosion performance of the alloys becomes much worse with high levels of B and low levels of Cr in the braze filler metal and results in chromium boride precipitation. This pulls the Cr from the solid solution state of the base material reducing the corrosion resistance in the braze interface [5].

Substituting the B for P in the foil prevents the chromium boride precipitation in the base material. However, there is little information on the joint strength properties available. The following study describes the microstructure and singlelap shear strength results of both types of stainless steel alloys when joined with Ni-Cr-B based foils as well as Ni-Cr-P based foils. Table 1 shows the chemistry and melting characteristics of the MBF51 and MBF67 foils which are available in commercial form. The MBF67 foil is designed to be a low melting point, high corrosion resistant alloy for applications such as exhaust gas recirculation coolers.

Table 1:	Metglas	Brazing	Foils	nominal	chemistries	and
	m	elting ch	naracte	eristics.		

Alloy	Nominal Composition, wt%					Melting Temp C			
	Cr	Fe	Si	В	Р	Мо	Ni	Sol	Liq
MBF51	15		7.3	1.4			Bal	1030	1126
MBF67	25	<1	1.5	0.5	6	1.5	Bal	890	970

### **Experiments**

Samples of SS316 and SS444 brushed to a surface finish of 0.17 micron average roughness were obtained for brazing trials using MBF51 and MBF67 foil. The brazing process and mechanical testing procedures followed the AWS C3.2M procedure for single-lap shear specimens. Figure 1 shows images of the samples after the braze cycle where the sample thickness is 0.125 " and the braze overlap distance is 0.5 ". Brazement samples joining two 4" by 1" SS316 and SS444 sample coupons were also carried out in the vacuum brazing furnace for cross-sectional analysis. The samples of SS316 and SS444 were put in the vacuum furnace together, along with the sample coupons for both of the MBF51 foil and MBF67 foil heating cycles. The vacuum in the furnace was held at  $10^{-4}$  torr minimum during the brazing cycle. The furnace temperature was ramped up and held for 20-45 minutes at dwell temperature 1 (260°C) and then ramped to dwell temperature 2 and held for another 20-45 minutes to ensure temperature and pressure stabilization. The temperature was then ramped to required brazing temperature for each alloy and held for 15 minutes. Table 3 lists the dwell and brazing temperatures for each alloy. The furnace was then back filled with nitrogen and quick cooled to a temperature about 200-300°C below which oxidation of joints would occur.

After the brazing cycles were completed the shear lap samples were analyzed using an Instron machine for the average stress at failure. The results of the tests for each base material and foil combination are given in Table 3. It is seen that the samples using the MBF51 foil have much higher stress at failure and that the failure occurs within the base material for both the SS316 and SS444 alloys. The samples using the MBF67 foil showed lower stress at failure and fractured within the braze layer. When the failure occurs in the braze layer, the maximum stress on the base material is estimated using the maximum load at failure. Similarly, when the failure occurs in the base metal the corresponding joint shear stress is reported and it is implied that the joint strength is greater than the reported value since the failure did not occur in the joint.



Figure 1. Single-lap shear specimens of SS444 after vacuum brazing with MBF67 foil.

 Table 2: Dwell temperatures and brazing temperature for each of the MBF alloys.

Alloy	Dwell Temp. 1	Dwell Temp. 2	Brazing Temp.
MBF 51	260°C	1000°C	1195°C
MBF 67	260°C	870°C	1090°C

Table 3: Joint stress at maximum load for SS316 and SS444brazed with MBF51 and MBF67 foil.

Alloy	Foil	Failure	Base Metal	Joint Strong of
		Location	Max Load (ksi)	Max Load (ksi)
SS316	MBF51	Base Material	86.1 +/- 0.8	> 21.5
SS316	MBF67	Braze Layer	> 43	10.8 +/- 0.5
SS444	MBF51	Base Material	54.6 +/- 4.6	>13.6
SS444	MBF67	Braze Layer	> 43	10.7 +/- 1.3

Following the vacuum braze cycle, the brazement sample coupons were cross sectioned and then progressively polished down to a sub-micron colloidal silica solution finish using standard metallographic techniques. The samples where then analyzed on a Hitachi S3400N Scanning Electron Microscope (SEM) and an elemental map using an EDAX Genesis energy dispersive x-ray analysis was performed.

## **Results and Discussion**

The SEM images from the brazement sample coupons for SS316 and SS444 brazed with MBF51 foil are shown in Fig. 2a and Fig. 2b respectively. It is observed that there is a much greater penetration into the base material for the SS316 material relative to the SS444 material and has been observed previously [6].



Figure 2. SEM images of a) SS316 brazed with MBF51 foil and b) SS444 brazed with MBF51 foil.

The elemental maps for the SS316 material are given in Fig 3 showing the relative concentrations of Cr, Fe, Ni and Si. Light elements such as B are not easy to identify in this investigation but it is inferred that the B diffuses into the base metal leaving a solid solution of Ni, Cr and Si in the braze joint as discussed elsewhere [6]. This results in high levels of chromium borides in the grain boundaries of the base SS316 and a corresponding absence of Fe and Ni.

Figure 4 shows the elemental maps for the SS444 base material brazed with MBF51 foil. There is not the same base material penetration along the grain boundaries indicating that the B remains mainly within the braze layer. Here it is inferred that the chromium boride phases remain along the interface of



Figure 3. Elemental analysis of SS316 brazed with MBF51 showing the relative concentrations of Cr, Fe, Ni and Si.



Figure 4. Elemental analysis of SS444 brazed with MBF51 showing the relative concentrations of Cr, Fe, Ni and Si.

the base material and along the centerline of the braze layer where the strong presence of Cr is observed. There are also Ni-Si intermetallic phases along the centerline of the braze layer which is surrounded by a solid solution of Ni-Cr-Si-Fe.

The SEM images from the brazement sample coupons for SS316 and SS444 brazed with MBF67 foil are shown in Fig 5a and Fig 5b respectively. It is observed that there is a very little penetration into the base material through the grain boundaries due to the low B levels of MBF67 foil. The interface between the base material and the braze layer is sharper for the SS444 material compared to the SS316 material.



Figure 5. SEM images of a) SS316 brazed with MBF67 foil and b) SS444 brazed with MBF67 foil.

The elemental maps for the SS316 material is given in Fig 6 showing the relative concentrations of Cr, Fe, Ni and P. Here the center line of the braze layer consists of Ni-Cr-P intermetallic phases along with block phases of Cr. The center line is surrounded by a Ni-Cr solid solution. Similar results for the elemental maps SS444 brazed with MBF67 foil are shown in Fig 7. The major difference noted between the elemental maps in Fig. 6 and Fig. 7 is the Cr distribution. It is very uniform throughout the brazement in the SS316 samples, with higher concentrations seen in the blocky chromium precipitates. However, for the SS444 samples there is a lower concentration of Cr seen in the Ni rich interface zone of braze joint.



Figure 6. Elemental analysis of SS316 brazed with MBF67 showing the relative concentrations of Cr, Fe, Ni and P.



Figure 7. Elemental analysis of SS444 brazed with MBF67 showing the relative concentrations of Cr, Fe, Ni and P.

The joint strength data given in Table 3 show that the failures occur within the base SS316 and SS444 material when using the MBF51 foil. The failures occur near the ultimate tensile strength of the base material, which are 75 ksi and 40 ksi respectively, and indicate a strong and ductile braze joint. However, the failure location is within the braze joint for each of the MBF67 brazed samples and occur at the same applied stress for both the SS316 and SS444 base materials. The intermetallic phases within the braze layer are brittle and allow for crack propagation as discussed elsewhere [7]. This is likely the cause of the lower shear strength in the material brazed with the MBF67 foil. Analysis of the single-lap shear samples show that the braze layer fractures along the center line of the braze layer.

#### Conclusions

Newly developed MBF67 foil is a Ni-Cr-P-Si based foil the can be cast with good ductility, high corrosion resistance and low melting points [2, 3, 4]. Brazing austenitic stainless steel and ferritic stainless steel with MBF67 foil is compared to brazing with MBF51 foil, a Ni-Cr-B-Si based foil, and significant differences are found. The MBF51 brazements show deep B diffusion within the grain boundaries of the base material for austenitic SS316. A solid solution of Ni-Cr-Si remained in the braze layer. However, the ferritic SS444 did not show the B penetration into the base material. Rather B seems to remain in the braze layer and a number in intermetallic phases remained in the braze layer. The MBF67 brazements also show very little penetration into the base metals for both SS316 and SS444 materials. There also tends to be more intermetallic phases contained within the braze layer for the P containing foils. The intermetallic phases in the MBF67 brazement reduces the shear strength of the braze layer and shows fracture along these phases. The stress at failure was almost the same when the failure occurs within the braze layer for the samples brazed with MBF67 foil. The stress at failure was near the ultimate tensile strength of the base materials for the samples brazed with MBF51 foil. While other studies have shown that there is a greater corrosion resistance in the brazement when using MBF67 foil, there seems to be a trade-off where the joint strength is not as large. The choice of brazing foil may depend on which aspect is more important for the application.

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