OPTIMIZATION OF BRAZING TECHNOLOGY, STRUCTURAL INTEGRITY, AND PERFORMANCE OF MULTI-CHANNELED, THREE DIMENSIONAL METALLIC STRUCTURES

by

Anatol Rabinkin, Metglas®, Inc.
Amorphous Metals

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Optimization Of Brazing Technology, Structural Integrity, & Performance Of Multi-Channeled, Three Dimensional Metallic Structures

by A. Rabinkin

- Brazed 3D Structures in Modern Machinery
  - Growing Importance of Heat Exchangers (HE) for Energy Conservation
    - Heating, Ventilation, Air Conditioning, Food Processing, Chemical Industry, etc
      - Types of Brazed HE: Finned Coil, Plate/Fin, Plate/Plate
        Total Product Cost in This Group: > $0.5B
  - Structural Parts for Airspace Industry with High *Strength/Weight* Ratio
    - Parts of Airplane Fuselages-BRAZECORE®
    - Parts of Jet Engines-Blades/Vanes to Rotor/Stator, Turbine Seals
  - Fuel Cells-High Corrosion Resistant Structures
- Joining 3D Structures Using Ni-based Amorphous Brazing Foil
  - Plate/Fin/Plate 436 Stainless Steel/BNi-2 (METGLAS® MBF-20 Foil) Joints
    - Brazing Process Variables
      - Foil Thickness: 25, 37, and 50 μm
      - Two Brazing Cycles: Short and Long with Post Brazing Annealing
        Total: 2 x 3 =6 variables
    - Tested Parameters and Microstructural Observations of Brazed Structures
      - Hot Tensile Strength at 650°C in Air
      - Tensile Stress Rupture Under 0.69 MPa/1.38 MPa (100 psi/200 psi) Load at 650°C
      - Optical and SEM+EDAX Microscopy
      - Low Mag. Optical Observations of As-Brazed and Failed Specimens
    - Results
      - Dimensions of As-Brazed Structures and MBF-20 Foil Thickness
      - Mechanical Strength as a Function of MBF-20 Foil Thickness
      - Short and Long Time of Exposure to 650°C in Air
      - Failure Mode Analysis
      - Microstructure, Brazing Cycle, and Mechanical Properties

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Optimization Of Brazing Technology, Structural Integrity, And Performance Of Multi-Channeled, Three Dimensional Metallic Structures

(continued)

by A. Rabinkin

- Inconel 625 Plate/Fin Structures Brazed Using BNi-5b (MBF-51 METGLAS ® Foil)
  - Effect of Heat Treating on Microstructure and Joint Integrity
- Pipe/Fin Heat Recuperators Brazed with BNi-2 (METGLAS® MBF-20 Foil)
  - Optimization of Low Carbon Steel Pipe/Fin Brazing in Nitrogen Atmosphere
- High Corrosion And Oxidation Resistant Structures Brazed Using New Modified Ni- And Co-Based Alloys
  - Performance of Thin Joints Brazed with Modified Ni-based Alloys in a Corrosive Medium
  - Performance of New Co-based Alloys in Air at Very High Service Temperature-Multicell Seals, Blades, etc
- Summary

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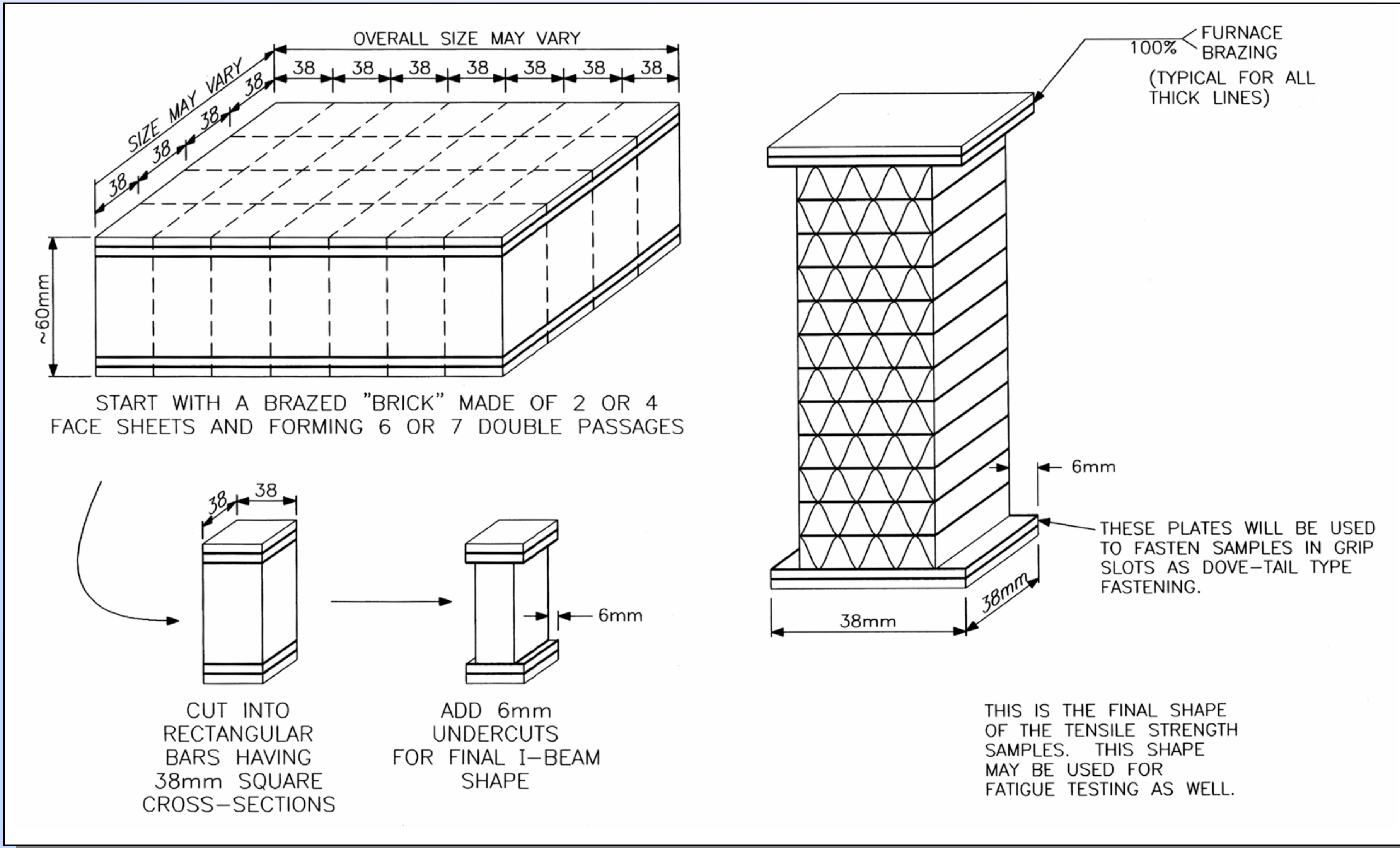
Sequence Of Sample Manufacture



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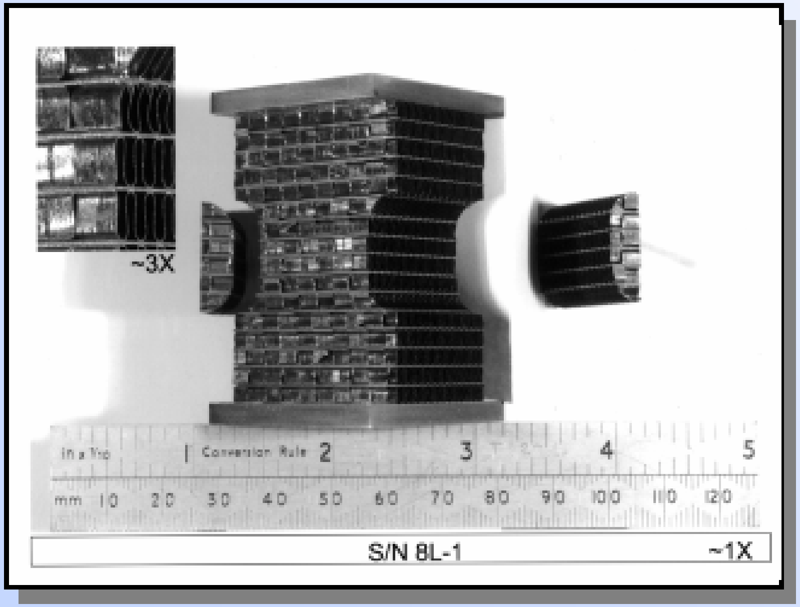
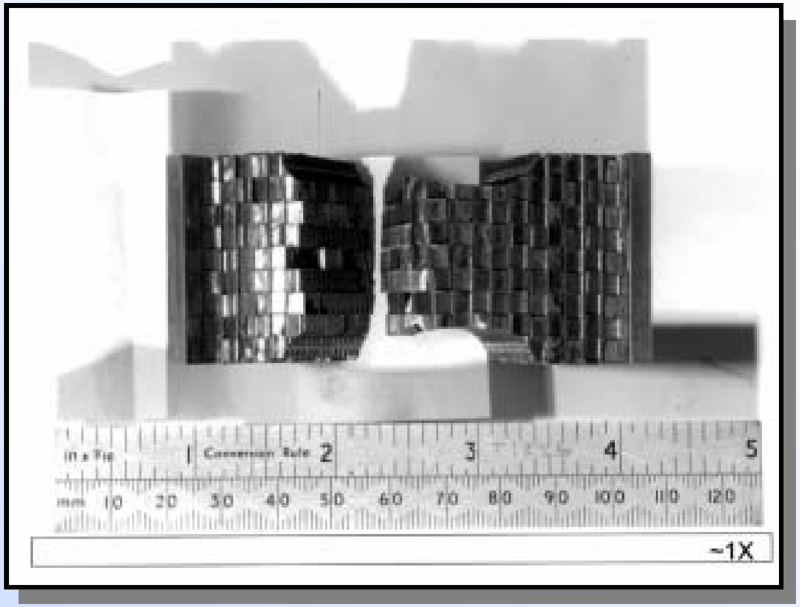
Samples For Mechanical Testing After Electroerosion Cutting



Sample After Failure Under Tensile Mode Mechanical Testing At 650° C

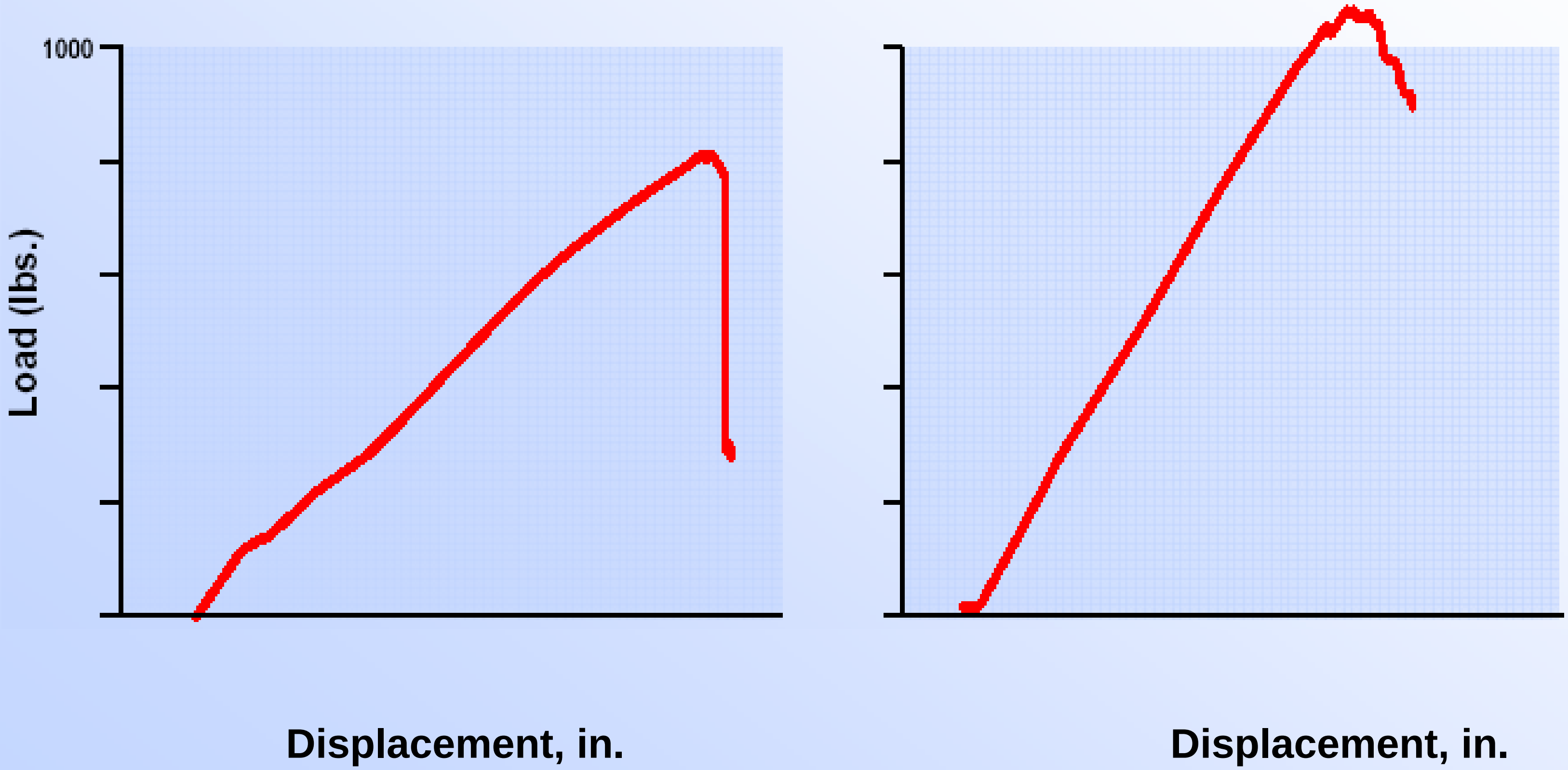


Samples Of Brazed Plate/Fin Structures For Mechanical Testing.

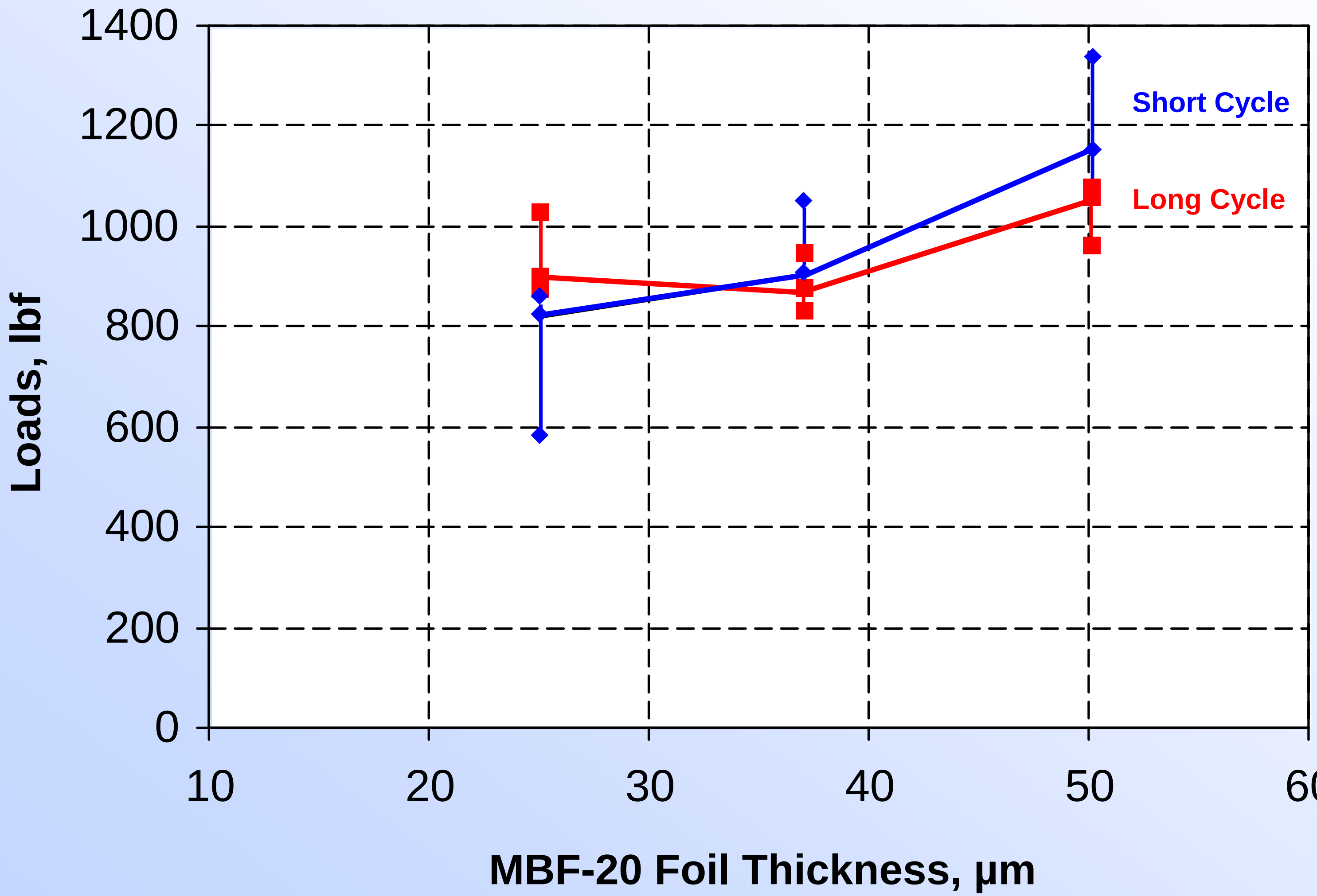
Displacement-Load Curves Of Tensile Testing

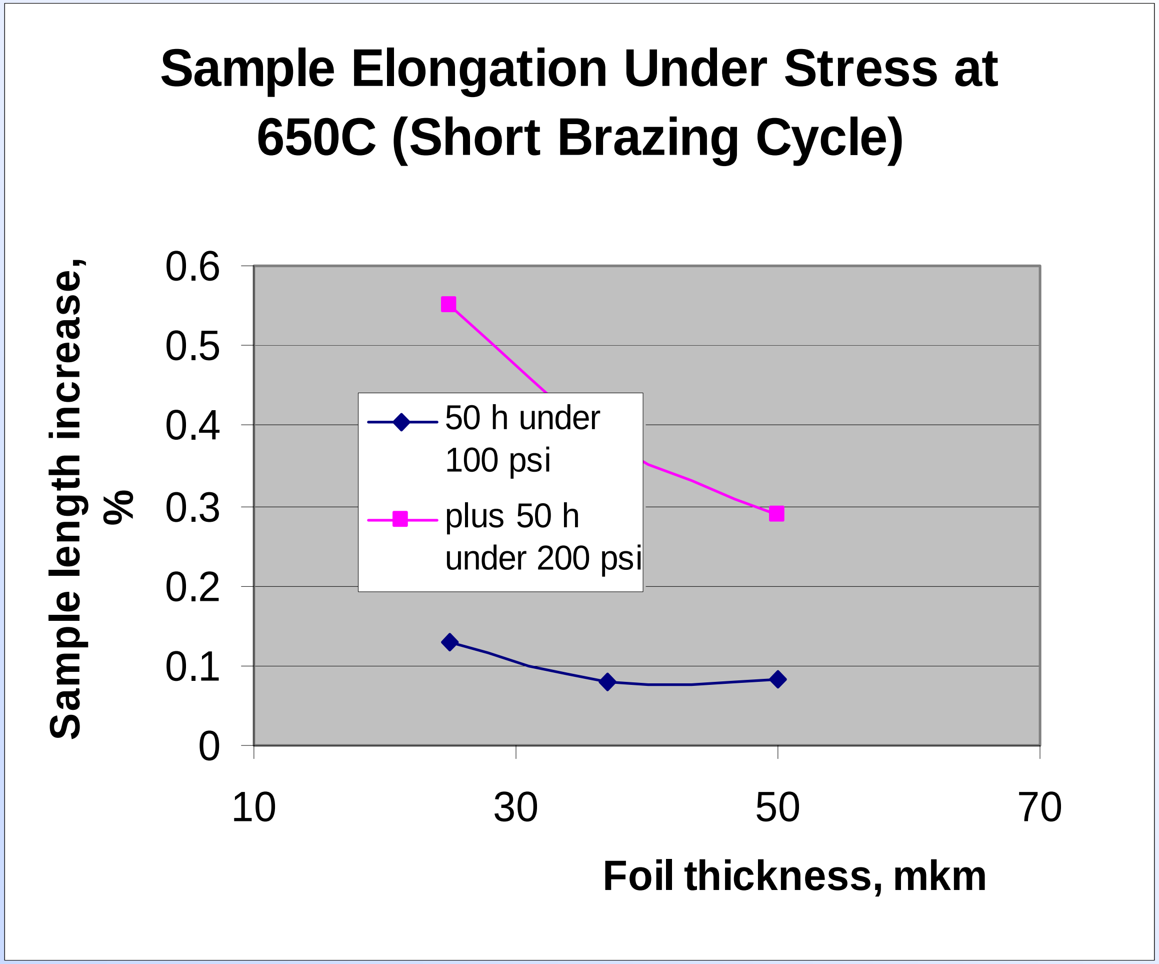
R/N 297138
S/N 25µm Foil/@650°C
TL 823 lbs.

R/N 297138
S/N 50µm Foil/@650°C
TL 1068 lbs.



Maximum Load, lbf At Failure Of Brazed Samples at 650°C After 0.5h Preliminary Exposure At This Temperature





Tensile stress rupture of 436 SS plate/fin/plate specimens brazed using BNi-2 (MBF-20 METGLAS® Foil)

TABLE 2

Passage Heights of Different Brazed Samples.

(All Numbers in Mil) Total Number of Passages-16.

	Short brazing cycle						Long brazing cyle			
	1 mil foil		1.5 mil foil		2.0 mil foil		1.0 mil foil		2.0 mil foil	
	Left Side	Right Side	Left Side	Right Side	Left Side	Right Side	Left Side	Right Side	Left Side	Right Side
	130.1	128.3	129.1	129.6	129.4	127.6	128.6	129.3	128.8	129
	129.8	123.7	130.4	129.8	129.4	129.1	128.1	129.1	128.9	129.2
	128.3	128.7	129.2	130.1	129.2	129.4	128.6	129.1	128.4	128.2
	129.5	129.4	128.8	129.1	129.1	129.5	128.9	129.2	128.7	129.7
	130.2	129.1	129.4	129	130.4	129.8	129	128.7	128.7	129.3
	130.1	129.9	128.7	128.9	128.7	129.7	127.9	129.1	129	128.4
	129.5	128.7	128.7	129.6	129.4	129	127.2	127.6	128.6	128.9
	129.9	129	128.9	129.3	128.9	128.6	129.3	129.3	128.4	129.2
	128.5	129.3	129.9	129.3	129	129.3	128.7	128	128.8	129.4
	129.8	129.1	128.4	129.1	130.2	129.9	128	130.2	129	129.1
	128.9	129.8	129.8	129.6	129.6	129.4	129.1	128.9	129.1	128.7
	130	129.7	129.1	129.8	128.7	128.9	128	128.9	129.4	130.1
	129.6	129.8	130	128.8	130.1	129.1	129.4	128.1	128.4	128.2
	129.9	129.8	129.1	129.6	129.5	130.3	128.5	129.2	128.1	128.6
	129.8	128.4	130.2	129.4	129.6	128.3	127.6	128.8	128.3	129.8
	130	128.4	130.2	130.1	128.7	130.6	128.6	128.8	129	130.3
Average passage height on each side	129.6188	128.8188	129.3688	129.4438	129.3688	129.2813	128.4688	128.8938	128.725	129.1313
Min	128.3	123.7??	128.7	128.8	128.7	127.6	127.2	127.6	128.1	128.2
Max	130.2	129.9	130.4	130.1	130.4	130.6	129.4	130.2	129.4	130.3
Max-Min	1.9	6.2??	1.7	1.3	1.7	3	2.2	2.6	1.3	2.1
Stdev	0.620605	1.4707	0.628987	0.399948	0.530055	0.740467	0.621524	0.606046	0.343511	0.632159
Average passage height	129.2188		129.4		129.3		128.6813		128.8938	
Delta (av h each side-av height)	-0.4	0.4	0 (!)	0(!)	0(!)	0(!)	0.2125	-0.2125	0.16875	-0.2375
Total height of 16 passages	2073.9	2061.1	2069.9	2071.1	2069.9	2068.5	2055.5	2062.3	2059.6	2066.1
AV total height	2067.5		2070.5		2069.2		2058.9		2062.85	

General Remarks

1. Incredible **constancy** of total 16 passage height **regardless of the thickness of brazing** foil used.

2. Remarkable constacy of the average individual passage height regardles of the thickness of brazing foil used.

3. Postbrazing annealing decreases slightly the individual and total passage heights.

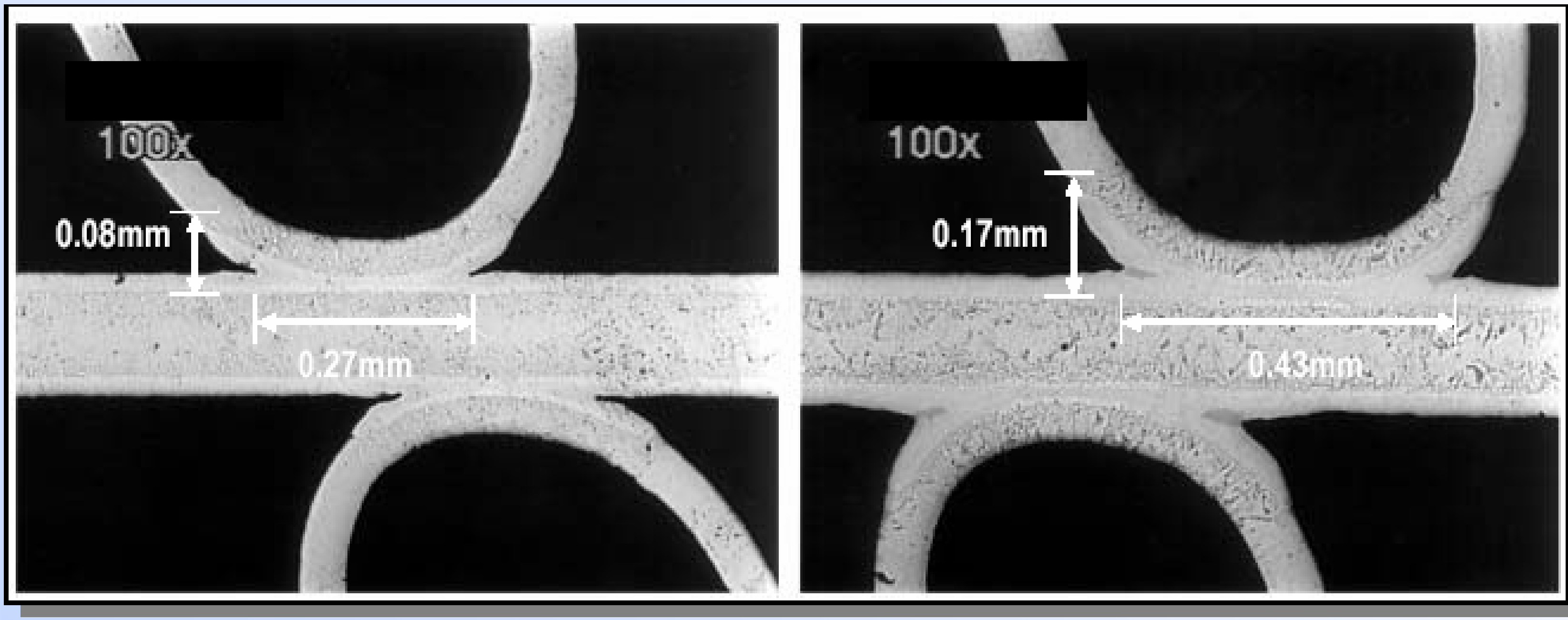
4. There are seldom but very large variations in the passage heigh. **Most important: the foil thickness in this case is not the only parameter setting the joint thickness-the cappilary effect does. Result: Variation in the foil thickness is not the major reason for possible pores and holes in joints and joint leakage.**

Average passage height and total height of 16 passages of plate/fin/plate samples as a function of MBF-20 foil thickness

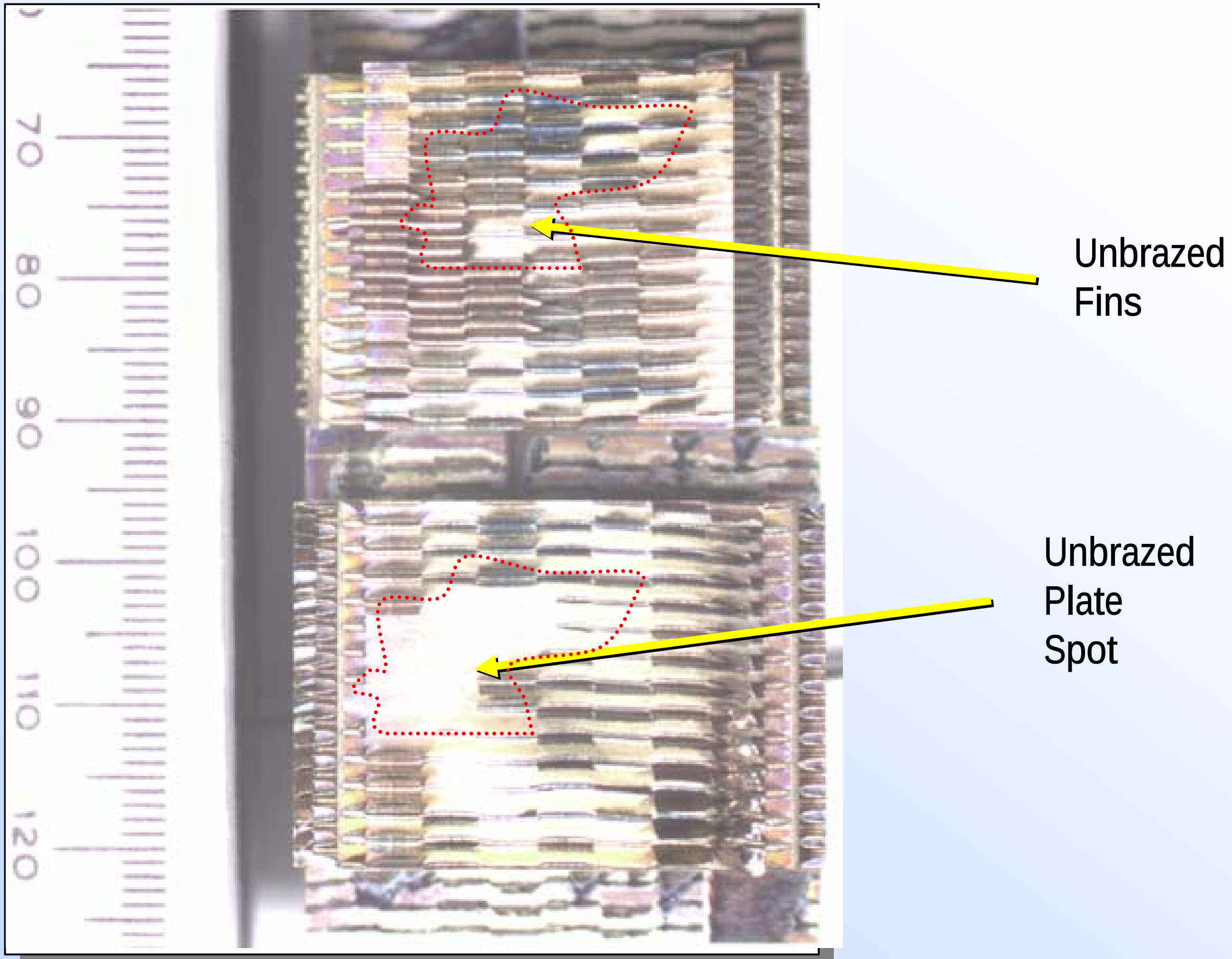
Filler Metal Thickness, μm	Average Passage Height, μm	Total Height of 16 Passages, μm
25	3,282	52,514
37	3,287	52,590
50	3,284	52,557

Maximum load at sample failure at 650°C as a function of filler metal thickness

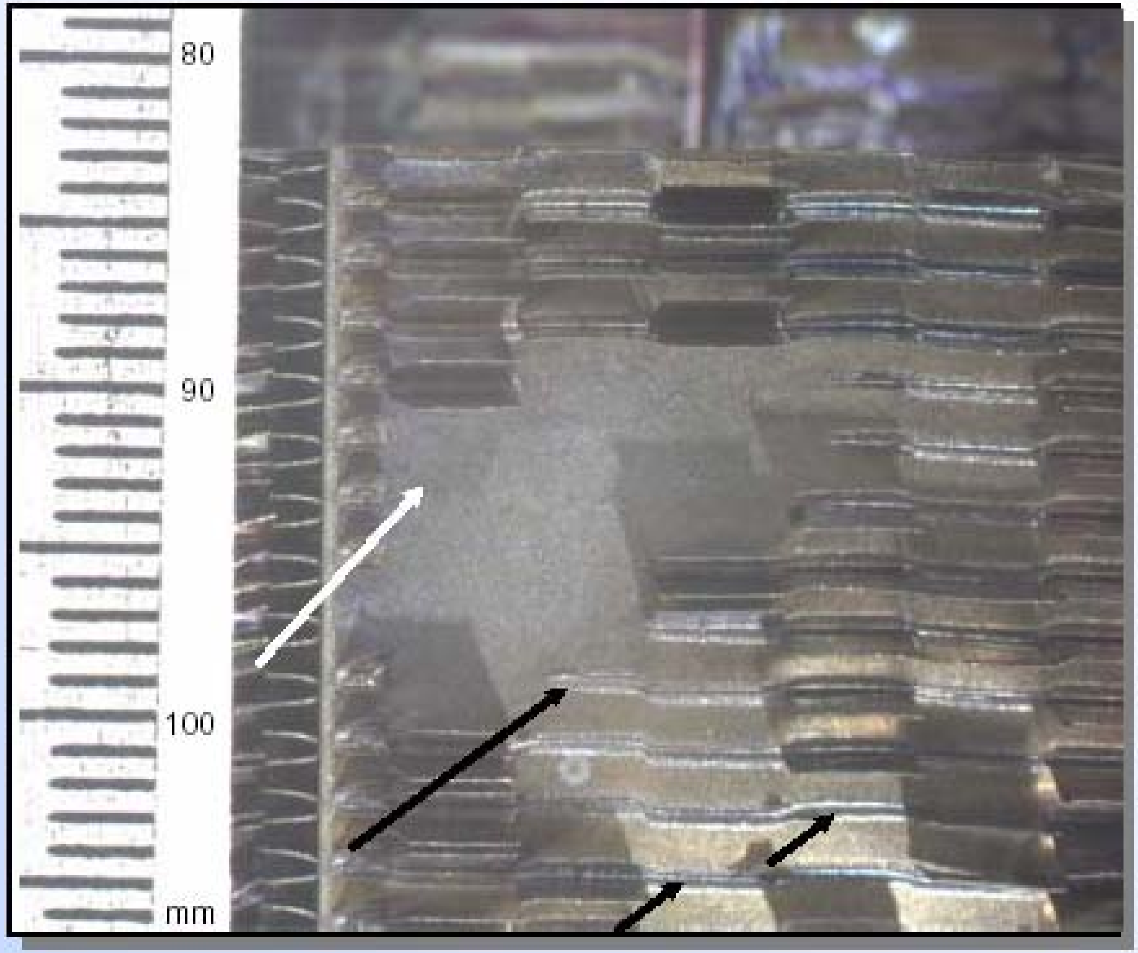
Filler Metal Thickness, μm	Maximum Load at Sample Failure at 650°C, kg
25	342
37	429
50	537



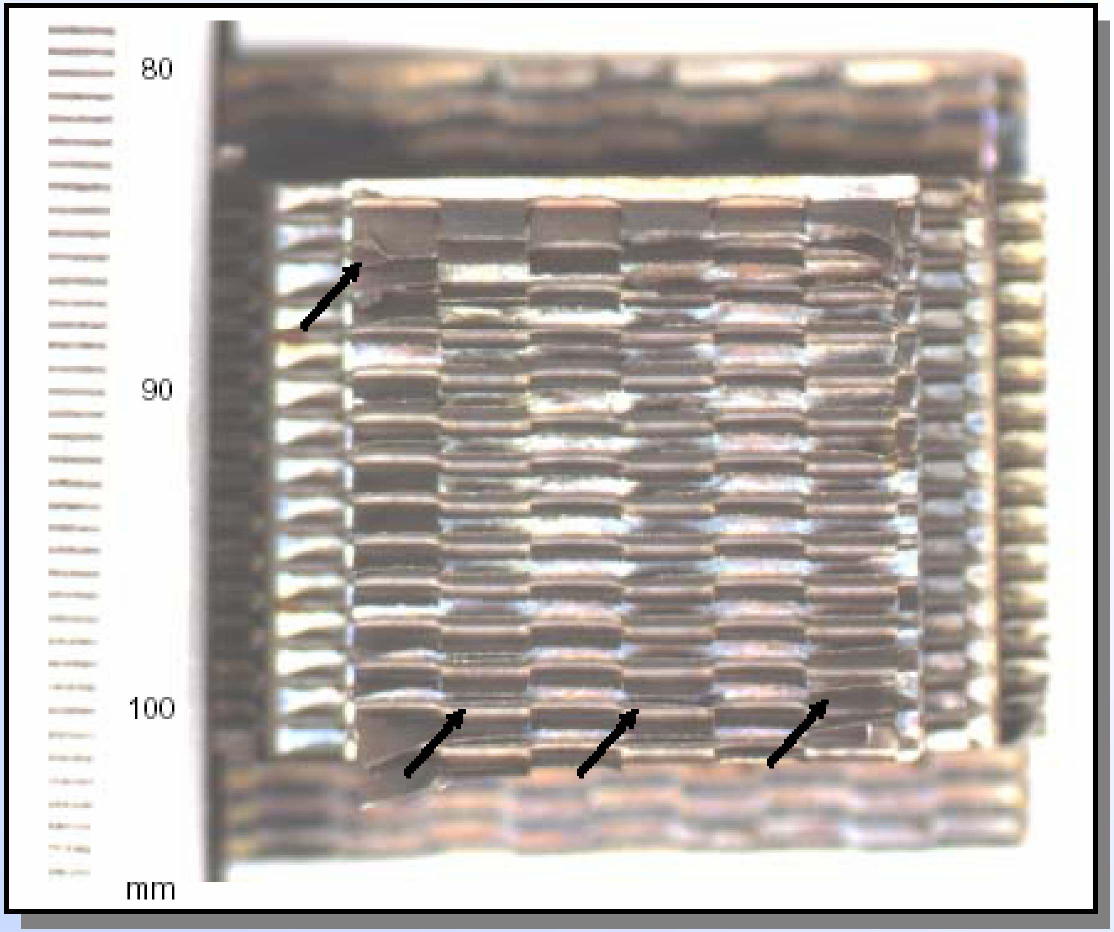
Microstructure of two 436 SS stainless steel plate/fin samples brazed using 25µm (1 mil) and 50µm (2 mil) thick MBF-20 ribbon. Note that while inside of the brazes the joint thickness is the same, the joint cross-section is wider and the fillet height is higher when the thicker foil is used.



Two halves of a sample (25µm thick MBF-20, short cycle) after failure the tensile strength testing. Sample has a large unbrazed area due to presence of a small dent in the fin and too thin MBF-20 foil thickness to compensate the large brazing gap in this spot. The result is unusually low tensile stress, 580 psi, of this sample.



Unbrazed area of a sample (25 µm thick MBF-20, short cycle) after tensile testing (white arrow). Note that failure occurred at the lean fillets (black arrows).



Sample (50µm MBF-20, long brazing cycle) after failure under the tensile testing. Failure with σ_t =1070 psi occurred in the middle of the fin base metal (arrows) due to large joint cross-sections formed using thick brazing foil.

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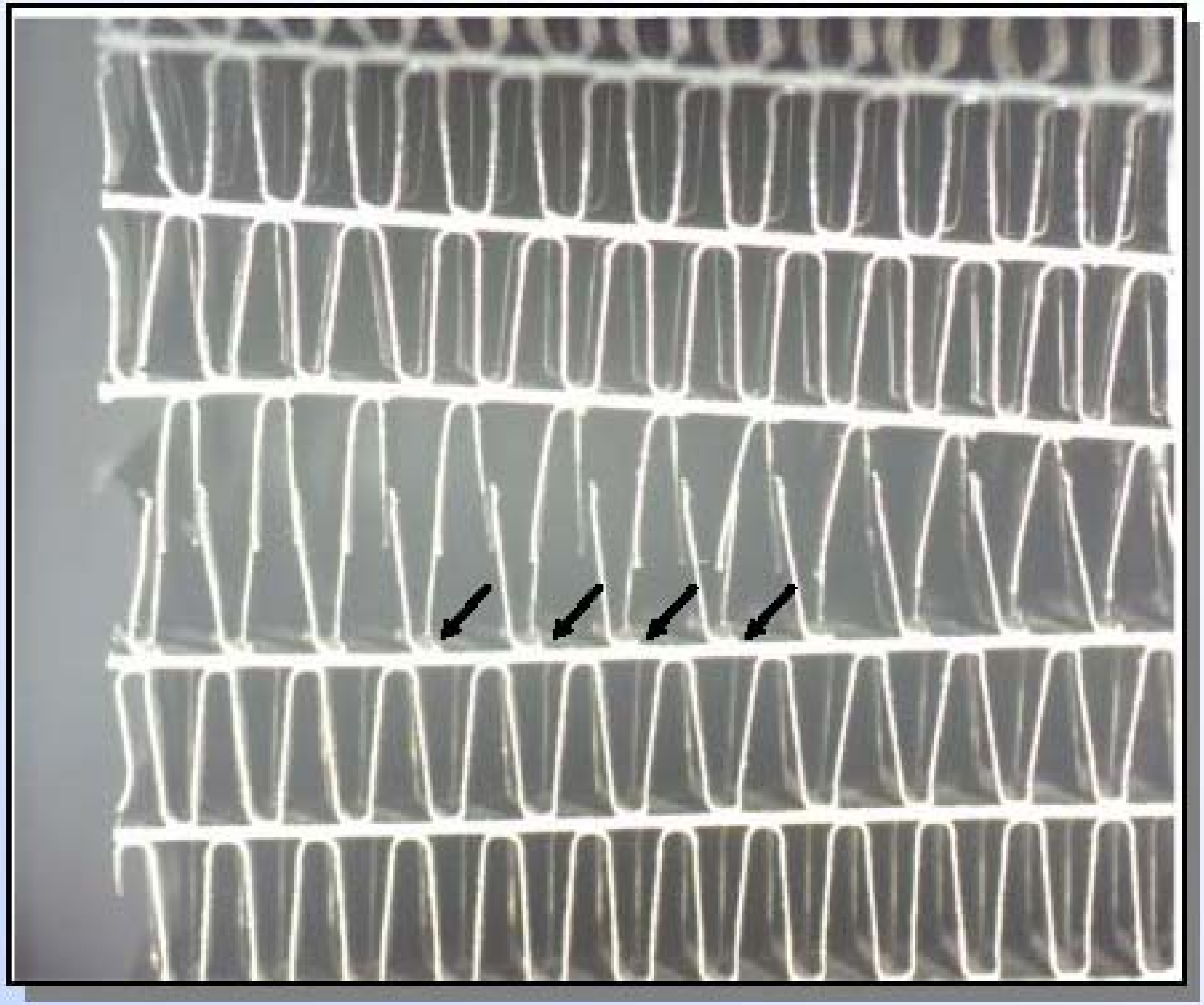
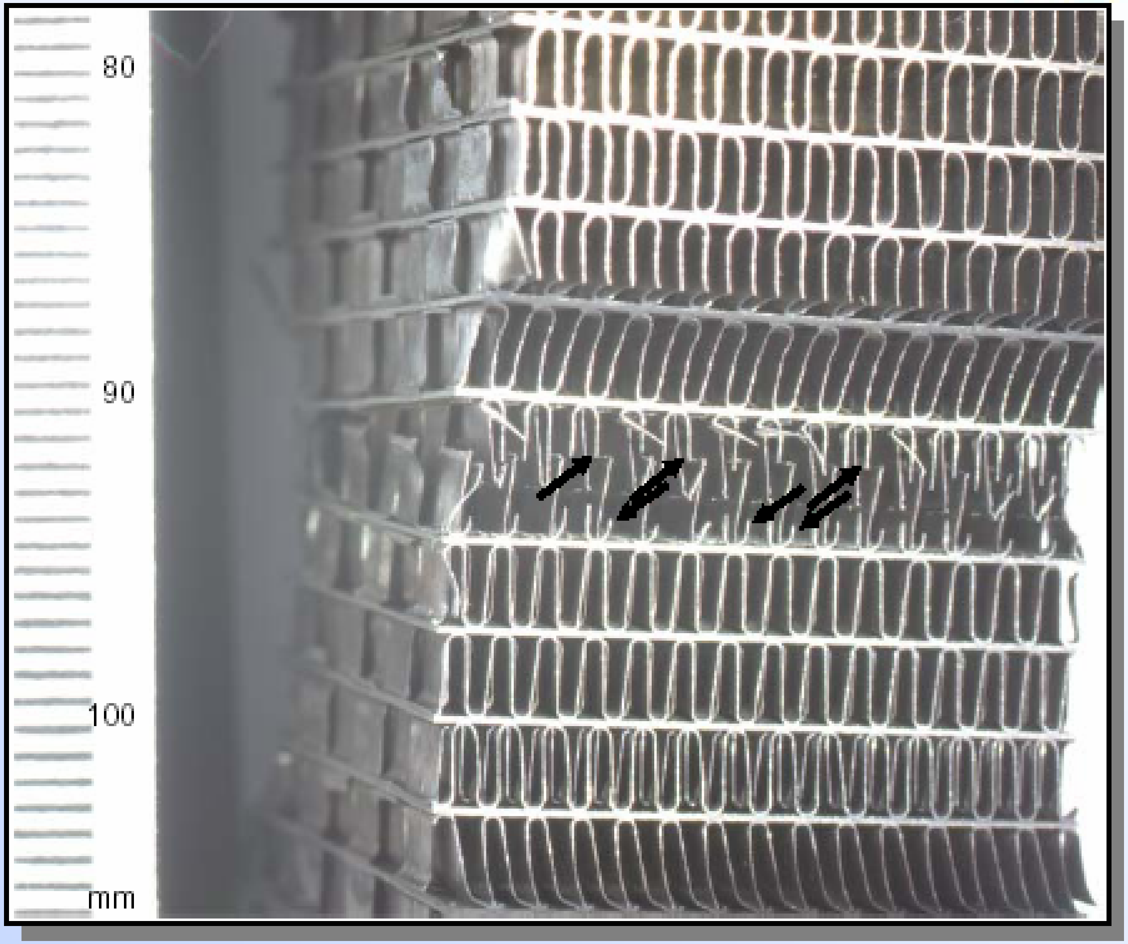


Sample (25 µm MBF-20, long brazing cycle) after failure under the tensile testing. Failure with σ_t =875 psi occurred in the lean fillets (arrows) formed due to too thin MBF-20 brazing foil used.



Sample (50 µm MBF-20, long brazing cycle) after failure under the tensile testing. Failure with σ_t =1070 psi occurred in the middle of the fin base metal (arrows) due to large joint cross-sections formed using thick brazing foil.

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- The practical consequence of our observations is that the product integrity has low sensitivity to variations in brazing foil thickness when the ribbon thickness and the loading of part's assembly during brazing are properly chosen.
- All joints manufactured using foil with at least 0.037 mm (1.5 mil) thickness have complete, non-porous brazes that should not be prone to any gas/liquid leakage.
- In order to achieve an optimal joint strength and long term dimensional stability to loading at 650°C and a complete joint integrity, the minimal suggested MBF-20 foil thickness is 0.037 mm (1.5 mil).

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Observations and Practical Recommendations

Observations of Unconstrained Joints

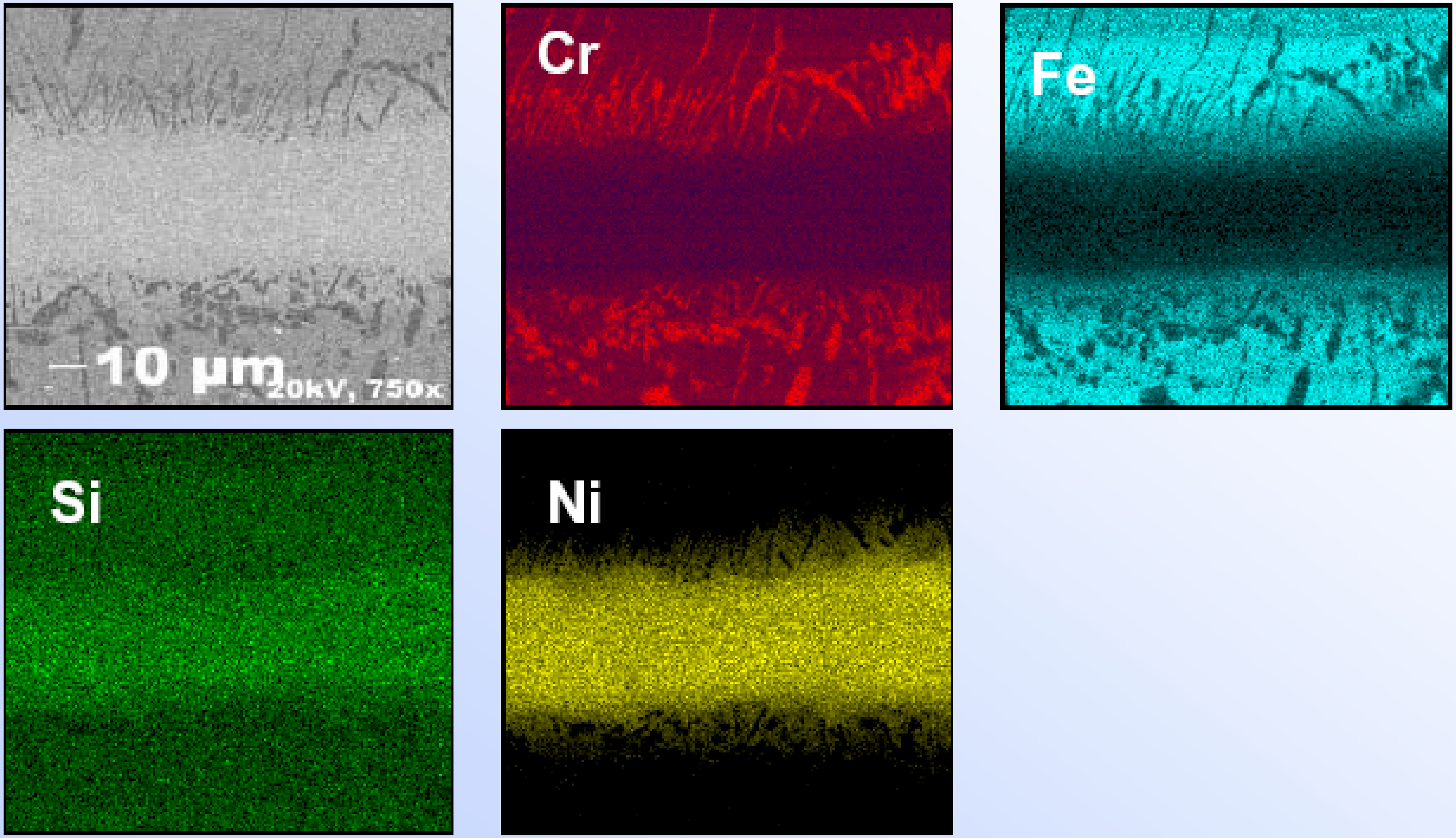
1. Passage spacing of brazed samples and joint thickness are equal for all foil thicknesses
2. Braze fillet cross-section increases with foil thickness
3. Joint strength increases with foil thickness
   - 25 μm foil → large unbrazed areas observed
   - 37 μm foil → pore and defect free joints; tensile failure at joints
   - 50 μm foil → pore and defect free joints; tensile failure in base metal

Practical Recommendations

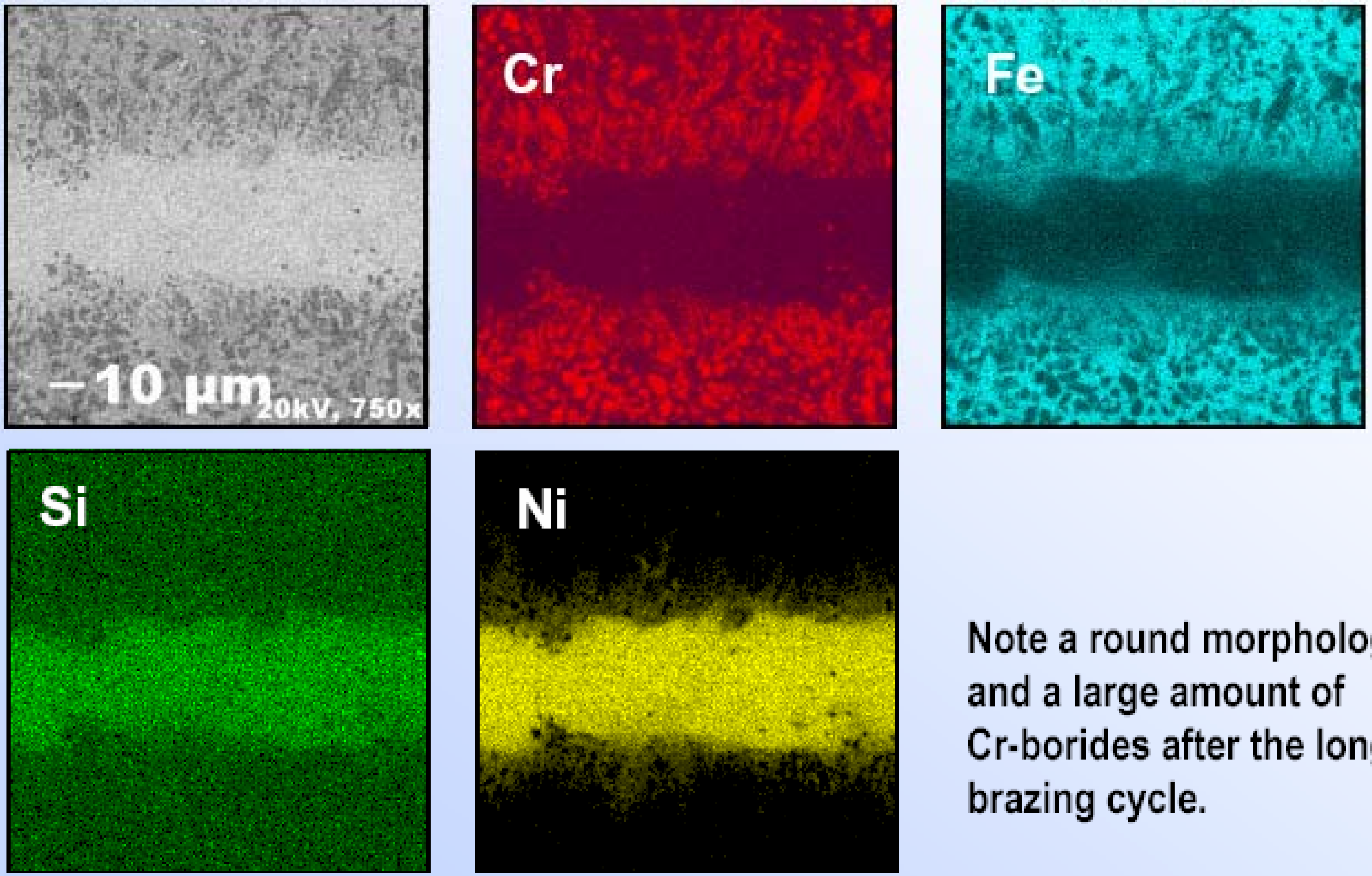
Unconstrained Structures → Foil thickness ≥37 μm or Add Compressive Load During Brazing If Foil Thickness <37 μm

Constrained Structures → 50 μm Foil Thickness Probably The Best

436 S/MBF-20/436 SS Braze Joint
50μm Thick MBF-20 Foil
Short Brazing Cycle



436 S/MBF-20/436 SS Braze Joint
50µm Thick MBF-20 Foil
Long Brazing Cycle



Note a round morphology and a large amount of Cr-borides after the long brazing cycle.

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Shear strength of the low carbon steel fin /low carbon steel pipe and low carbon fin/Inconel pipe joints brazed using MBF-20 foil*

Surface Treatment	Load at Max Load, lbf	St. Dev. Of Load at Max Load, lbf ??	Shear Stress @Max. Load, MPa (ksi)	St. Dev. Of Shear Stress @Max. Load, MPa (psi)	Joint Integrity
Steel Wool	1,260	105.5	83.8 (12.16)	7.0 (1.02)	Small porosity, some joints are clean
Scotch Guard	1,417	104.0	94.3 (13.67)	6.9 (1.00)	Small pores on some joints
Sand Paper	1,483	262.1	98.7 (14.31)	17.4 (2.53)	Porosity on both fin/braze and pipe/braze interfaces
Wire Brash	1,513	144.8	100.7 (14.60)	9.6 (1.40)	Most joints are clean, small porosity at pipe/braze interfaces
Acetone	1,742	56.2	116.0 (16.8)	3.7 (0.32)	Small porosity, some joints are clean
Base Line Steel/Inconel	1,908	320.8	127.0 (19.8)	18.4 (20.7) !!	No pores, large fillets

** The low carbon pipe surface was subjected to different cleaning treatments before the brazing operation.*

Testing of low-carbon steel pipe/fin parts brazed with BNi-2 (MBF-20 METGLAS® Foil) narrow (~3 mm) foil strip. (a) Tested part; (b) Instron setting during loading; (c) Parts after failure

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Corrosion Weight Losses of Some Brazed Samples in an Acid Solution

Brazing Filler Metals Used In Tested Samples	Weight Change, %, Relative to the Initial Weight After 781 h Exposure	
	316 SS coupons	321 SS coupons
MBF-51 (BNi-5b) (Ni-15Cr-7.3Si-1.4B)	-6.14	-22.3
MBF-51+5% Mo (Ni-15Cr-7.3Si-1.4B-5Mo)	-1.74	-11.23
MBF-101 (Co-21Cr-4.5W-4.4Si-1.55B)	-0.59	-0.1
Unbrazed base metal 316SS and 321SS coupons having the same weight as the tested samples and used for comparison	-0.31	-0.05

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Brazability and Oxidation Resistance in Open Air at 1165°C/65 Hours of PM2000 Honeycombs Brazed Using Ni- and Co-based Amorphous Alloys (according to D. Sporer, Plansee)

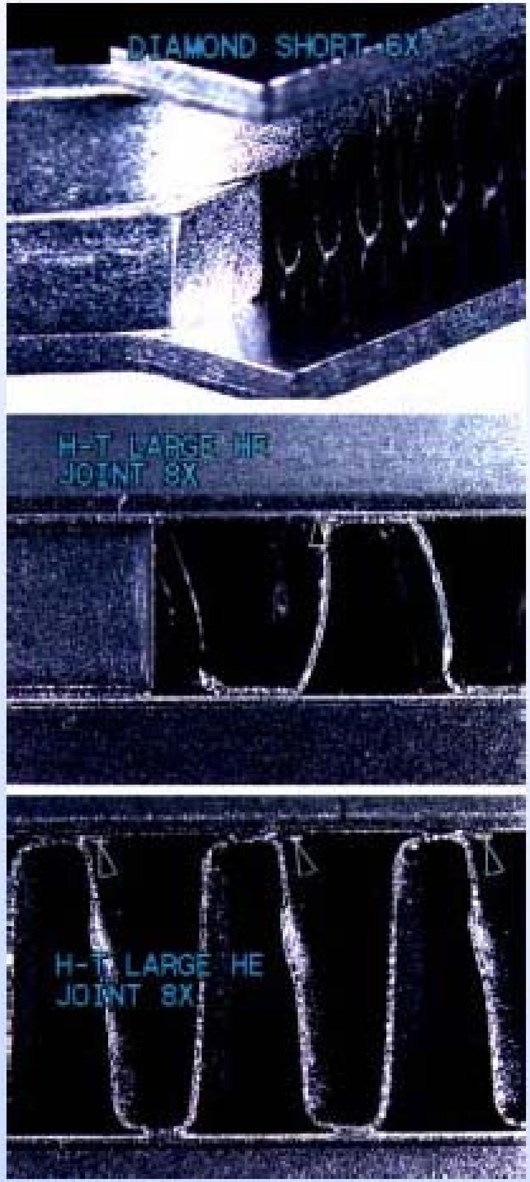
MBF Alloy And Its Composition, Wt.	Honeycomb Cell Size Height, mm	Wicking, (M1) %	Brazing/Oxidation Quality (BQN)**, %
MBF-50 (BNi-5a) (Ni-19Cr-7.3Si-1.25B	5 x 6.4	95***	6
MBF-100 (Co-21Cr-4.5W-1.6Si-2.15B)	1.6 x 10	100	61
MBF-101 (Co-21Cr-4.5W-4.4Si-1.55B	2.5 x 6.6	100	44
MBF-102 (Co-15Ni 21Cr-4.5W-4.4Si-1.55B)	2.5 x 6.8	65	61
MBF-103 (Co-15Ni-21Cr-4.5W-3Pd-4.4Si-1.55B)	1.6 x 10	59	65
MBF-104 (Co-15Ni-21Cr-4.5W-5Pd-4.4Si-1.55B	1.6 x 10	71	62

* Brazing was made at about 1200°C for 2-5 min in high vacuum, <1x10(E-5) mbar.

** BQN [%]=(10xM1xH)/(10+N_b)xH_n, where M1 is braze flow in %, H-honeycomb height, mm;

N_b number of double cell walls showing "through" or breakaway oxidation; H-normalized honeycomb height.

*** Three 25 mkm thick foils were preplaced from each of both sides of the honeycomb.



Three macrographs of an Inconel 625/MBF-51brazed heat exchanger depicting a general view and magnified views of a narrow and a wide passages.

A family of SWEP (Sweden) stainless steel heat exchangers brazed using BNi-5b (MBF-51 METGLAS® Foil)

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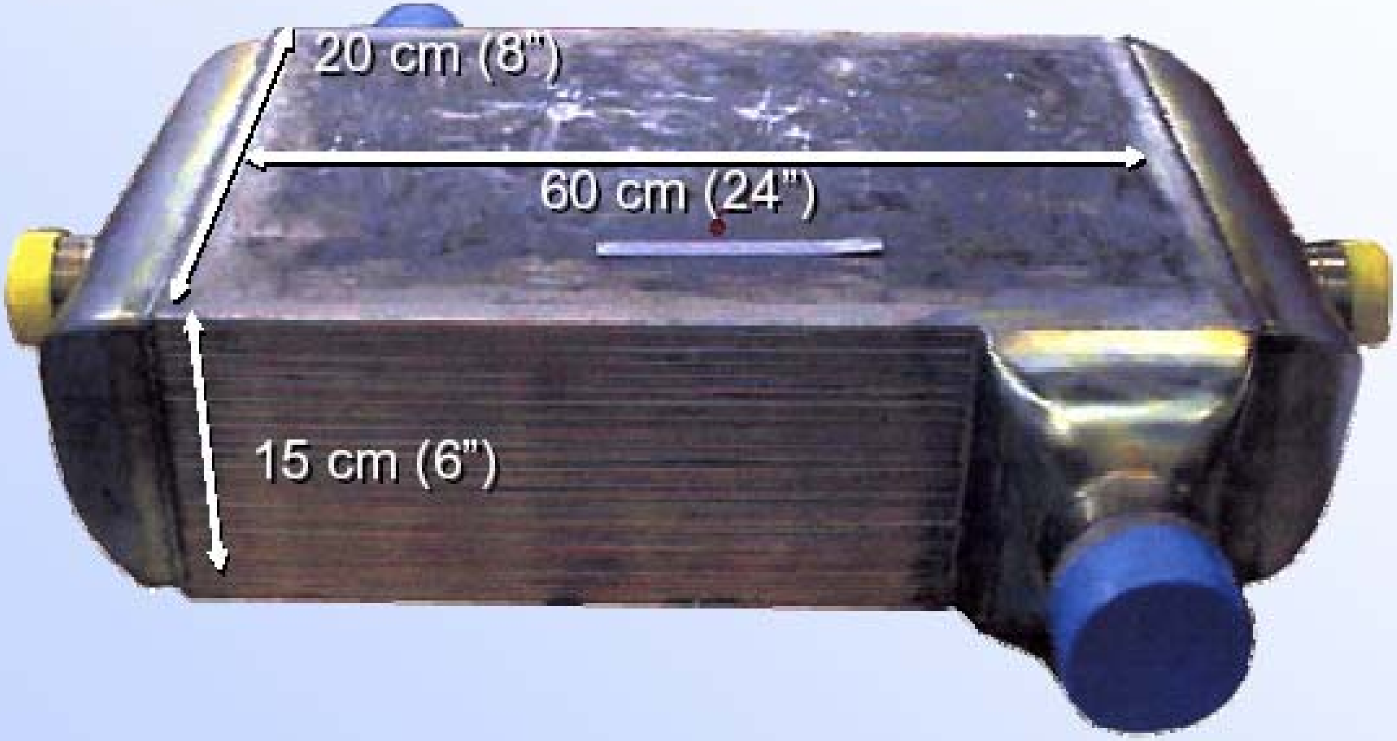
Heat Exchanger For Fuel Cell Generator
Made of Inconel / MBF-51 by Hughes-Treitler Military Co.
9 Pieces Made, 15 Expected



Brazed Core Dimensions: 60x15x20 cm (24"x6"x8"); 43 Passages; Total MBF-51 Weight ~6 kg

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SUMMARY

- Strength of the plate/fin structure is directly proportional to the cross-section area of individual joints and that, in turn, is proportional to the foil thickness. The strength can be easily optimized by varying the foil thickness to a degree when it is determined by the base metal strength and not by the brazed joints.
- Dimensions of unconstrained plate/fin brazed structures are practically constant regardless of the thickness of the MBF-20 brazing foil. This dimensional constancy is due to an interplay between the capillary forces of the liquid MBF-20 filler metal in the narrow 316 SS gaps and an applied external load that includes the own weight of the structure.
- Plate-like microstructure of 436SS/MBF-20/436SS joints is observed in samples after the short brazing cycle with Cr_xB_y plates occupying about 10% of sample cross-section mostly in base metal Their strength is moderately higher than that of samples after the long brazing cycle which have microstructure with a round morphology of Cr_xB_y phase that occupies a much larger volume (25% of the cross-section).

- Low carbon steel fins can be easily brazed to low carbon steel pipes in the "virgin", hot rolled state using a narrow BNi-2 (MBF-20 foil) strip and an industrial nitrogen atmosphere, if inexpensive cleaning operations are applied to these pipes. Interestingly, the joint strength depends strongly on the type of cleaning.
- Large and small Inconel 626 and 347 SS plate/fin structures with various plate and fin thickness were successfully brazed,-no porosity in and cracking of joints,-using BNi-5b (MBF-51) brazing foil and applying slow heating and cooling stages of the brazing cycle.
- A series of high corrosion and high oxidation resistant Ni- and Co-based amorphous alloys were developed. These alloys were successfully tested under severe service conditions in some air space and automotive applications.

ACKNOWLEDGEMENT

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