Influence of Gap Clearance on Brazing Joint Strength for Ni- and Fe-base Filler Metals for Brazing Ferritic Stainless Steels

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Ferritic stainless steels are gaining increasing interest for brazed components due to the combination of low cost, low thermal expansion and good high temperature scaling resistance, compared to the commonly used austenitic stainless steels. As a continuation of our recent work on the effect of gap clearance on joint strength for austenitic stainless steels, the same effect has been studied for ferritic stainless steels. Due to differences in diffusivity of elements in ferritic stainless steels compared to austenitic stainless steels, the data from austenitic stainless steels cannot easily be extrapolated to ferritic stainless steels. In this investigation, AISI 430 butt-joint specimens were brazed with different nominal gap clearances ranging up to 300 µm, and the effect on the joint tensile strength was measured. The common Ni-base brazing filler metals BNi-2, BNi-5, BNi-7, Ni613 and Höganäs iron-base brazing filler metal BrazeLet® F300 was tested. The gap clearance effect on joint microstructure was evaluated by metallographic analysis. The joints brazed with Ni-base fillers have a significant strength increase at low gap clearances, which is attributed to changes in the joint microstructure. At large gap clearances, the fracture propagated along the brittle centreline eutectic. At gap clearances low enough to eliminate these brittle centreline eutectics, the fracture propagated along the filler-metal / base-metal interface. The joint strength variation with gap clearance for the ferritic stainless steels is different from the austenitic stainless steels tested previously. This is attributed to differences in the diffusivity of the melting point depressant elements in the filler metals. Joints brazed with Ni613 as well as Höganäs' iron-based alloy BrazeLet® F300 were not sensitive to variations in the gap clearance.

1 Introduction

Ferritic stainless steels are gaining increasing interest for brazed components due to the combination of low cost, low thermal expansion and good high temperature scaling resistance, compared to the commonly used austenitic stainless steels. The use of ferritic stainless steels is growing particularly for industrial and automotive heat exchanger applications, where these properties are beneficial. Further, Exhaust Gas Recirculation (EGR) coolers are becoming more common also in gasoline and hybrid gasoline engines, to meet more stringent emission standards. As the temperatures in gasoline engines are generally higher than in diesel engines, the ferritic stainless steels provide a benefit for such applications.

Limited data is published on the joint strength of ferritic stainless steel brazements, although some have looked at specific base material – brazing filler metal combinations. For example, Theisen and Coughlan found significant differences in the joint microstructure and the joint strength, especially for the boron containing brazing filler metals, but their investigation was limited to two Ni-Cr-P-type brazing foils [1]. More recently, Biglari et al. investigated the brazing behaviour of three Ni-base brazing filler metals on AISI 436 and AISI 441 ferritic stainless steels [2]. They discuss the topic of grain growth sensitivity of ferritic stainless steels, and show results of substantial grain growth after brazing. However, they do not provide any actual strength data to quantify the effect on the overall brazed joint strength.

As a continuation of our recent work on the effect of gap clearance on joint strength for austenitic stainless steels [3], the same effect has been studied for ferritic stainless steels. Due to differences in diffusivity of elements in ferritic stainless steels as well as different elastic-plastic behaviour compared to austenitic stainless steels, the data from austenitic stainless steels cannot necessarily be extrapolated to ferritic stainless steels. Therefore, experimental data is required for the actual base material – brazing filler metal combination at the relevant brazing conditions.

There are many different types of possible joint configurations when brazing components or test specimens, resulting in different stress states. In practice, the joints produced in a component are often very complex and thus it is difficult to know the strength of the brazed joint without performing some sort of destructive testing on actual components. Most strength data for brazed joints is produced for shear loading on various types of lap-joint geometries, as the method is less complicated compared to butt-brazed test specimens. The uniaxial tension test with butt-brazed test specimens is a good complement to evaluate some of the brazed joints within components which are closer to this type of stress state, e.g. within brazed plate heat exchangers. The stress state of a brazed joint has been found to significantly affect the joint strength and deformation behaviour, and therefore using the relevant test results is very important [4].

It is well established in the brazing community that brazed joint strength generally increases as gap clearance decreases for Ni-base brazing filler metals. However, our previous work on AISI 316L austenitic stainless steel butt joints have shown that this is not the case for all brazing filler metals. This current work is aimed at comparing the brazed joint strength of AISI 430 ferritic stainless steels compared with the existing data on AISI 316L austenitic stainless steel. The well established Ni-base brazing filler metals BNi-2, BNi-5, BNi-7, Ni613 as well as Höganäs iron-based brazing filler metals BrazeLet® F300 and BrazeLet F86 was evaluated.

2 Experimental Procedure

2.1 Brazing filler metals and base material

The brazing filler metals investigated in this work are listed in Table 1. They include the most commonly used Ni-base alloys BNi-2, BNi-5 and BNi-7 along with BrazeLet Ni613 and BrazeLet F300.

Table 1. Brazing filler metals evaluated in this report

Product name	AWS A5.8	ISO 17672 [5]	Composition
BrazeLet BNi2	BNi-2	Ni620	Ni82CrSiBFe
BrazeLet BNi5	BNi-5	Ni650	Ni71CrSi
BrazeLet BNi7	BNi-7	Ni710	Ni76CrP
BrazeLet Ni613(Note 1)	-	-	Ni60CrPSi
BrazeLet F300	-	-	Fe39CrNiCuPSi
Note 1: Ni613 is a licensed product, patented by Fukuda Metal Foil & Powder co. Ltd.			

AISI 430 (W.No. 1.4016) ferritic stainless steel was evaluated in this work, as that was what was available in the bar product form needed to prepare the test specimen geometry. The base material was manufactured as drawn, annealed and cold drawn bar. The chemical composition of the base material is shown in Table 2.

Table 2. Chemical analysis of AISI 430 base material used for the test specimens. All values are in wt %.

Fe	C	Si	Mn	Ni	Cr	Mo	Cu	S	P
Bal.	0.012	0.373	0.474	0.186	16.115	0.024	0.070	0.0265	0.0215

2.2 Test specimen preparation

The test specimen geometry consisting of two parts were prepared by machining. Different gaps between the two specimen halves were created by use of various diameter stainless steel wires (AISI 316L was used due to availability). The wire diameters used are listed in Table 3.

Table 3. Wire diameters used to create specific gap clearances.

Wire diameter [µm]
“0” (No wire)
25 µm
41 µm
78 µm
100 µm
300 µm

Small wire pieces were aligned along the two outside edges of the lower test specimen, as shown in Figure 1 below. The top half of the test specimen was mounted and fixtured with a specialized fixture designed for the test specimen geometry. In this way, any impact of the stainless steel wire on the joint area where the tensile test specimen was machined was avoided.

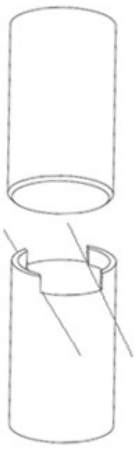


Figure 1. Assembly of test specimen halves with stainless steel wires aligned along the two edges.

2.3 Brazing of test specimens

Brazing paste was applied to the specimens outside the gap, on the ledge as seen in Figure 2. The amount of brazing paste was adjusted to be sufficient to fill the nominal gap, with a small safety factor to account for variations. For 100 µm and 300 µm specimens, brazing paste was applied inside the gap to ensure that brazed joints were produced even for the brazing filler metals, which normally will not fill such gaps by capillary action. A brazed sample after removal from the fixture is shown in Figure 3.



Figure 2. Sample prepared for brazing. Paste applied outside the joint.



Figure 3. Sample after brazing

Brazing was performed in a Carbolite tube vacuum furnace under high vacuum (~ 10^{-5} mbar) at the standard recommended brazing temperature for each filler metal. These temperatures are summarised in Table 4 below. The temperature ramping speed was 9 °C/min, and a 30-minute hold at 450 °C was implemented to ensure complete burnout of the binder. The time at the brazing temperature was 30 minutes. Natural cooling in high vacuum was used for all samples.

Table 4. Brazing temperatures used for the tested brazing filler metals.

Filler metal	Brazing temperature
BrazeLet BNi2	1,050 °C / 1,922 °F
BrazeLet BNi5	1,150 °C / 2,102 °F
BrazeLet BNi7	980 °C / 1,796 °F
BrazeLet Ni613	1,100 °C / 2,012 °F
BrazeLet F300	1,120 °C / 2,048 °F

2.4 Tensile testing

After brazing, tensile testing specimen geometries were machined from the test specimens. The test specimen geometry is shown in Figure 4. The length of the parallel section (L_0) was 21 mm. The actual gap clearance was measured non-destructively by examining the machined specimens in a Hitachi TM3030 Scanning Electron Microscope. This was done to couple the actual gap clearance of each individual specimen with the tensile strength. Tensile testing was performed in a Zwick/Roell 10 kN tensile testing machine. Testing was done according to EN 12797 [6], and SS-EN ISO 6892-1 [7], at room temperature. Although EN 12797 recommends a specimen diameter of 4.5 mm, a diameter of 4.0 mm was used to ensure that all specimens would be within the capacity of the tensile testing machine.

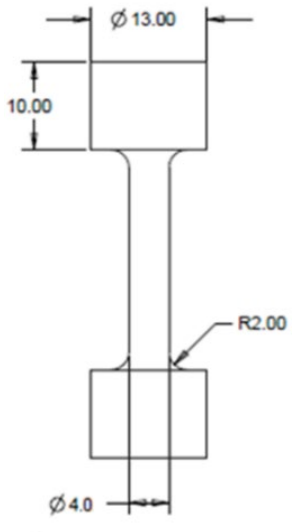


Figure 4. Tensile test specimen geometry.

After tensile testing, some of the specimens were investigated by Light Optical Microscopy in a Leica DM6000 microscope. The fractured surfaces were glued back together by Loctite 407 super glue and prepared by metallographic methods to investigate where the fracture had propagated in the test specimens.

2.5 AISI 430 base material reference specimens

As AISI 430 ferritic stainless steel is subject to significant grain growth when exposed to brazing temperatures in the range used in this investigation, reference specimens without brazed joints in the centre were also machined to the tensile test specimen geometry from the same base material rods. These reference specimens were subjected to the same brazing cycle as for the tested filler metals. Two specimens were tested for each condition, with heat treatment in the Carbolite vacuum furnace corresponding to brazing at 980 °C (BNi-7), 1,050 °C (BNi-2), 1,100 °C (Ni613 and F300) and 1,150 °C (BNi-5). Two reference specimens without heat treatment was also tested to compare with the yield and tensile strength stated on the material certificate, and eliminate any influence of the different test specimen geometry. These specimens were tensile tested in the same manner as the brazed test specimens.

3 Results and Discussion

3.1 Tensile strength evaluation and brazed joint stress state

The measured tensile strength (Rm) as a function of gap clearance is shown for each brazing filler metal in Figure 5 – Figure 9. For test specimens where visual examination after fracture revealed incomplete joint filling, the test results were invalidated and excluded from the graphs. A summary of the observed variations in tensile strength with gap clearance for each brazing filler metal is provided below:

BrazeLet BNi2: Slight increase in tensile strength observed for gap clearances below 50 µm, with values up to 350 MPa. For gap clearances between 50 µm and 100 µm the tensile strength was in the area of 250 – 300 MPa. For larger gap clearances than 100 µm the tensile strength decreased significantly.

BrazeLet BNi5: Significant increase in tensile strength for gap clearances below 50 µm, with the maximum value of 366 MPa. At larger gap clearances than 50 µm the tensile strength is around 170 – 245 MPa. At very large gap clearances (> 400 µm), the tensile strength is even lower, but the results are somewhat unreliable due to uneven gap filling.

BrazeLet BNi7: Slight increase in tensile strength observed for gap clearances below 70 µm, with values up to 200 MPa. For larger gap clearances, the tensile strength varied between 100 and 170 MPa. The lowest strength filler metal out of the ones tested in this work.

BrazeLet Ni613: Relatively stable tensile strength with variations in gap clearance, all the way up to 425 µm. Actually, there is a slight increasing trend in the tensile strength with increasing gap clearance from 50 to 425 µm, where tensile strength increases from 250 MPa to 305 MPa. This is attributed to the test specimen constraint. The sample with 20 µm gap clearance broke partly in the brazed joint and partly in the base material and showed the highest tensile strength for this brazing filler metal with 342 MPa.

BrazeLet F300: Relatively stable tensile strength with variations in gap clearance, all the way up to 420 µm. Similarly to BrazeLet Ni613 there is a slight increasing trend in the tensile strength with increasing gap clearance from 40 to 420 µm, where tensile strength increased from 250 MPa to 333 MPa. This is attributed to the test specimen constraint. For specimens with gap clearance below 30 µm, the brazed joint was stronger than the base material and tensile strength values (430-432 MPa) are therefore for fracture of the base material after significant plastic deformation and necking.

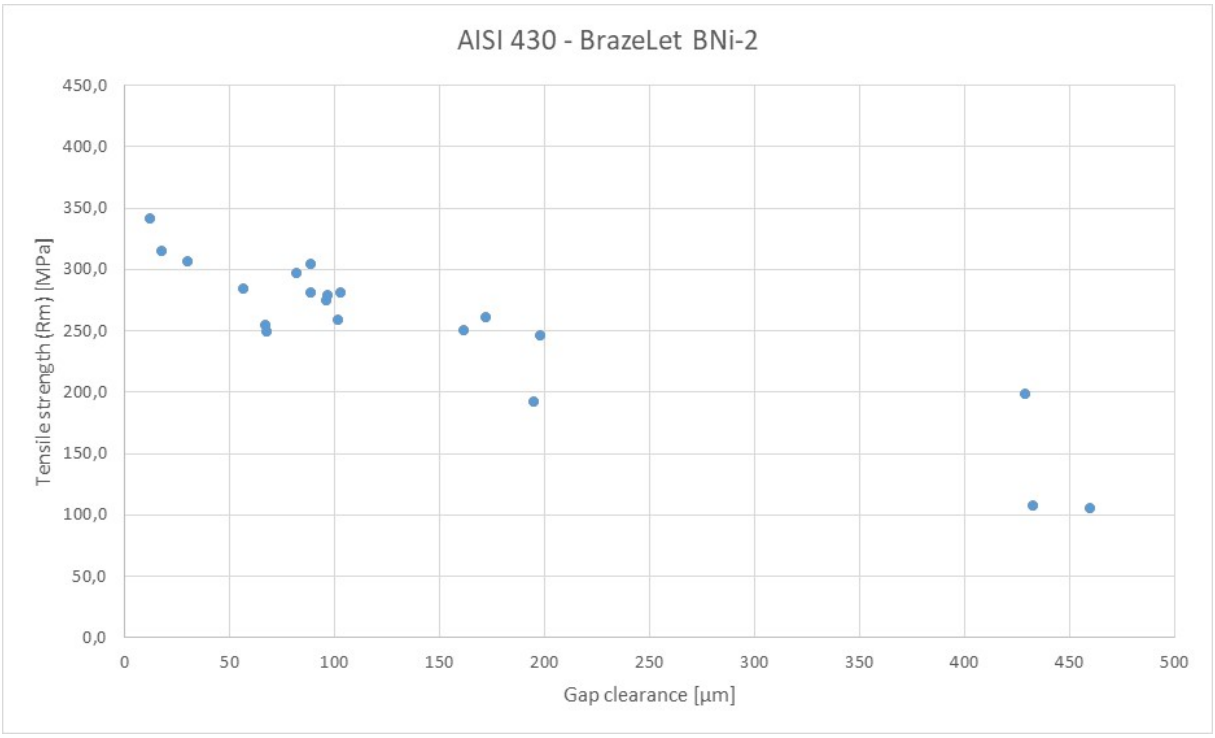


Figure 5. Measured gap clearance versus tensile strength (R_m) of AISI 430 brazed with BNi-2 at 1050 °C for 30 minutes in vacuum.

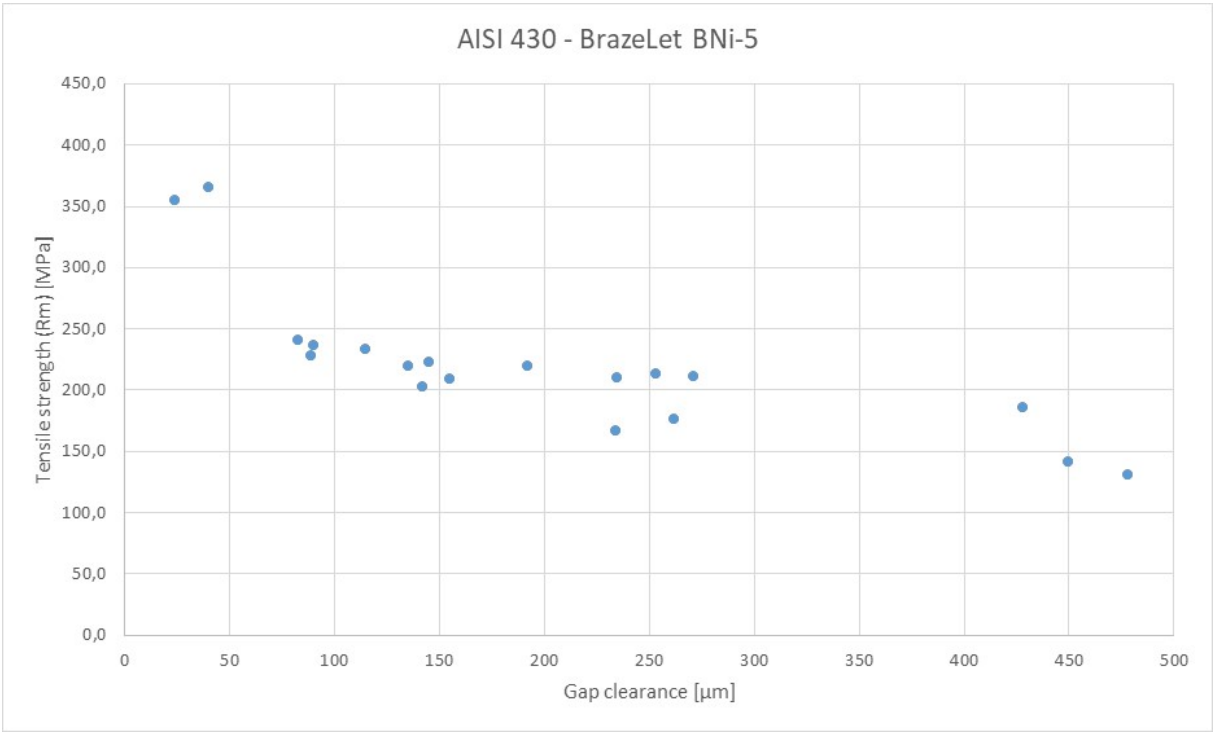


Figure 6. Measured gap clearance versus tensile strength (R_m) of AISI 430 brazed with BNi-5 at 1,150 °C for 30 minutes in vacuum.

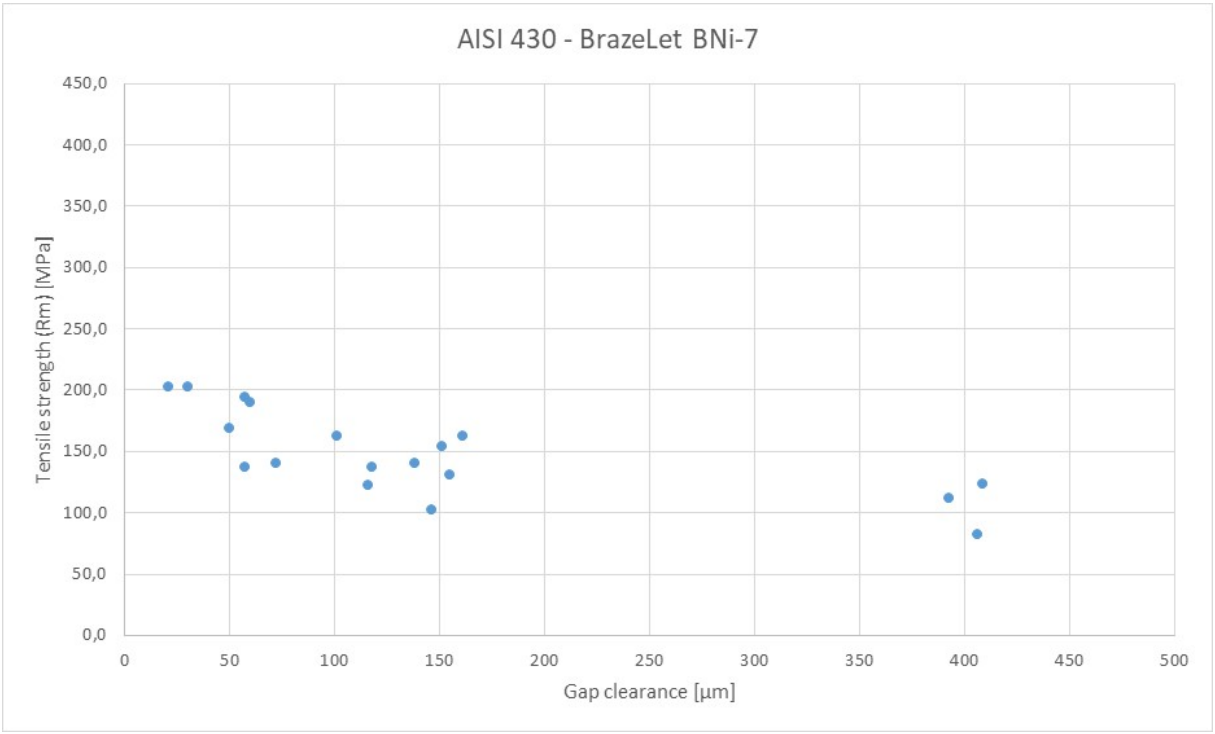


Figure 7. Measured gap clearance versus tensile strength (R_m) of AISI 430 brazed with BNi-7 at 980 °C for 30 minutes in vacuum.

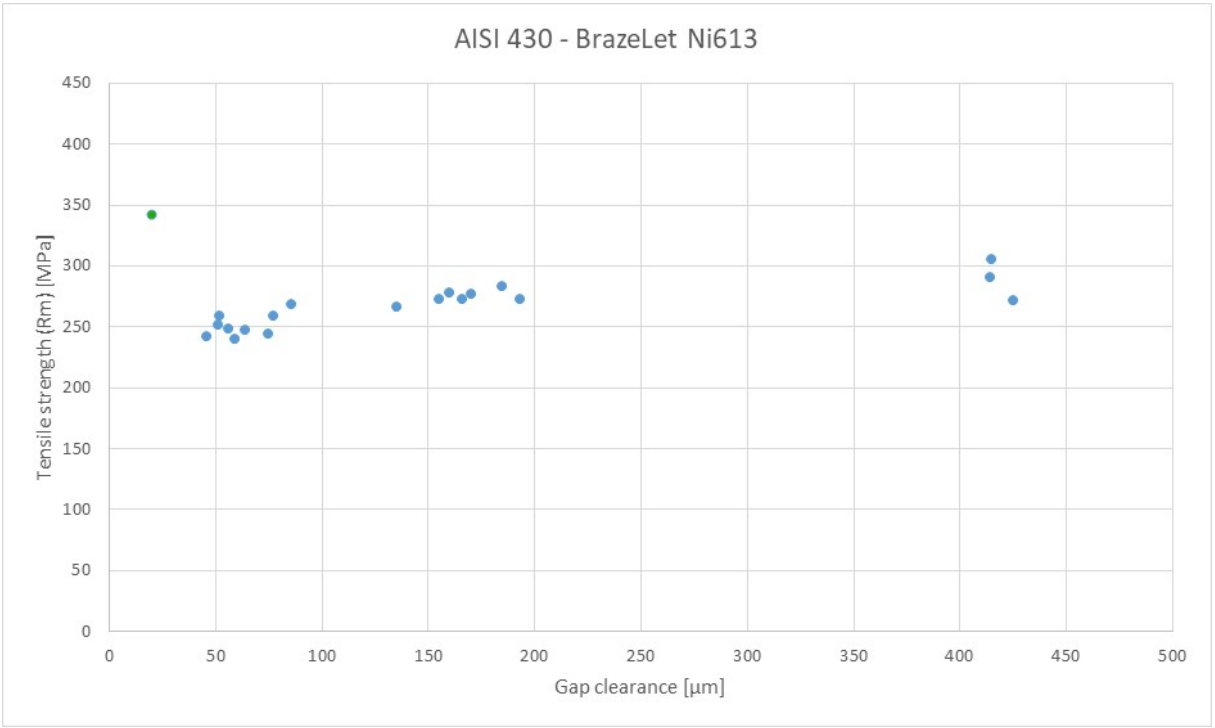


Figure 8. Measured gap clearance versus tensile strength (R_m) of AISI 430 brazed with BrazeLet Ni613 at 1,100 °C for 30 minutes in vacuum. Specimen indicated in green fractured partly in the base material and partly in the Ni613 brazing filler metal.

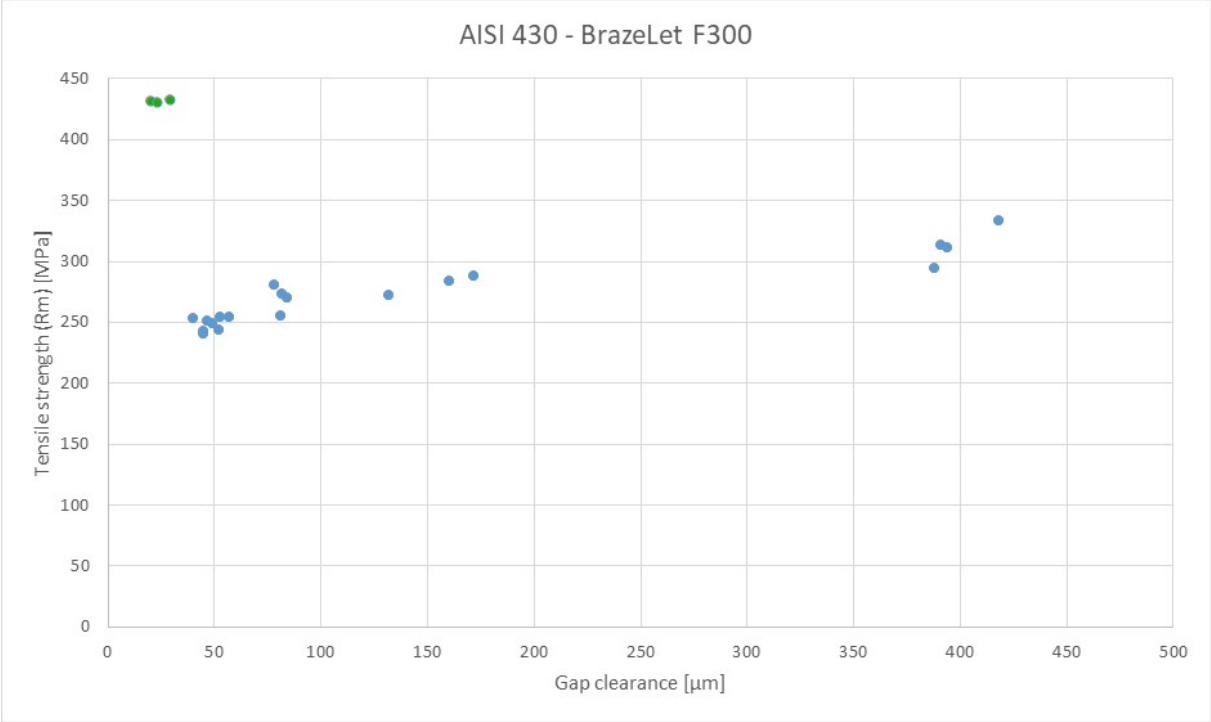


Figure 9. Measured gap clearance versus tensile strength (R_m) of AISI 430 brazed with BrazeLet F300 at 1120 °C for 30 minutes in vacuum. Specimens indicated in green fractured in the base material.

Test specimens which from visual examination contained incompletely filled brazed joints are excluded from the above test results. Generally, brazing filler metal wetting of ferritic stainless steels is worse than for austenitic stainless steels. For some brazing filler metals, it was observed incomplete gap filling at very low or very large gap clearances. This effect was most pronounced for BNi-7, which has poor wetting on AISI 430 ferritic stainless steel, where none of the samples with a gap clearance below 25 µm were completely filled. The same was seen for BrazeLet Ni613 at a gap clearance of 13 µm. At extremely low gap clearances, the wetting and flowing behaviour of the brazing filler metal becomes more important for the joint filling and thereby overall joint strength.

Evaluating the strength of brazed joints is a complex task that is strongly depending on the test specimen geometry and loading conditions. For example, single lap-joint shear strength values are not necessarily directly transferrable to the stress state in actual brazed components such as brazed plate heat exchangers or EGR coolers. In cases where brazed assemblies are subject to internal pressure, some of the brazed joints might be closer to uniaxial tensile loading. This motivates the trials with brazed butt-joint geometry, tested in uniaxial tension. These trials show the strength of the brazed joint geometry as a whole, not the strength of the brazing filler metal or the base material individually. The tensile strength of butt-brazed joints exceeds, by far, the tensile strength of the filler metal tested in bulk form [8].

To achieve high brazed joint strength, the elastic-plastic behaviour of the whole system needs to be taken into account. The brazing filler metals should ideally match the properties of the base material as closely as possible when it comes to modulus of elasticity, plastic deformation and work hardening [9]. In practice, matching such properties is a difficult task as measuring the brazing filler metal itself is most of the time not possible. Therefore, it is most of the time dependent on evaluating the actual brazing filler metal – base material combinations to verify which brazing filler metal can be most suitable.

The stress state also largely influences how the brazed joint behaves during testing. Uniaxial loaded butt joints are subject to high brazing filler metal constraint which results in a highly tri-axial stress-state causing the braze joints to behave in a quasi-brittle manner [4]. In the pure hydrostatic stress state, failure occurs without any plastic deformation. This is reflected in our test results where almost all brazed joints tested, fractured with little or no plastic deformation. The exceptions are some of the test specimens brazed with BrazeLet Ni613 and F300 at very low gap clearances, where the joint consists of a primary phase with only a few scattered or no intermetallic phases. For these test specimens fracture occurred in the base material by necking after significant plastic deformation of both the base material and brazing filler metal.

For transferring these results to other braze joint components loaded in tension, the stress state should be considered. In this case, a test specimen diameter of 4.0 mm was evaluated. Brazed joint with smaller width or larger gap clearance will lead to lower constraint, and lower degree of hydrostatic stress.

3.2 Microstructural evaluation of brazed joints and fractured test specimens

In order to evaluate how fracture propagates through the brazed joints at different gap clearances, metallographic investigation of un-tested specimens was compared with appearance after tensile testing. The evident changes in the microstructure of the brazed joint influence how fracture propagates through the joint. The microstructural changes as function of gap clearance are summarised for the different brazing filler metals below, and can be seen in Figure 10.

BrazeLet BNi2: Significant diffusion of boron into the base material, but contrary to austenitic stainless steels, Cr-boride precipitation is not concentrated to the grain boundaries, but scattered as thin needle-like precipitates also inside the ferrite grains. The Cr-borides are oriented mainly perpendicular to the brazed joint direction. For small gap clearances below 50 µm there is no continuous centreline eutectic, and fracture propagates along the interface line between the brazing filler metal and the base material. For larger gaps than 50 µm, a continuous brittle centreline eutectic with three distinct phases is visible, and fracture propagates along these phases in a brittle manner.

BrazeLet BNi5: Even at low gap clearances, there are scattered intermetallic phases with an octahedral morphology located along the brazed joint. As there is no continuous line of brittle phases, fracture propagates along the interface line between the brazing filler metal and the base material. For larger gaps than 50 µm, a continuous brittle centreline eutectic is visible and fracture propagates along this line in a brittle manner.

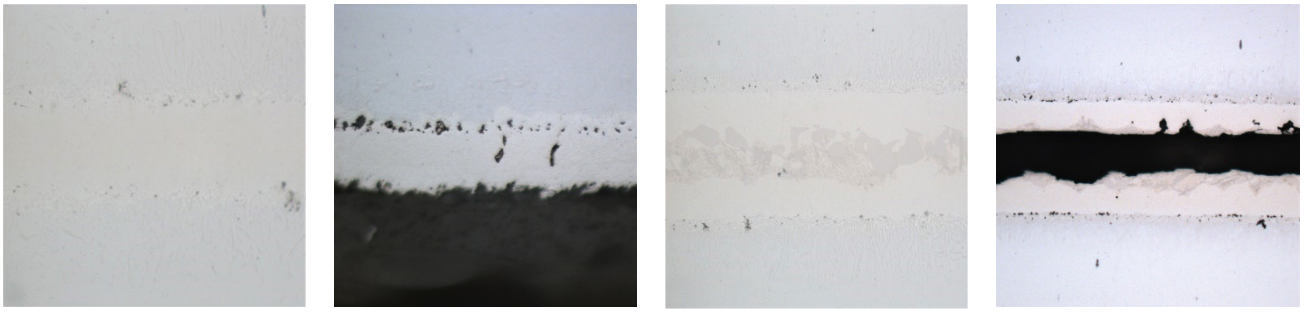
BrazeLet BNi7: Even at low gap clearances below 50 µm a continuous centreline of two intermetallic phases can be observed. Hence, reducing the gap clearance is not sufficient to avoid these brittle phases for BNi-7, which is also seen from the tensile strength versus gap clearance curves. For gap clearances larger than 50 µm, the amount of brittle intermetallic phases increases and fracture propagates in the same manner, through the centre of the joint.

BrazeLet Ni613: At very low gap clearances below 20-30 µm, the brazed joint contains scattered intermetallic phases along the centre of the joint, or in some instances even a homogeneous joint without any secondary phases. In such cases, fracture propagated through the base material. For larger gap clearances, the brazed joint consists of a fine heterogeneous mix of different intermetallic phases and primary phase. As these phases are finely distributed, even at larger gap clearances fracture cannot easily go through a brittle centre of the joint, but needs to propagate through a mixture of phases. Hence, the strength of joints brazed with Ni613 is not negatively affected by increasing gap clearance.

BrazeLet F300: At gap clearances below 30 µm, a homogenous brazed joint consisting of only primary phase is found, and fracture occurred in the base material. For larger gap clearances than 30 µm, a fine heterogeneous mix of different intermetallic phases and primary phase can be found. The amount of these phases increase with increasing gap clearance, but they remain finely distributed even at large gap clearances. Fracture propagates through the mixture of phases, and similarly to Ni613, the tensile strength of the brazed joint remains good even at high gap clearances.

BNi-2

< 50 µm gap > 50 µm gap



(31 µm gap) (81 µm gap)

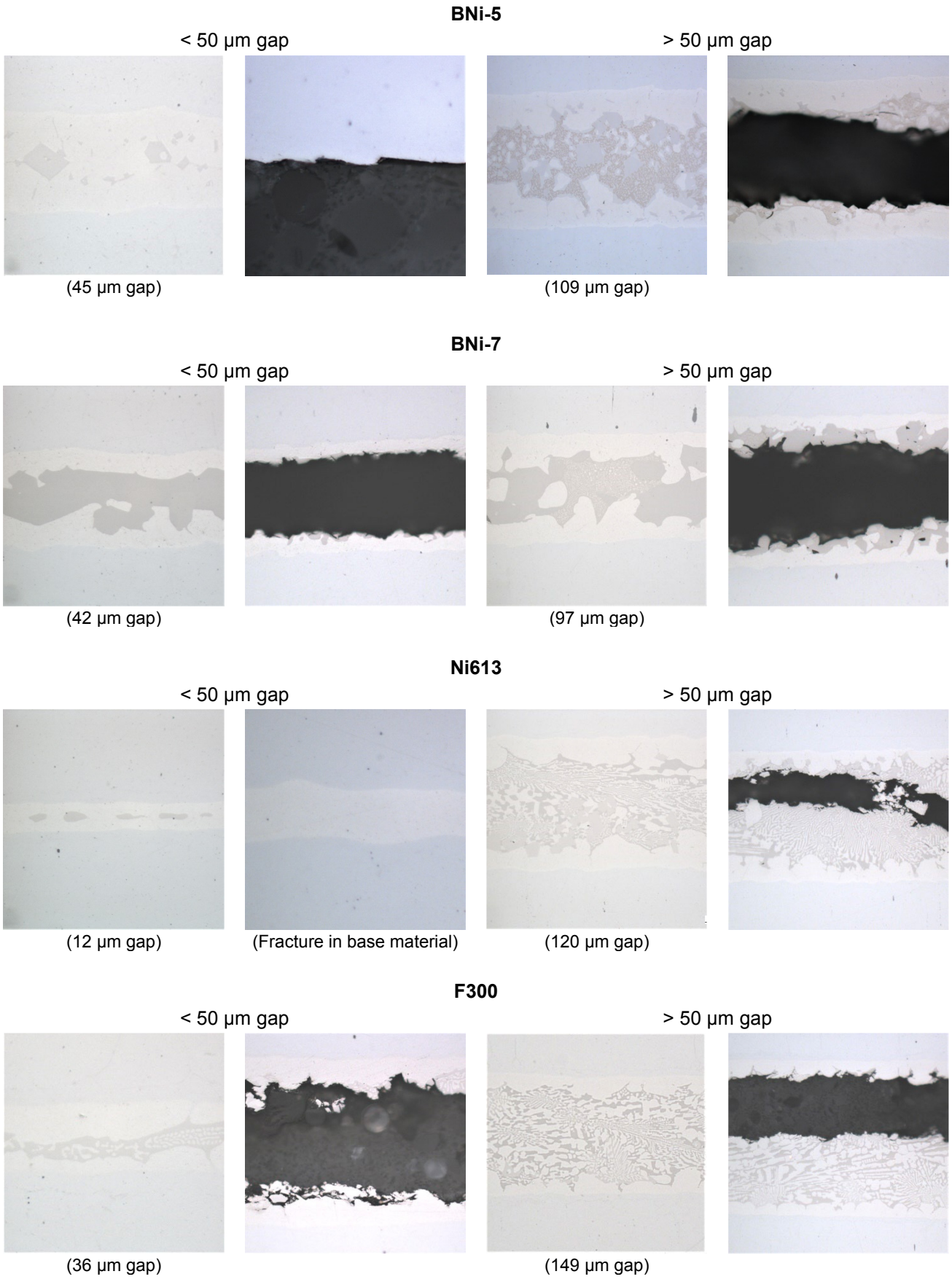


Figure 10. Brazed joint microstructures and fracture propagation path for AISI 430 joints brazed with the tested brazing filler metals BNi-2, BNi-5, BNi-7, BrazeLet Ni613 and BrazeLet F300 at low gap clearances and intermediate gap clearances.

It is well established that microstructural features will affect the brazed joint strength and ductility. For the same brazing filler metal - base material combination the joint microstructure will change depending on the gap clearance, the brazing temperature and time. Lugscheider and Krappitz showed that increasing the brazing temperature and brazing time can increase the maximum gap clearance for BNi-2 / Inconel 625 joints up to 80-90 µm from around 20 µm at the worst brazing conditions [9]. When increasing the brazing temperature, diffusion is more rapid and the melting point depressant elements (e.g. B, Si, P) can diffuse more readily to the base material, which in turn reduces the tendency of forming brittle phases in the brazed joint. In this work, it has not been sought to optimize the brazing profile for a certain brazing filler metal – base material combination. All trials have been done at the Höganäs standard recommended brazing temperature, with a holding time of 30 minutes.

In our previous work with AISI 316L austenitic stainless steel with otherwise same brazing conditions as used in this work, a significant increase in joint strength was observed at low gap clearances for the conventional Ni-base brazing filler metals BNi-2, BNi-5 and BNi-7. A threshold for gap clearance of 50 µm was established for BNi-2, BNi-5 and BNi-7. Below this gap clearance, there were no continuous brittle intermetallic phases along the centre of the joint.

In this work with AISI 430 ferritic stainless steel base material, the microstructure still affects the joint strength as expected. For BNi-2, a slight increase in joint strength is observed for gap clearances below 50 µm. Likewise, for BNi-5 a substantial increase in joint strength is observed for gap clearances below 50 µm. However, in the case of BNi-7 there is no evident increase even at low gap clearances and the joint strength in all cases is quite low compared to the other brazing filler metals. The substantial increase in joint strength can only be seen in the cases where there is no continuous intermetallic phases in the brazed joint centre. For BNi-7, this brittle centreline remains at all gap clearances achieved. New for this current work is that the brazing filler metals that previously showed no increase in joint strength with reducing gap clearance such as BrazeLet Ni613 and F300 resulted in joints exceeding the AISI 430 base material strength for very low gap clearances. Microstructural investigation shows that these brazed joints contains only scattered or no intermetallic phases in the brazed joint.

The boron-containing brazing filler metal BNi-2, show void formation around the borides that precipitate along the brazing filler metal – base material interface. These voids are a result of crack formation around the boride precipitates. This crack propagation is obstructed at the phase-boundaries between the borides and ferrite grains by plastic deformation of the base metal, followed by rounding of the cracks to form microvoids. As there is no continuous line of brittle phases along the interface line, the ductility and strength is higher compared to the larger gap clearances for BNi-2 where fracture rather propagates along the brittle phases in the joint centre. This has also been reported before [9].

The above, is also in part applicable to the microstructures of BrazeLet Ni613 and F300, which at larger gap clearances show a fine heterogeneous mixture of intermetallic phases mixed with primary phase. For such microstructures, there is no continuous brittle centreline where the crack can easily propagate. Rather, the ductile primary phase will arrest the cracks to some extent, increasing the joint strength.

Isolated hard phases in the brazed zone do not cause embrittlement of the joint. Cracks in these phases, which already occur at low stress levels, are stopped at the interfacial zone to the more ductile nickel or iron solid solution by plastic deformation [9].

3.3 Brazing temperature effect on joint strength

As ferritic stainless steels are sensitive to grain growth when exposed to high temperatures, reference specimens were prepared from the same bar material, machined into the same tensile test specimen geometry and heat treated in the brazing vacuum furnace at exactly the same conditions as the brazed test specimens. The impact on yield strength ($R_{p0.2}$) and tensile strength (R_m) was studied. The results are summarised in Table 5 below. As the base material was delivered as drawn, annealed and cold drawn bar the strength in the as delivered condition by far exceeds the strength after subject to a brazing cycle, with 563 MPa. Actually, the highest yield and tensile strength of the heat-treated specimens was seen for the ones subject to a heat treatment corresponding to brazing at 1,050 °C. At higher temperatures, the tensile strength drops to the lowest strength of 392 MPa, which was measured after heat treatment corresponding to brazing at 1,150 °C.

Table 5. Effect of brazing profile on AISI 430 base material yield and tensile strength

Specimen condition	$R_{p0.2}$ [MPa]	R_m [MPa]
As-delivered	549	563
980 °C, 30 minutes	235	433
1,050 °C, 30 minutes	240	441
1,100 °C, 30 minutes	225	410
1,150 °C, 30 minutes	227	392

The brazed joint strength in this work is affected by the brazing temperature from two main mechanisms. Firstly, higher brazing temperatures accelerates diffusion of the melting point depressant elements into the base material and thereby reduces the tendency of forming brittle intermetallic phases in the brazed joint as already discussed in the preceding section. However, in the case of ferritic stainless steels, which are sensitive to grain growth at high temperatures, increasing brazing temperatures could rather lead to loss of strength of the brazed joint as a whole. Ideally, a brazing filler metal for ferritic stainless steels should be possible to braze at sufficiently low temperatures where grain growth will not significantly impair the properties of the base material.

Previous investigations of grain growth in brazed joints have found that the holding time at the brazing temperature is of less importance than the brazing temperature itself [9]. This matches the established theories for grain growth well, where grain growth is normally modelled as an Arrhenius-type relationship, which is linearly dependent on time and exponentially dependent on temperature. Hence, where possible, a reduction in brazing temperature is normally much more effective than reducing the brazing time to limit grain growth. For ferritic stainless steels, increasing grain size will reduce the yield and tensile strength. For the reference specimens tested in this work, both the yield and the tensile strength is in fact decreasing with increasing brazing temperatures. The exception is the tests run at 980 °C, where the yield and tensile strengths are slightly lower than at 1,050 °C. The reason for this difference is not studied in detail in this work, and can be the result of several factors. As the as-delivered material was substantially cold-worked, re-crystallisation will occur first in the brazing cycle prior to further grain growth. In addition, the brazing temperature of 980 °C is the closest condition to the ferrite + austenite (α + γ) loop in the phase diagram, indicating that there could be some effect of austenite (γ) in the base material. Further investigations would be needed to establish which mechanisms cause the observed lower strength after a brazing cycle at 980 °C. While the test specimen material is made from cold rolled bar material, the same effects would be expected in brazed assemblies, as the components to be joined normally are cold formed to various extents.

3.4 Comparison with previous test results for AISI 316L austenitic stainless steel

As corresponding work has already been done with AISI 316L austenitic stainless steel as the base material, and presented during the IBSC2018 [3], it can be worth comparing the results from the trials with different base material. It is observed that the very high tensile strength at low gap clearances observed for BNi-2 and BNi-5 in combination with AISI 316L is not seen for the AISI 430 test specimens evaluated here. The differences for BNi-2 could be an attribute of the differences in boride precipitation along the brazing filler metal – base metal interface. In AISI 430 borides precipitate both along the grain boundaries, but also within the grains with needle-like morphology, attributed to preferential diffusion passes for B in ferrite [10]. For AISI 316L borides precipitate mainly along the grain boundaries, or as small rounded particles within the grains. It is believed that the needle like borides in AISI 430 are more prone to cracking, which could prevent the large strength increase at low gap clearances. For BNi-5 there is no evident explanation of the different behaviour at low gap clearances except different elastic-plastic compatibility with AISI 316L and AISI 430.

In general, there are few other significant differences between the AISI 316L and AISI 430 trials. If anything, the trend for all brazing filler metals except BNi-7 is that AISI 430 brazed joints tend to have a slightly higher strength compared to AISI 316L joints at the same gap clearance.

4 Conclusions

In this work the influence of gap clearance on brazing joint strength was studied for conventional Ni-base brazing filler metals BNi-2, BNi-5, BNi-7 and BrazeLet Ni613, and also Höganäs patented iron-based brazing filler metal BrazeLet F300. Tensile testing is combined with metallographic investigation of the joint microstructure to establish safe gap clearance recommendations for the tested brazing filler metal – base material combinations. It was found that:

- Reducing the gap clearance leads to a slight increase in joint tensile strength for BNi-2 from 250-300 MPa at 50-100 µm up to 350 MPa at gap clearances below 50 µm. For BNi-5, the increase was considerably larger from 170-245 MPa at gap clearances exceeding 50 µm up to 366 MPa at gap clearances below 50 µm. Compared to AISI 316L austenitic stainless steel specimens with these brazing filler metals, the increase in strength due to reduced gap clearance was considerably lower for AISI 430 ferritic stainless steel.
- Boride precipitation in the base material when brazed with BNi-2 is of a needle-like morphology attributed to differences in diffusion behaviour of B in ferrite compared to austenite. The larger needle-like borides observed along the BNi-2 – AISI 430 interface are believed to be more detrimental to the joint strength compared to boride precipitation in AISI 316L austenitic stainless steels which are rounded more finely dispersed particles.
- The brazing filler metals BrazeLet Ni613 and BrazeLet F300, which have otherwise proven not to be very dependent on the gap clearance, achieved very high strength at gap clearances sufficiently low to eliminate intermetallic phases in the joint. In these specimens, fracture occurred in the AISI 430 base material.

- Grain coarsening for the tested specimens was impact the overall joint strength, but it is evident that proper brazing filler metal selection is significantly more important than maintaining a low brazing temperature for good overall brazed joint strength with AISI 430.
- Test specimen constraint led to a slight decrease in brazed joint strength with decreasing gap clearance for BrazeLet Ni613 and BrazeLet F300, which are otherwise not sensitive to variations in gap clearance. The same effect cannot be seen for the other tested brazing filler metals as large gap clearances results in brittle joints that fail at a lower stress. The test specimen constraint increases with lower gap clearances, leading to a more hydrostatic stress state in which brazed joints fail in a quasi-brittle manner.

5 Literature

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