



Seulbi Lee <sup>1,†</sup>, Hanjong Kim <sup>2,†</sup>, Seonghun Park <sup>2,\*</sup> and Yoon Suk Choi <sup>1,\*</sup>

- School of Materials Science and Engineering, Pusan National University, Busan 46241, Korea; seulbi0921@pusan.ac.kr
- <sup>2</sup> School of Mechanical Engineering, Pusan National University, Busan 46241, Korea; hkim@pusan.ac.kr
  \* Correspondence: paks@pusan.ac.kr (S.P.); choiys@pusan.ac.kr (Y.S.C.); Tel.: +82-51-510-2330 (S.P.);
- +82-51-510-2382 (Y.S.C.); Fax: +82-51-514-0685 (S.P.); +82-51-512-0528 (Y.S.C.)

t All authors contributed equally to this study.

Abstract: As an advanced heat exchanger for aero-turbine applications, a tubular-type heat exchanger was developed. To ensure the optimum performance of the heat exchanger, it is necessary to assess the structural integrity of the tubes, considering the assembly processes such as brazing. In this study, fatigue tests at room temperature and 1000 K were performed for 0.135 mm-thick alloy 625 tubes (outer diameter of 1.5 mm), which were brazed to the grip of the fatigue specimen. The variability in fatigue life was investigated by analyzing the locations of the fatigue failure, fracture surfaces, and microstructures of the brazed joint and tube. At room temperature, the specimens failed near the brazed joint for high  $\sigma_{max}$  values, while both brazed joint failure and tube side failure were observed for low  $\sigma_{max}$  values. The largest variability in fatigue life under the same test conditions was found when one specimen failed in the brazed joint, while the other specimen failed in the middle of the tube. The specimen with brazed joint failure showed multiple crack initiations circumferentially near the surface of the filler metal layer and growth of cracks in the tube, resulting in a short fatigue life. At 1000 K, all the specimens exhibited failure in the middle of the tube. In this case, the short-life specimen showed crack initiation and growth along the grains with large through thickness in addition to multiple crack initiations at the carbides inside the tube. The results suggest that the variability in the fatigue life of the alloy 625 thin-tube brazed specimen is affected by the presence of the brazed joint, as well as the spatial distribution of the grain size and carbides.

Keywords: fatigue variability; alloy 625; thin tube; fractography; microstructure

# 1. Introduction

Heat exchangers are one of the key components for environmentally friendly gasturbine engines with lower emissions and higher specific fuel consumption ratings to meet environmental requirements and airline operation conditions [1–5]. Advanced heat exchangers for aero-turbine applications require compact and complicated shapes to achieve high efficiency and size limitations. Such a design limitation sometimes necessitates the use of submillimeter-scale thin tubes to maximize the heat exchange rate in a limited space. However, the use of such thin tubes requires an additional assembly process called "brazing" to connect the thin tubes to the inlet and outlet of the heat exchanger. Here, the mechanical integrity of thin tubes (including the brazed joint) needs to be thoroughly evaluated to ensure the optimum performance of the heat exchanger. However, it is difficult to assess the thermo-mechanical strengths of thin tubes and brazed joints under fluctuating loads, which simulate actual service conditions [6–14].

In the present study, a thin-tube brazed fatigue specimen was designed to evaluate the fatigue properties of thin tubes including brazed joints at room and elevated (1000 K) temperatures, considering the actual operating conditions of heat exchangers for the aeroturbine engine. Here, solid-solution-strengthened Ni-based alloy 625 was chosen as the thin-tube material. Alloy 625 has been used for a variety of components in the aerospace,



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aeronautics, marine, chemical, and nuclear industries because of its high-temperature strength, corrosion resistance in a variety of environments, excellent fabricability, and weld-ability (for tubing) [15–18]. Since alloy 625 components in industry fields were subjected to high temperature operations for a long duration, it is important to secure the mechanical properties at service temperature. V. Shankar et al. [19] extensively investigated the tensile properties at intermediate temperatures with various strain rates. L.M. Suave et al. [20] investigated the high temperature fatigue properties and clarified the thermal aging effect on the mechanical properties. Additionally, evaluation of the mechanical properties of the component. For the brazed superalloys, low-cycle fatigue [21,22], creep [23,24], and thermal cycling [25] have been studied, but high-cycle fatigue has been conducted in few studies [26,27]. In terms of the structural applications for brazed joints, J. Chen et al. [26,27] performed a high-cycle fatigue test of alloy 625 joints brazed with the Palnicro-36M<sup>TM</sup> filler metal to clarify the effect of single-lap joints under various lap distance-to-thickness ratios.

The alloy 625 thin-tube brazed fatigue specimens used in this study were designed similarly to the final configuration installed in an actual heat exchanger to reliably assess the fatigue properties of the alloy 625 thin tubes and brazed joints. A systematic study was conducted to understand the source of fatigue variability observed in alloy 625 thin-tube specimens. In particular, an effort was made to interpret the observed fatigue variability in terms of the microstructural variability of thin tubes, including the brazed joint, using microstructure analysis and fractography. The thermo-mechanical responses of the thin tube and brazed joint were also investigated to clarify the fracture mechanism.

## 2. Experiments

An alloy 625 tube with a thickness of 0.135 mm and an outer diameter of 1.5 mm was prepared by repeated drawing and heat treatment processes after initial tubing via tungsten inert gas welding of a 0.2 mm thick strip roll. Figure 1 shows the geometry of the newly designed thin-tube fatigue specimen. As can be seen, the thin tube was connected to the grip (also made of alloy 625) using brazing, in the same way that a tube is brazed to a tube sheet in an actual heat exchanger. This type of fatigue specimen allows us to investigate the fatigue behavior of the thin tube, including the influence of the brazed joint. The filler metal used for brazing was BNi-2, containing boron and silicon as melting point depressants. The chemical compositions of the alloy 625 tube and filler metal are listed in Table 1.



Figure 1. Geometry of the thin-tube brazed fatigue specimen.

_			Composition (wt.%)										
		Ni	Cr	Fe	Со	Мо	Nb	Ti	Al	С	Mn	Si	В
	Alloy 625	61.4	21.2	4.7	0.1	8.6	3.34	0.18	0.14	0.03	0.07	0.20	-
	BNi-2	82	7	3	-	-	-	-	-	-	-	4.5	3.1

Table 1. Chemical compositions of alloy 625 and BNi-2 used in this study.

Before the fatigue tests, the microstructure of the brazed specimen was analyzed. The sample was polished to a 0.04  $\mu$ M finish using colloidal silica and etched in 15 mL of HCl, 10 mL of acetic acid, and 10 mL of HNO<sub>3</sub>. The microstructures were then characterized using optical microscopy and scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). To measure the local mechanical properties, the hardness across the brazed joint was measured using a micro-Vickers hardness tester. The applied load was 4.903 N for the dwell time of 10 s.

Fatigue tests were performed using the MTS 810 system (MTS Systems Corp., Eden Prairie, MN, USA). The fatigue specimen shown in Figure 1 was connected to a ball-joint grip with a pin for the tilt- and twist-free alignment of the specimen along the loading direction. The applied load was measured using a 2 kN load cell (BCA-200K, TESTA Corp., Gyeonggi-do, Korea). Fatigue tests were performed under cyclic loading with a stress ratio (R) of 0.1 and a frequency of 10 Hz. Fatigue tests were performed at six different maximum stresses ( $\sigma_{max}$ ) for the two temperatures as follows: 495, 526, 557, 587, 618, and 649 MPa for room temperature (RT), and 355, 371, 386, 402, 418, and 433 MPa for 1000 K. Here, three to seven tests were conducted for each test condition. Fatigue test conditions are summarized in Table 2. After the tests, fractography was performed on the failed specimens to clarify the failure mechanisms and fatigue variability of the thin-tube brazed specimens.

Table 2. Fatigue test conditions used in this study.

Test Temperature (K)	Fatigue Limit (Cycles)	Test Type	Stress Ratio, R	Loading Frequency (Hz)	Maximum Stress Level, σ <sub>max</sub> (MPa)		
300	$1 \times 10^{6}$	Tension-tension	0.1	10	495, 526, 557, 587, 618, 649		
1000	1 × 10	cyclic loading	0.1	10	355, 371, 386, 402, 418, 433		

## 3. Results and Discussion

Figure 2 shows the SEM images of the longitudinal and radial cross-sections of an alloy 625 thin tube prior to the fatigue test. The EDS analysis indicated that carbides of (Nb, Ti)C were present in the tube. The size of the carbides distributed outside the tube was larger than those distributed inside the tube. Carbide streaks along the drawing direction were also observed, which originated from the drawing process. Figure 3 shows the metallographs of the radial cross-section of the tube, including the weld zone in Figure 3b. As can be seen, the grain size appears to be finer in the weld zone than in the other regions (base metal). Despite the repeated annealing process after every drawing step, microstructural differences between the weld zone and the base metal are still observed. Therefore, the grain size distribution through the thickness is quite heterogeneous in the range of approximately 1–8 grains.



**Figure 2.** SEM images of an alloy 625 thin tube prior to the fatigue test: (**a**) longitudinal and (**b**) radial cross-sections.



**Figure 3.** Metallographs at the radial cross-section of the tube: (**a**) typical base metal region and (**b**) region including the weld zone.

Figure 4 shows the SEM images of the cross-section for the as-brazed fatigue specimen. Here, Figure 4b,c presents enlarged images of the areas labeled in Figure 4a. A typical brazing microstructure of Ni-base alloys is apparent, comprising various intermetallic phases [28,29]. An EDS analysis in an athermal solidification zone (Figure 4b) demonstrated that the phases marked by Z1, Z2, and Z3 are nickel boride, Ni–Si–B ternary intermetallic, and eutectic of  $\gamma$ -nickel and fine nickel silicide, respectively. The microstructure at the interface between the filler metal and the base metal shown in Figure 4c consisted of phases marked by Z4 and Z5, which are chromium boride, and the  $\gamma$ -nickel solid solution, respectively. In addition, the microhardness profile across the brazed joint was measured, as displayed in Figure 5. The microhardness in the tube was approximately 182 HV. In the filler metal region, however, the hardness increased to as high as 710 HV. This high hardness value is attributed to intermetallic constituents, including nickel boride, chromium boride, and nickel silicide, which are known for hard and brittle phases.

Fatigue tests were conducted at RT and 1000 K on the thin-tube brazed specimens, and the S–N curves are plotted in Figure 6. Each fatigue test condition shows different variabilities in the fatigue life ( $N_f$ ). For the RT fatigue tests, the maximum variability in  $N_f$  was found at  $\sigma_{max} = 495$  MPa, which exhibited maximum and minimum  $N_f$  values of 2,891,024 and 444,361 cycles, respectively. For the 1000 K fatigue tests, however, an even higher maximum variability in  $N_f$  was found at  $\sigma_{max} = 402$  MPa, which showed maximum and minimum  $N_f$  values of 781,877 and 31,909 cycles, respectively. In addition, such a variability in  $N_f$  does not seem to show any particular relationship with the level of the maximum stress applied, particularly for the 1000 K fatigue tests. The fatigue strengths determined at  $N_f = 1 \times 10^6$  cycles were 511 and 371 MPa at RT and 1000 K, respectively. The modified fatigue strengths with various standard deviations are listed in Table 3.



Figure 4. (a) SEM image of the brazed region; (b,c) enlarged SEM images of the areas marked in (a).



Figure 5. Microhardness profile across the brazed region.



Figure 6. S–N plots for all fatigue data tested at RT and 1000 K.

Stendard Deviation	Fatigue Str	Polishility (%)	
Standard Deviation —	RT	1000 K	- Kenabinty (70)
σ	490	357	84.2
$2\sigma$	468	343	97.7
$3\sigma$	446	329	99.9

Table 3. Modified fatigue strength at 10<sup>6</sup> cycles with various standard deviations.

Because the thin-tube fatigue specimen has an unusual geometry, i.e., a thin tube brazed to the grip (Figure 1), further analysis was performed to clarify whether the brazed joint affected the variability of the fatigue life. In Figure 7, the fatigue fracture locations of all tested specimens are plotted as a function of  $N_{\rm f}$  for different applied stresses ( $\sigma_{\rm max}$ ). Here, the fracture location (%) is the percentile fracture location relative to the distance from the grip section: 0% for fracturing at the brazed joint and 50% for fracturing in the middle of the thin tube. As can be seen, the fatigue fracture at RT was mainly near the brazed joint for high  $\sigma_{\rm max}$  (approximately  $\sigma_{\rm max} \ge 557$  MPa and  $N_{\rm f} < 400,000$  cycles), while the fatigue fracture was either near the brazed joint or in the thin tube for low  $\sigma_{\rm max}$  ( $N_{\rm f} > 400,000$  cycles). However, the fatigue fracture at 1000 K was mainly in the thin tube away from the brazed joint, regardless of the magnitude of  $\sigma_{\rm max}$ . This result implies that the presence of the brazed joint affects the fatigue life mainly for RT fatigue at a high  $\sigma_{\rm max}$ .



**Figure 7.** Variations of the fracture location as a function of fatigue life ( $N_f$ ) for different  $\sigma_{max}$  values at (**a**) RT and (**b**) 1000 K.

To further investigate the relationship between the fracture location and the fatigue life at RT, fractography was performed for the two specimens, which showed a difference of approximately seven times in fatigue life even under the same test conditions ( $\sigma_{\text{max}}$  = 495 MPa). Here, the short-life tube specimen fractured near the brazed joint at 444,361 cycles, whereas the long-life tube specimen fractured in the middle of the tube at 2,891,024 cycles, as shown in Figure 8a,b, respectively. Figure 9 shows the fractography of the two specimens tested at RT and  $\sigma_{max}$  = 495 MPa. In Figure 9, the crack initiation sites are indicated by arrows. The fracture surfaces of the short-life specimen presented in Figure 9a,b show typical brittle fractures with multiple crack initiations (indicated by the arrow in Figure 9b) almost everywhere near the surrounding filler metal surfaces. These initial cracks circumferentially formed on the surfaces of the filler metal seem to propagate toward the inside of the thin tube, leading to premature fatigue failure. The gradual change in the fracture type from the transgranular quasi-cleavage fracture in the filler metal layer of the outer tube to the relatively dimpled fracture of the inner tube indirectly supports crack propagation. The microhardness profile displayed in Figure 5 indicates that the filler metal layer in the vicinity of the brazed joint is brittle, as expected, compared with the thin tube, owing to the presence of various intermetallic compounds (see Figure 4). Moreover, a certain degree of stress concentration is expected at the brazed joint owing to the geometric discontinuity (a notch effect) between the thin tube and the grip. The stress concentration factor of the fillet in the brazed joint can be calculated quantitatively using the factor of  $k_f$ shown in Equation (1) [30]:

$$k_f = 0.268 \left(\frac{D_0}{r}\right) + 0.998 \tag{1}$$

where  $k_f$  is the stress concentration factor and  $D_0$  and r the outer diameter and radius of fillet, respectively. By Equation (1), the  $k_f$  is calculated at 1.40, which is well-coincident with S.H. Kang et al.'s study [31]. They verified the local mechanical response of alloy 625 brazed tubes with BNi-2 filler metal by considering the geometry and the local material properties of the brazed part, using a finite element method. Under these circumstances, the stress caused by cycling loading tends to be unevenly distributed in the brazed joint, and the incompatible deformation response of the filler metal layer (due to the presence of different intermetallic compounds) facilitate crack initiation on the surfaces of the filler metal near the brazed joint, causing a relatively short fatigue life.



**Figure 8.** (a) Short-life (444,361 cycles) and (b) long-life (2,891,024 cycles) tube specimens at RT and  $\sigma_{max} = 495$  MPa.



**Figure 9.** Fracture surfaces for (**a**,**b**) short-life (444,361 cycles) and (**c**,**d**) long-life (2,891,024 cycles) specimens tested at RT and  $\sigma_{max}$  = 495 MPa.

In contrast to the short-life specimen, the long-life specimen, which fractured in the middle of the tube (Figure 8b), exhibited single crack initiation near the outer surface, as shown in Figure 9c,d. It can be seen that the initial crack formed a facet perpendicular to the loading direction (Figure 9d), which is typical for high-cycle fatigue. Unlike the short-life specimen, which displays simultaneous crack propagation from the filler metal layer of the outer tube to the inner tube, the long-life specimen shows a single crack propagating from the outer tube surface through the thickness, then spreading out to the neighboring area.

The fatigue lives at 1000 K also exhibited large variability, as shown in Figure 6. However, almost all fatigue fractures were observed in the region of the thin tube and not in the brazed joint, as shown in Figure 7b. Accordingly, fractography was performed for the two specimens, which showed a difference of approximately 10 times in fatigue life ( $N_{\rm f}$  = 781,887 and 78,621 cycles for the long-life and short-life specimens, respectively) at 1000 K and  $\sigma_{\rm max}$  = 402 MPa. As shown in Figure 10, both specimens displayed failure in the tube region away from the brazed joint. Figure 11 presents the fracture surfaces

for the short- and long-life specimens tested at 1000 K and  $\sigma_{max} = 402$  MPa. Regarding the short-life specimen, multiple crack initiations both at the outer surface and carbides inside the tube were observed, as indicated by the arrows in Figure 11b,c. In particular, cracks initiated at the outer surface (arrow in Figure 11b) showed progress through the tube thickness. Metallographs (Figure 12a,c) taken directly underneath the fracture surface presented in Figure 11a indicate that the grain size at the crack initiation site (marked with an arrow) is very large (only approximately two grains through the thickness). In addition, based on the non-uniform microstructure distribution compared to the surrounding area, the crack initiation site corresponds to the weld zone. Hence, during cyclic loading at 1000 K, the heterogeneous grain distribution can cause premature fracture, particularly in the weld zone.



**Figure 10.** (a) Short-life (78,621 cycles) and (b) long-life (781,887 cycles) tube specimens at 1000 K and  $\sigma_{max} = 402$  MPa.



**Figure 11.** Fracture surfaces for (**a**–**c**) short-life (78,621 cycles) and (**d**,**e**) long-life (781,887 cycles) specimens tested at 1000 K and  $\sigma_{max} = 402$  MPa. The arrows in (**a**,**b**,**d**,**e**) indicate the crack initiation sites. (**c**) presents the enlarged image of the area highlighted in (**b**).



**Figure 12.** Microstructures directly underneath the fracture surfaces fatigue-tested at 1000 K and  $\sigma max = 402$  MPa for (**a**,**c**) short-life (78,621 cycles) and (**b**,**d**) long-life (781,887 cycles) specimens. The arrows indicate the locations of the fatigue crack initiation.

For the long-life specimen, a single crack initiation was observed near the outer surface, as shown in Figure 11d,e. Here, the initial surface crack is indicated by an arrow in Figure 11e. Metallographs (Figure 12b,d) obtained directly underneath the fracture surface presented in Figure 11d show homogeneous grain distribution over the tube. This indicates that, for the long-life specimen, if the inhomogeneity of the weld zone does not directly lead to fracture at the beginning of the fatigue test, the effect of grain size on the fatigue life is reduced owing to homogenization by long-term exposure at 1000 K.

Combining the results of the fatigue life variability for the alloy 625 thin-tube brazed specimens tested at RT and 1000 K, the following factors were found to affect the fatigue variability: the brazed joint (particularly, the filler metal layer at the joint) and the spatial distribution of the grain size and carbides. The presence of the brazed joint shown in Figure 1 (and the filler metal layer provided in Figures 4 and 5) can cause a notch stress concentration effect. Hence, the filler metal layer in the brazed part can act as a crack initiation site, particularly for the RT fatigue and under high  $\sigma_{max}$ , because the various intermetallic phases in the filler metal layer, as well as the geometrical effect of the brazed part, cause local deformation incompatibility under cycling loading. The fatigue crack initiation in the filler metal layer (near the brazed joint) occurred at high  $\sigma_{max}$  values (approximately  $\geq$  557 MPa) and resulted in short fatigue lives (N<sub>f</sub> < 400,000 cycles), as shown in Figure 7a. In this case, multiple cracks initiated circumferentially in the filler metal layer and propagated inward into the thin tube, as shown in Figure 9a,b. The largest fatigue life variability at RT was found when one specimen failed near the brazed joint, whereas the other specimen failed in the tube region, as shown in Figure 8, at  $\sigma_{\text{max}}$  = 495 MPa, which seems to be in a transient stress range between the brazed joint failure and the tube failure (see Figure 7a). This result indicates that the presence of the brazed joint causes variability in fatigue life, particularly for low  $\sigma_{max}$  values.

For 1000 K fatigue, however, no apparent brazed joint failure was observed, as shown in Figure 7b. This is because the deformation incompatibility among different intermetallic phases in the filler metal layer was fully accommodated (even under cycling loading) at such a high temperature [32]. In this case, the spatial distribution of the grain size and carbides seems to affect the fatigue life variability. The presence of a large near-surface grain (corresponding to the weld zone), which has approximately 1–2 through-thickness grains and can facilitate the initiation of a fatigue crack near the outer surface, as shown in Figure 11b,c, leads to a short fatigue life. In particular, the fatigue life will be even shorter if multiple crack initiations at carbides inside the tube occur simultaneously, as shown in Figure 11b,c, in addition to the crack initiation at a large near-surface grain.

## 4. Conclusions

Variability in fatigue life at room temperature and 1000 K was investigated for brazed alloy 625 thin-tube specimens. The fatigue life variability was found to be influenced by the presence of the brazed joint (and its properties), as well as the spatial distribution of the grain size and carbides.

At room temperature, a correlation between the fracture location and fatigue life was observed. Specimens tested at  $\sigma_{max} \ge 557$  MPa exhibited failure near the brazed joint and relatively short fatigue lives (typically,  $N_{\rm f} < 400,000$  cycles). For  $\sigma_{max} < 557$  MPa, however, a short-life specimen failed at the brazed joint, whereas a long-life specimen failed in the middle of the tube. The brazed-joint failed specimens showed multiple crack initiations circumferentially in the filler metal layer and growth of cracks through the thickness of the tube, leading to a short fatigue life.

At 1000 K, all test specimens failed in the middle of the tube. Specifically, the short-life specimen showed fatigue crack initiation and growth at a location with only 1–2 through thickness grains. Crack growth seemed to be further facilitated by multiple crack initiations at the carbides inside the tube. In conclusion, homogeneous grain distribution within the tube and small grains through the tube thickness can prevent premature fracture, leading to a long fatigue life.

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#### References

- 1. McDonald, C.F.; Wilson, D.G. The utilization of recuperated and regenerated engine cycles for high-efficiency gas turbines in the 21st century. *Appl. Therm. Eng.* **1996**, *16*, 635–653. [CrossRef]
- Wilfert, G.; Sieber, J.; Rolt, A.; Baker, N.; Touyeras, A.; Colantuoni, S. New Environmental Friendly Aero Engine Core Concepts. In Proceedings of the XVIII International Symposium of Air Breathing Engines, The International Society for Air Breathing Engines (ISABE), Beijing, China, 2–7 September 2007.
- Jeong, J.H.; Kim, L.S.; Lee, J.K.; Ha, M.Y.; Kim, K.S.; Ahn, Y.C. Review of heat exchanger studies for high-efficiency gas turbines. In Proceedings of the Turbo Expo: Power for Land, Sea, and Air, American Society of Mechanical Engineers, Montreal, CA, USA, 14–17 May 2007.
- 4. McDonald, C.F. Recuperator considerations for future higher efficiency microturbines. *Appl. Therm. Eng.* **2003**, *23*, 1463–1487. [CrossRef]
- 5. Min, J.K.; Jeong, J.H.; Ha, M.Y.; Kim, K.S. High temperature heat exchanger studies for applications to gas turbines. *Heat Mass Transf.* 2009, *46*, 175–186. [CrossRef]
- Bruening, G.B.; Chang, W.S. Cooled cooling air systems for turbine thermal management. In Proceedings of the ASME 1999 International Gas Turbine and Aeroengine Congress and Exhibition, Proceeding of the Turbo Expo: Power for Land, Sea, and Air, American Society of Mechanical Engineers, Indianapolis, IN, USA, 7–10 June 1999.

- Maziasz, P.J.; Pint, B.A.; Shingledecker, J.P.; Evans, N.D.; Yamamoto, Y.; More, K.L.; Lara-Curzio, E. Advanced alloys for compact, high-efficiency, high-temperature heat-exchangers. *Int. J. Hydrog. Energ.* 2007, *32*, 3622–3630. [CrossRef]
- 8. MacKenzie, P.M.; Walker, C.A.; McKelvie, J. A method for evaluating the mechanical performance of thin-walled titanium tubes. *Thin-Walled Struct.* **2007**, *45*, 400–406. [CrossRef]
- 9. Sonsino, C.M.; Bruder, T.; Baumgartner, J. S-N Lines for welded thin joints-suggested slopes and fat values for applying the notch stress concept with various reference radii. *Weld. J.* **2010**, *54*, R375–R392. [CrossRef]
- 10. Fayard, J.L.; Bignonnet, A.; Van, K.D. Fatigue design criterion for welded structures. *Fatigue Fract. Eng. Mater. Struct.* **1996**, *19*, 723–729. [CrossRef]
- 11. Lazzarin, P.; Sonsino, C.M.; Zambardi, R. A notch stress intensity approach to assess the multiaxial fatigue strength of welded tube-to-flange joints subjected to combined loadings. *Fatigue Fract. Eng. Mater. Struct.* **2004**, *27*, 127–140. [CrossRef]
- 12. Yokobori, T.; Yamanouchi, H.; Yamamoto, S. Low cycle fatigue of thin-walled hollow cylindrical specimens of mild steel in uni-axial and torsional tests at constant strain amplitude. *Int. J. Fract.* **1965**, *1*, 3–13. [CrossRef]
- 13. Carstensen, J.; Mayer, H.; Brøndsted, P. Very high cycle regime fatigue of thin walled tubes made from austenitic stainless steel. *Fatigue Fract. Eng. Mater. Struct.* **2002**, *25*, 837–844. [CrossRef]
- 14. Baumgartner, J.; Tillmann, W.; Bobzin, K.; Ote, M.; Wiesner, S.; Sievers, N. Fatigue of brazed joints made of X5CrNi18-10 and Cu110 and derivation of reliable assessment approaches. *Weld. World.* **2020**, *64*, 707–719. [CrossRef]
- 15. Floreen, S.; Fuchs, G.E.; Yang, W.J. The Metallurgy of Alloy 625. *Superalloys* **1994**, *718*, 13–37.
- 16. Radavich, J.F.; Fort, A. Effects of Long-Time Exposure in Alloy 625 at 1200 °F, 1400 °F and 1600 °F. Superalloys 1994, 718, 635–647.
- Conder, C.R.; Smith, G.D. Microstructural and mechanical property characterization of aged Inconel625LCF. In *Proceedings of the International Symposium on Superalloys 718, 625, 706 and Various Derivatives*; The Minerals, Metals, and Materials Society (TMS): Pittsburgh, PA, USA, 1997; pp. 447–458.
- 18. Marchese, G.; Beretta, M.; Aversa, A.; Biamino, S. In situ alloying of a modified Inconel 625 via laser powder bed fusion: Microstructure and mechanical properties. *Metals* **2021**, *11*, 988. [CrossRef]
- 19. Shankar, V.; Valsan, M.; Rao, K.B.S.; Mannan, S.L. Effects of temperature and strain rate on tensile properties and activation energy for dynamic strain aging in alloy 625. *Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.* 2004, 35A, 3129–3139. [CrossRef]
- 20. Suave, L.M.; Cormier, J.; Bertheau, D.; Villechaise, R.; Soula, A.; Hervier, Z.; Hamon, F. High temperature low cycle fatigue properties of alloy 625. *Mater. Sci. Eng. A* 2016, 630, 161–170. [CrossRef]
- 21. Osoba, L.O.; Ojo, O.A. Influence of solid-state diffusion during equilibration on microstructure and fatigue life of superalloy wide gap brazements. *Metall. Mater. Trans. A* 2013, 44, 4020–4024. [CrossRef]
- 22. Yang, X.; Dong, C.; Shi, D.; Zhang, L. Experimental Investigation on Both Low Cycle Fatigue and Fracture Behavior of DZ125 Base Metal and the Brazed Joint at Elevated Temperature. *Mater. Sci. Eng. A* 2011, 528, 7005–7011. [CrossRef]
- 23. Shi, D.; Dong, C.; Yang, X.; Sun, Y.; Wang, J.; Liu, J. Creep and fatigue lifetime analysis of directionally solidified superalloy and its brazed joints based on continuum damage mechanics at elevated temperature. *Mater. Des.* **2013**, *45*, 643–652. [CrossRef]
- 24. Kim, Y.H.; Kim, I.H.; Kim, C.S. Asian Pacific Conference for Fracture and Strength, 4th ed.; Trans Tech Publications Ltd.: Bäch SZ, Switzerland, 2005; pp. 2876–2882.
- 25. Kim, Y.H.; Kim, K.T. *Multifunctional Materials and Structures*; Trans Tech Publications Ltd.: Bäch SZ, Switzerland, 2008; pp. 894–897.
- Chen, J.; Deners, V.; Turner, D.P.; Bocher, P. Experimental investigation on high-cycle fatigue of Inconel 625 superalloy brazed joints. *Metall. Mater. Trans. A: Phys. Metall. Mater. Sci.* 2018, 49A, 1244–1253. [CrossRef]
- Chen, J.; Demers, V.; Cadotte, E.-L.; Turner, D.; Bocher, P. Structural performance of Inconel 625 superalloy brazed joints. J. Mater. Eng. Perform. 2017, 26, 547–553. [CrossRef]
- 28. Pouranvari, M.; Ekrami, A.; Kokabi, A.H. Solidification and solid state phenomena during TLP bonding of IN718 superalloy using Ni–Si–B ternary filler alloy. *J. Alloys Compd.* **2013**, *563*, 143–149. [CrossRef]
- 29. Tung, S.K.; Lim, L.C.; Lai, M.O. Solidification phenomena in nickel base brazes containing boron and silicon. *Scr. Mater.* **1996**, *34*, 763–769. [CrossRef]
- Garrell, M.G.; Shih, A.J.; Lara-Curzio, E.; Scattergood, R.O. Finite-element analysis of stress concentration in ASTM D 638 tension specimens. J. Test. Eval. 2003, 31, 1–6.
- 31. Kang, S.-H.; Park, S.H.; Min, J.K.; Cho, J.R.; Ha, M.-Y. Evaluation of mechanical integrity on the brazing joint of a tube-type heat exchanger with considering local material properties. *Proc. Inst. Mech. Eng. C* 2013, 227, 420–433. [CrossRef]
- 32. Zhang, Y.-C.; Yu, X.-T.; Jiang, W.; Tu, S.-T.; Zhang, X.-C. Elastic modulus and hardness characterization for microregion of Inconel 625/BNi-2 vacuum brazed joint by high temperature nanoindentation. *Vacuum* 2020, *181*, 109582. [CrossRef]