Microstructure and Mechanical Performance of the DD98M-DD98M Single Crystal Superalloy Joints Brazed Using a Pd-Si Composite Filler

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Abstract: In this work, the DD98M single crystal superalloys were brazed to themselves using a Pd-Si composite filler. The effect of brazing temperature and soaking time on the microstructure and mechanical behavior of the joints was studied. The microstructure and phase constitution in the joint were identified by the SEM and EDS analysis. The results indicated that the joint obtained was constituted by DD98M/zone 2/zone 1/zone 2/DD98M. The zone 1 was primarily made up of the Ni (Pd, Cr, Co) (s.s), Pd₄Si, Pd (Ni, Ti, Al) (s.s) and Pd-rich Ni (Pd, Cr, Co) (s.s), while the zone 2 consisted of the Ni (Pd, Cr, Co) (s.s) and Al₂Pd₅. During the brazing process, increasing the brazing temperature strengthened the fluidity of the liquid filler, which was favorable to eliminating the solidified pores in the brazing seam. Furthermore, a higher brazing temperature would cause the phases in the zones 1 and 2 to be coarsened remarkably. When setting the brazing temperature to 1060 °C, extending the soaking time made the amount of Pd (Ni, Ti, Al) (s.s) decrease, whereas the amount of Pd₄Si increased, because the peritectic reaction between the Pd (Ni, Ti, Al) (s.s) and remnant liquid filler was enhanced. Among the brazing process parameters under investigation, the maximum joint average shear strength obtained reached 338 MPa when the joint was brazed at 1060 °C for 30 min. A ductile fracture mode happened during the shear tests under a joining condition. The work performed can provide valuable data to design the single crystal superalloy brazed joint.

Keywords: single crystal superalloy; brazing; microstructure; shear strength

1. Introduction

Compared with traditional polycrystalline alloys, single crystal superalloys have a much lower susceptibility to pores and cracks because of the elimination of crystal boundaries. In addition, incorporation of a high proportion of alloying elements into the single crystal superalloys strengthened their properties greatly [1–3]. Generally, the single crystal superalloys exhibit excellent resistances to
creep, oxidation, and thermal corrosion, making them significant materials in industrial and aerospace fields as hot components (such as gas turbine engine blades) [4,5]. However, the complex structure inside the gas turbine blades makes them very difficult to produce using traditional casting [6]. Therefore, joining them becomes necessary [7–11]. To date, the high-quality joining of gas turbine blades still remains a problem, which is urgently needs to be overcome. Several methods, such as fusion welding, solid-state bonding, friction welding, transient liquid phase (TLP) bonding, and brazing can be employed to join the single crystal superalloys [12]. It should be mentioned that most of the superalloys contain Al and Ti. The hot cracking will happen easily in the fusion zone and heat-affected zone during the fusion welding, when the amount of the Al and Ti in the superalloys is over 6 at.% [13,14]. Therefore, joining of the single crystal superalloys by the fusion welding is restrained. The solid-state bonding and friction welding can obtain a high-quality joint with uniform microstructure and excellent mechanical performance. For example, T.J. Ma et al. [15] employed linear friction welding to join the DD6 single crystal superalloy, and the tensile strength of the joints obtained reached 837.5 MPa. A large load, however, will be needed when introducing such joining technologies (solid-state bonding and friction welding), making them unsuitable for the joining of the single crystal superalloy gas turbine blades with a complicated structure.

The technologies of TLP bonding and brazing are usually used to join the single crystal superalloys. J.D. Liu et al. [16] joined the DD98 single crystal superalloy and M963 superalloy using Ni-15Cr-3B filler foil by TLP bonding. The rupture life of the joint reached 140 h when tested at 800 °C under a pressure of 350 MPa, which was comparable with the rupture life of the M963-based alloy. However, this method will merely be used when the welding seam is less than 0.05 mm [17]. Considering the gas turbine blades have a complicated structure, the TLP method in the joining of single crystal superalloys is restrained. The brazing is widely introduced to join the structure-complicated components and repair the parts with defects, due to its simplicity, adaptability in shape and size, and limited influence toward the substrates. From this, the brazing has been widely used to join the superalloys. D. Liu et al. [18] brazed the GH99 superalloy with a novel graphene reinforced-BNi2 composite filler at 1200 °C for 30 min. The joint shear strength obtained reached 410.4 MPa at room temperature and 329.7 MPa at 800 °C, respectively. G.L. Wang et al. [19] reported the brazing of Ni-based single crystal superalloy using Ni-Cr-W-B with the incorporation of Ni at 1260 °C. The stress-fracture life of the joint was over 120 h when tested at 980 °C for 250 MPa. X.H. Shi et al. [20] described the joining of C/C composite with GH3044 using a Ni71CrSi filler alloy. The maximum shear strength of the joints obtained reached 54.4 MPa. Y. Sun et al. [21] designed a Ni-Co-Cr-W-B + DD99 powder filler to braze the DD5 superalloy. The tensile strength of the joint reported reached 1010 MPa when tested at 870 °C.

To facilitate comparison, these results were summarized in Table 1.

| Substrates | Filler alloy | Mechanical properties |
|------------|--------------|-----------------------|
| DD6 [15]   | -            | Tensile strength: 837.5 MPa |
| DD98 to M963 [16] | Ni-15Cr-3B | Rupture life: 140 h at 800 °C for 350 MPa |
| GH99 [18]  | Graphene reinforced-BNi2 | Shear strength: 410.4 MPa at room temperature and 329.7 MPa at 800 °C |
| Ni-based single crystal superalloy [19] | Ni-Cr-W-B + Ni | Rupture life: over 120 h at 980 °C for 250 MPa |
| C/C to GH3044 [20] | Ni71CrSi | Shear strength: 54.4 MPa |
| DD5 [21]   | Ni-Co-Cr-W-B + DD99 | Tensile strength: 1010 MPa at 870 °C |

Generally, the Ni-based brazing filler alloys are widely used to braze the superalloys. Most of them exhibit good bonding toward the Ni-based superalloys. However, the melting point depressants (such as B and Si) in the filler alloys will induce lots of brittle phases into the brazing seam, being detrimental to the mechanical properties and high-temperature service stability of the joints. To solve this problem, a new type of filler is highly needed. The element Pd with a melting point of 1554 °C can
maintain stability at high temperatures. Besides, Pd exhibiting excellent ductile properties can relieve the thermal stresses residing in the joint upon cooling from the joining temperature. Therefore, Pd was employed to be the main constituent of the filler alloy in this work. To lower the melting point of the filler alloy, Si was doped in Pd, which could also depress the influence toward the substrates when brazed at high temperatures. In this work, the Si-doped Pd composite filler was devised and employed to braze the DD98M single crystal superalloy with the aim to decrease the amount of brittle phases in the joint and achieve high-quality bonding. The microstructure was studied thoroughly and the formation mechanism of the joint was discussed. Then, the effect of brazing temperature and soaking time on the microstructure and mechanical performance of the joints were also investigated.

2. Materials and Methods

The DD98M Ni-based single crystal superalloy was developed by Institute of Metal Research, Chinese Academy of Science. Its chemical composition was shown in Table 2. The base material was fabricated though the grain selection method with the crystallographic orientation of [001]. The superalloys were cut into the dimensions of 4 mm × 4 mm × 3.8 mm and 8 mm × 8 mm × 3.8 mm blocks. The bonding surfaces (4 mm × 4 mm) were ground by SiC paper and then polished. Before assembling, all the samples were ultrasonically cleaned in alcohol for 10 min to remove the contaminants. The filler consisted of Pd foil and Si powder. The Pd foil with a purity of 99.9% had a thickness of 25 µm, while the Si powder with a purity of 99.99% had an average particle size of 50 µm. To get a composite filler with a liquidus temperature of around 1000 °C, the mass ratio of Pd and Si was set as 25:1 according to Pd-Si phase diagram [22]. The schematic drawings of the joint during assembly are illustrated in Figure 1a,b. The Si powders with the designed amount were mixed with the hydroxyethyl cellulose to form Si paste. Then the Si paste was put between two pieces of Pd foil, and the composite filler was placed between two substrates. A pressure of 0.1 MPa was applied on the assembly to make them contact closely. The 4 mm × 4 mm × 3.8 mm/4 mm × 4 mm × 3.8 mm assembling blocks (Figure 1a) were used for microstructural examination, while the 4 mm × 4 mm × 3.8 mm/8 mm × 8 mm × 3.8 mm assembling blocks (Figure 1b) were prepared for mechanical testing.

Table 2. Chemical composition of the DD98M single crystal superalloy (at.%).

| C  | Cr | Co | W  | Mo | Ta | Al | Ti | Ni |
|----|----|----|----|----|----|----|----|----|
| 0.10 | 9.31 | 8.20 | 2.63 | 1.26 | 2.01 | 12.32 | 0.63 | Bal. |

Figure 1. (a) The assembling block for microstructural examination, (b) the assembling block for mechanical testing, and (c) schematic of shear testing experiment.

The brazing experiments were conducted in a high-temperature vacuum furnace (VAF-30). The vacuum should be kept around (1.0–9.0) × 10⁻³ Pa during brazing. At the beginning of the brazing process, the brazing assembly was first heated up to 300 °C at a rate of 20 °C/min and held steady for 10 min to make the organic glue volatilize and keep the brazing surfaces clean. Then
the temperature was continuously increased to the brazing temperature (1020–1100 °C) at a rate of 10 °C/min, and soaked for a definite time (10–90 min). After that, the samples were cooled from the brazing temperature to 300 °C at a rate of 6 °C/min. Finally, the furnace was cooled down to room temperature without power. The melting temperature of the Pd-Si composite filler, as mentioned, was designed to be approximately 1000 °C. In general, the brazing temperature used should be at least 20–50 °C over the liquidus temperature of the filler alloy. From this, the lowest brazing temperature used was set as 1020 °C in this work. Some pores were observed in the joint brazed at 1020 °C, suggesting the poor fluidity of the filler. A higher brazing temperature or longer soaking time was indispensable to improve the fluidity of the liquid filler during brazing. Then the brazing temperatures of 1060 °C and 1100 °C were employed. Similarly, the soaking time was set as 10 min, 30 min, 60 min, and 90 min. After brazing, the cross-sections of the joints were cut, ground, and polished. After that, the samples were ultrasonically cleaned in alcohol for 10 min. The microstructure and phase constitution in the joints were analyzed using optical microscopy (OM) and scanning electron microscopy (SEM) in combination with energy dispersive spectrometer (EDS). The schematic of experimental set-up for the shear strength test is displayed in Figure 1c. The shear test was performed using a universal testing machine (MTS CMT4204, Eden Prairie, MN, USA) and the load was applied on the samples with a rate of 0.1 mm/min. At least 5 samples were tested for each joining condition to get a mean value. To explore the fracture mode, the fractured surfaces of the samples brazed at different processing parameters were also observed using the SEM after the shear test.

3. Results and Discussions

3.1. Microstructural Characterization

Figure 2 shows the typical macro- and micro-structure of the DD98M-DD98M joint brazed at 1060 °C for 30 min. It is seen from Figure 2a that a good bonding is achieved between the DD98M and Pd-Si composite filler. The brazed joint, as shown in Figure 2b, can be divided into two zones (zones 1 and 2). The zone 1 is located in the middle of the brazing seam, while the zone 2 is close to the DD98M substrates. The detailed microstructure of the two zones is depicted in Figure 2c,e. It is demonstrated from Figure 2c that the zone 1 is primarily composed of the light grey phase A, grey phase B and black phase C. The high magnification of the phase C in Figure 2d reveals that some fine strip-like phase D are scattered in them. The matrix in the zone 2 is dark grey phase E, in which a number of white particles (phase F) are distributed. The EDS results of these phases are depicted in Table 3. Pd and Si, as shown in the table, are enriched in the light grey phase A. The stoichiometric ratio of Pd and Si is approximately 4:1, indicating that they are actually the Pd$_4$Si. The grey phase B contains a great amount of Pd while a small amount of Ni, Ti, Cr, Co and Al. Inspired by this, they should be the Ni-, Ti- and Al-rich Pd-based solid solution, which is designated as Pd (Ni, Ti, Al) (s.s). The black phase C contains Ni57.3Pd14.8Cr11.1Co8.0 (at.%), which is identified to be the Ni (Pd, Cr, Co) (s.s). Compared with the phase C, the phase D has a higher amount of Pd but a lower amount of Ni, which should be the Pd-rich Ni (Pd, Cr, Co) (s.s). The Phase E, mainly containing Ni63.2Cr12.2Co10.5Pd5.7 (at.%), should be the Ni (Cr, Co, Pd) (s.s). The phase F has the main constitution of Pd63.8Al23.5Ni6.2Si4.1 (at.%). The stoichiometric ratio of Al and Pd is approximately 2:5, suggesting that they should be the Al$_2$Pd$_5$. 
When the Pd-Si composite filler was melted during brazing, the DD98M substrates beside the brazing seam would be dissolved into the liquid filler under the concentration gradient. Then the brazing seam became a complicated multi-component alloy system at 1060 °C. In the brazing seam, the Pd (Ni, Ti, Al) (s.s) would be first precipitated from the melt due to the high melting point of Pd. Subsequently the Ni (Pd, Cr, Co) (s.s) were generated. Upon cooling, a peritectic reaction happened between the Pd (Ni, Ti, Al) (s.s) and remnant liquid, when the temperature was cooled to 830 °C [22], leading to the production of the Pd$_4$Si. After decreasing the temperature further, Pd was precipitated from the Ni (Pd, Cr, Co) (s.s), producing the strip-like Pd-rich Ni (Pd, Cr, Co) (s.s) in them.
this, the zone 1 was formed. At the brazing seam/DD98M interface, it can be seen from Figure 2e that the zone 2 was mainly composed of Ni (Pd, Cr, Co) (s.s), in which a number of Al$_2$Pd$_5$ particles were scattered. When the DD98M substrates beside the brazing seam were dissolved, Pd had a higher affinity toward Al, leading to the formation of the Al$_2$Pd$_5$ in the Ni (Pd, Cr, Co) (s.s). Several Pd-Al binary compounds might take place according to the Pd-Al phase diagram [23]. The following reaction might happen during brazing:

1055 °C : $L \rightarrow AlPd_2 + (Pd)$

980 °C : $AlPd_2 \rightarrow Al_2Pd_5$

858 °C : $AlPd_2 \rightarrow Al_2Pd_5 + (Pd)$

To compare the stability of the AlPd$_2$ and Al$_2$Pd$_5$, their formation energy was studied. The formation energy of the AlPd$_2$ and Al$_2$Pd$_5$, as reported in Ref. [24,25], was $-4.38$ eV/atom and $-4.48$ eV/atom, respectively. Both of them were negative, suggesting that the AlPd$_2$ and Al$_2$Pd$_5$ were stable during brazing. However, the absolute value of formation energy of the Al$_2$Pd$_5$ was more negative, hinting that the Al$_2$Pd$_5$ was more stable. Therefore, the Al$_2$Pd$_5$ instead of the AlPd$_2$ was formed in the brazing conditions.

3.2. Effect of Brazing Temperature on the Microstructure and Mechanical Properties of the Joint

Figure 3 depicts the SEM morphologies of the joints brazed at different temperatures for 30 min. It can be seen from the figure that the DD98M-DD98M joints brazed at different temperatures exhibit discrepancy. The width of zone 1 decreases when the joint was brazed at a higher temperature. The fluidity of the liquid filler was strengthened at higher temperatures, making more liquid to be squeezed out of the joint. Then few liquids remained in the brazing seam. When brazed at 1020 °C, the Pd$_4$Si and Ni (Pd, Cr, Co) (s.s) with a small size can be observed. In addition, some pores also occurred in the zone 1. Nearly none of pores can be found when the brazing temperature is increased to 1060 °C or 1100 °C. Furthermore, the Pd$_4$Si and Ni (Pd, Cr, Co) (s.s) grew up and formed continuous blocks at 1100 °C.

![Figure 3](image-url)

**Figure 3.** SEM back-scattered electron micrographs of the DD98M/Pd-Si/DD98M joints brazed at different temperatures for 30 min: (a) 1020 °C, (b) 1060 °C, and (c) 1100 °C.
Figure 4 presents the detailed morphology of zone 1 in the joints brazed at different temperatures for 30 min. The Pd₄Si and Ni (Pd, Cr, Co) (s.s), as demonstrated, grew remarkably after increasing the brazing temperature. The Pd (Ni, Ti, Al) (s.s) and Ni (Pd, Cr, Co) (s.s), as mentioned, were nucleated and grew in the liquid during brazing. However, they did not exhibit fast growth because the reaction was relatively slow at 1020 °C. From this, the fine-sized Pd (Ni, Ti, Al) (s.s) and Ni (Pd, Cr, Co) (s.s) were formed. Upon cooling, the Pd (Ni, Ti, Al) (s.s) reacted with the remnant liquid, giving rise to the production of Pd₄Si with a small size, as has been displayed in Figures 3a and 4a. After increasing the brazing temperature, the elemental diffusion was intensified, accelerating the growth of the Pd (Ni, Ti, Al) (s.s) and Ni (Pd, Cr, Co) (s.s) in the liquid. It can be recognized that the large-sized Pd (Ni, Ti, Al) (s.s) and Ni (Pd, Cr, Co) (s.s) were precipitated from the liquid at a higher brazing temperature. After that the peritectic reaction likewise promoted the large-sized Pd₄Si to be generated upon cooling. Besides, the solubility of elements in the Ni (Pd, Cr, Co) (s.s) would decrease gradually, resulting in the precipitation of fine-sized Pd-rich Ni (Pd, Cr, Co) (s.s) in them, as was demonstrated in Figure 4b,c.

![SEM back-scattered electron images of the zone 1 in the DD98M/Pd-Si/DD98M joints brazed at different temperatures for 30 min: (a) 1020 °C, (b) 1060 °C, and (c) 1100 °C.](image)

Figure 4. SEM back-scattered electron images of the zone 1 in the DD98M/Pd-Si/DD98M joints brazed at different temperatures for 30 min: (a) 1020 °C, (b) 1060 °C, and (c) 1100 °C.

Figure 5 exhibits the microstructure of zone 2 in the joints brazed at different temperatures for 30 min. The width and constitution of the zone 2 (Ni (Pd, Cr, Co) (s.s) and Al₂Pd₅) does not change as the brazing temperature was increased. It can be seen from the figure that more Al₂Pd₅ were generated at a higher brazing temperature. During brazing, Al from the substrates and Pd from the liquid diffused toward the liquid/solid interface under the concentration gradient, and reacted to give birth to the Al₂Pd₅. A higher brazing temperature would speed up the elemental diffusion, enabling more Al and Pd to be gathered at the interface and then providing more chances for the Al₂Pd₅ to be nucleated.
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Figure 5. SEM back-scattered electron images of the zone 2 in the DD98M/Pd-Si/DD98M joints brazed at different temperatures for 30 min: (a) 1020 °C, (b) 1060 °C, and (c) 1100 °C.

Shear testing was performed to study the effect of brazing temperature on the mechanical properties of the joints. The results in Figure 6 indicate that the shear strength of the joints first increases and then decreases as the brazing temperature was increased from 1020 °C to 1100 °C. A maximum average value of 338 MPa was received when brazed at 1060 °C. It should be noted that some solidified pores occurred in the joint when brazed at 1020 °C, as has been demonstrated in Figure 3a, due to the relatively lower brazing temperature-induced poor fluidity of the liquid filler. These pores would act as the crack origin during the shear tests, which greatly deteriorated the properties of the joint. Once the cracks were initiated, they propagated quickly throughout the joint, leading to the poor shear strength. The pores had a great influence on the properties of the joint. The shear strength of the joint brazed at 1020 °C scattered greatly because these micro pores were distributed randomly in the joint. When the brazing temperature was increased to 1060 °C, an enhanced temperature improved the fluidity of the liquid filler. The pores disappeared from the joint (as shown in Figure 3b), improving the joint shear strength. Further increasing the brazing temperature to 1100 °C accelerated the elemental diffusion, encouraging the Ni (Pd, Cr, Co) (s.s) and Pd₄Si to grow into continuous large blocks. In general, the phases with a large size would reduce the crack propagation resistance. Considering this, the coarsening of the phases increased the brittleness of the joint and then decreased the properties of the joint, as has also been reported in references [26,27]. The joint average shear strength was decreased.

Figure 7 depicts the fracture morphologies of the joints brazed at different temperatures for 30 min. It can be seen from the figure that many cleavage steps and river patterns are observed on the fracture surface for the joint brazed at 1020 °C, suggesting a brittle quasi-cleavage fracture mode. When the DD98M superalloy was brazed at 1060 °C, many dimples appear on the fracture surface. A ductile fracture mode then predominates during the shear testing. The brittle quasi-cleavage fracture occurred again when the brazing temperature was increased to 1100 °C, because many smooth facets and river patterns can be found obviously on the fracture surface. This fact can be understood because the Ni (Pd, Cr, Co) (s.s) and Pd₄Si with a large size in the brazing seam would increase the brittleness of the joint. The fractography analysis suggested that the ductility of the brazing seam should be
ameliorated via adjusting the brazing process parameters, which should be closely correlated with the joint bond strength.

![Graph showing shear strength vs brazing temperature](image)

**Figure 6.** Shear strength of the DD98M-DD98M joints brazed at different temperatures for 30 min.

![SEM images showing fracture surfaces](image)

**Figure 7.** Fracture morphologies of DD98M-DD98M joints brazed at different temperatures for 30 min: (a) 1020 °C, (b) 1060 °C, and (c) 1100 °C.

### 3.3. Effect of Soaking Time on the Microstructure and Mechanical Properties of the Joint

Figure 8 displays the back-scattered electron images of the joints brazed at 1060 °C for different soaking time. It is shown from the figure that all of the joints exhibit integral interfaces without imperfection. Figure 9 shows the magnified zone 1 obtained for different soaking time. When the soaking time is 10 min (Figure 9a), the zone 1 is mainly comprised of the Pd (Ni, Ti, Al) (s.s), Ni (Pd, Cr, Co) (s.s) and Pd$_4$Si. Some solidified pores can be found in the zone, as presented in Figure 8a. After extending the soaking time to 30 min, none of pores can be observed. Apart from that, the amount of Pd (Ni, Ti, Al) (s.s) decreases distinctly, whereas a number of Pd$_4$Si occur. Further increasing the
soaking time to 60 min or 90 min promotes more Pd$_4$Si and Ni (Pd, Cr, Co) (s.s) to be dominated in
the zone. In addition, less Pd (Ni, Ti, Al) (s.s) can be found. Si had a high affinity toward Pd. During
brazing, Si was apt to react with the Pd (Ni, Ti, Al) (s.s) to generate the Pd$_4$Si in the brazing seam.
When the soaking time was 10 min, Si was not able to diffuse sufficiently, and then a small amount of
Pd$_4$Si phase was formed. As the soaking time was extended, Si diffused sufficiently, being beneficial for
the production of the Pd$_4$Si. Besides that, an increase in the soaking time also provided enough time
for the new phases to grow, leading to the Ni (Pd, Cr, Co) (s.s) and Pd (Ni, Ti, Al) (s.s) growing larger.

Figure 8. SEM back-scattered electron images of the DD98M/Pd-Si/DD98M joints brazed at 1060 °C
for different soaking time: (a) 10 min, (b) 30 min, (c) 60 min, and (d) 90 min.

Figure 9. SEM back-scattered electron images of the zone 1 in the DD98M/Pd-Si/DD98M joints brazed
at 1060 °C for different soaking time: (a) 10 min, (b) 30 min, (c) 60 min, and (d) 90 min.
When the soaking time is increased from 10 min to 30 min, the joint average shear strength increases. The maximum joint average shear strength reaches 338 MPa when brazed for 30 min. A slight decrease can be observed when the soaking time is extended to 60 min. When the joint was brazed for 90 min, the joint average shear strength decreases sharply to 152 MPa. It should be mentioned that the formation of Al2Pd5 depended on the diffusion of Al and Pd. An increase in the soaking time enhanced the elemental diffusion, which caused more Al2Pd5 to be nucleated.

Figure 10 shows the detailed microstructure of the zone 2 in the joints brazed at 1060 °C for different soaking times. It can be seen from the figure that the zone 2 always has a familiar constitution which is primarily composed of Ni (Pd, Cr, Co) (s.s) and Al2Pd5 under different joining conditions. It should be mentioned that the formation of Al2Pd5 depended on the diffusion of Al and Pd. An increase in the soaking time enhanced the elemental diffusion, which caused more Al2Pd5 to be nucleated.

Figure 10. SEM back-scattered electron images of the zone 2 in the DD98M/Pd-Si/DD98M joints brazed at 1060 °C for different soaking time: (a) 10 min, (b) 30 min, (c) 60 min, and (d) 90 min.

Figure 11 shows the shear testing results of joints brazed at 1060 °C for different soaking time. When the soaking time is increased from 10 min to 30 min, the joint average shear strength increases. The maximum joint average shear strength reaches 338 MPa when brazed for 30 min. A slight decrease can be observed when the soaking time is extended to 60 min. When the joint was brazed for 90 min, the joint average shear strength decreases sharply to 152 MPa. It should be mentioned that the shear strength obtained at 1060 °C for 60 min had a relatively large scatter, which should be acceptable. Considering the data obtained were authentic and reliable, the scatter was hard to be avoided during the shear tests, which has also been reported previously. In future, the tensile test will be employed to evaluate the joint bond strength and a comparison will be made between them.

The microstructure should be associated with the joint bond strength, and a relationship should be built between them. When the joint was soaked for 10 min, such a short soaking time would not guarantee the sufficient elemental diffusion, leading to some solidified pores in the brazing seam. From this, a poor joint shear strength was obtained. After extending the soaking time, a more homogeneous microstructure was formed in the brazing seam, as demonstrated in Figure 8b. Then the joint average shear strength was improved. With further extending the soaking time to 60 min or 90 min, the phases (Pd4Si and Ni (Pd, Cr, Co) (s.s)) in the brazing seam were coarsened obviously because a sufficient time would be beneficial to the growth of phases. The coarsened phases degraded the properties of the joint.
The fracture morphologies of the DD98M-DD98M joints brazed for different soaking time were examined, and the results are displayed in Figure 12. Some typical river patterns are found on the fracture surface when the joint was brazed for 10 min, indicating that the brittle quasi-cleavage fracture took place. A large number of dimples are observed in Figure 12b, revealing that the typical ductile fracture happened during the shear testing. The massive dimples observed suggest the good ductility of the joint soaked for 30 min, being beneficial to the joint shear strength. When the soaking time was increased to 60 min or 90 min (Figure 12c and d), many smooth facets, river patterns and secondary cracks are presented on the fracture surfaces, indicating a quasi-cleavage fracture mode.

The Ni (Pd, Cr, Co) (s.s) and Pd₄Si phases with a large size caused the brittleness of the joint and then decreased the shear strength. The fractography results revealed showed a good correlation between the microstructure and mechanical performance of the joint.

Figure 11. Shear strength of the DD98M-DD98M joints brazed at 1060 °C for different soaking time.

Figure 12. Fracture morphologies of DD98M-DD98M joints brazed at 1060 °C for different soaking times: (a) 10 min, (b) 30 min, (c) 60 min, and (d) 90 min.
The joining of superalloys was widely reported, and the related results were described in Table 1. The DD98M is a novel single crystal superalloy, which is thought to be the next-generation candidate material of the aircraft blades. No available work has been reported to join the DD98M superalloys. In the current work, a new Pd-Si composite filler was designed and the maximum joint average shear strength obtained reached 338 MPa. The work performed will pave the way for the joining of the next-generation single crystal superalloys.

4. Conclusions

The work investigated the microstructure and mechanical behavior of the DD98M/Pd-Si/DD98M joints brazed under different conditions. The main conclusions can be drawn as below:

(1) The DD98M-DD98M joints brazed using Pd-Si composite filler contained two zones: DD98M/zone 2/zone 1/zone 2/DD98M. The zone 1 was mainly composed of the Ni (Pd, Cr, Co) (s.s), Pd (Ni, Ti, Al) (s.s) and Pd$_4$Si. Lots of fine strip-like Pd-rich Ni (Pd, Cr, Co) (s.s) were distributed in the Ni (Pd, Cr, Co) (s.s). The matrix in the zone 2 was Ni (Pd, Cr, Co) (s.s), in which a number of Al$_2$Pd$_5$ particles were scattered.

(2) The microstructure in the joint brazed at different temperatures varied. The joint brazed at 1020 °C was constituted with fine phases. Some pores also occurred. An increase in the brazing temperature strengthened the elemental diffusion and fluidity of the liquid, which would cause the Ni (Pd, Cr, Co) (s.s) and Pd$_4$Si to be coarsened. In addition, the pores also disappeared. The maximum joint average shear strength reached 338 MPa when brazed at 1060 °C.

(3) Extending the soaking time strengthened the diffusional reaction, making the phases grow. When setting the brazing temperature to 1060 °C, the most appropriate soaking time was 30 min. A ductile fracture took place. A longer soaking time increased the joint brittleness and then degraded the properties of the joint.

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