CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter deals with the results of the different experiments conducted as well as the analysis of the same. The main scope of study is to analyze the effect of process parameters of diffusion bonding and friction welding on the joint quality of the chosen dissimilar combinations. Results of characterisation tests are given through five units, first four units are for the characterisation of bonded joints without any interlayer and the last unit is for the characterisation of bonded joints with a suitable interlayer.

4.2 CHARACTERISATION OF DIFFUSION BONDED Ti-6Al-4V WITH INCONEL 718 JOINTS WITHOUT INTERLAYERS

4.2.1 Ultrasonic C-Scan Analysis

The ultrasonic C-scan images were taken by fixing the gate region to include the interface of the Ti-6Al-4V - Inconel 718 diffusion bonded joint. The C-scan images of the joints corresponding to different process parameters are shown in Figure 4.1. The variation in the intensity of the ultrasonic waves that is reflected from the surface depends on the quality of the bonding. The intensity is represented in colour scale in the C-scan image. In the image, red color indicates the lower reflection of ultrasonic wave and purple color indicates the higher reflection of ultrasonic wave.
Figure 4.1 The ultrasonic C-scan images at the interface of the diffusion bonded Ti-6Al-4V - Inconel 718 joints
The images obtained from the ultrasonic C-scan system were further processed by image processing and analysis software to determine the area of higher reflection. The percentage of area of higher reflection determined is given in Table 4.1. It is seen that the Ti-6Al-4V - Inconel 718 joint diffusion bonded under the condition of 850\(^0\)C, 20 MPa and 2 h shows less percentage of area of higher reflection.

Table 4.1  The percentage of area of higher reflection determined by C-scan analysis - Ti-6Al-4V - Inconel 718 diffusion bonded joints

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Diffusion bonding parameters used</th>
<th>Percentage of area of higher reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900(^0)C, 30 MPa, 4 h</td>
<td>4.30</td>
</tr>
<tr>
<td>2</td>
<td>900(^0)C, 20 MPa, 4 h</td>
<td>3.62</td>
</tr>
<tr>
<td>3</td>
<td>850(^0)C, 20 MPa, 3 h</td>
<td>24.95</td>
</tr>
<tr>
<td>4</td>
<td>850(^0)C, 20 MPa, 2 h</td>
<td>13.29</td>
</tr>
<tr>
<td>5</td>
<td>850(^0)C, 20 MPa, 1 h</td>
<td>41.70</td>
</tr>
</tbody>
</table>

The details on determination of the percentage of area of higher reflection using the ultrasonic C-scan system are described in Appendix 1.

4.2.2 Tension Test

Tension test was carried out on diffusion bonded samples of Ti-6Al-4V - Inconel 718 joints to find out the ultimate tensile strength of the bonds. The average UTS values obtained are given in Table 4.2. The joint efficiency of the bonds was calculated. Joint efficiency is defined as the ratio between the Ultimate Tensile Strength (UTS) of the bond and the UTS of the
lower strength metal (i.e. Ti-6Al-4V alloy) in the dissimilar combination which has undergone similar thermal cycling in order to eliminate the metallurgical changes.

Table 4.2 Ultimate tensile strength of diffusion bonded samples - Ti-6Al-4V - Inconel 718 joints

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Diffusion bonding parameters used</th>
<th>Average UTS (MPa)</th>
<th>Joint efficiency* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900°C, 30 MPa, 4 h</td>
<td>292</td>
<td>28.4</td>
</tr>
<tr>
<td>2</td>
<td>900°C, 20 MPa, 4 h</td>
<td>250</td>
<td>24.3</td>
</tr>
<tr>
<td>3</td>
<td>850°C, 20 MPa, 3 h</td>
<td>298</td>
<td>28.9</td>
</tr>
<tr>
<td>4</td>
<td>850°C, 20 MPa, 2 h</td>
<td>471</td>
<td>45.9</td>
</tr>
<tr>
<td>5</td>
<td>850°C, 20 MPa, 1 h</td>
<td>346</td>
<td>32.9</td>
</tr>
</tbody>
</table>

*Joint efficiency is calculated as percentage of the UTS of the lower strength metal (i.e., Ti-6Al-4V alloy) in the dissimilar combination.

4.2.3 Optical Microscopy

The optical microstructures near the interface of the diffusion bonded Ti-6Al-4V - Inconel 718 joints are shown in Figures 4.2 and 4.3. As seen from the micrographs, the specimens exhibited good bonding with no voids or porosities at the interface of the joint. Also the microstructures of the base metals Ti-6Al-4V and Inconel 718 near to the interface were not much affected by diffusion bonding.
Figure 4.2  Microstructure near the interface of the Ti-6Al-4V - Inconel 718 joints diffusion bonded with 900°C and varying other process parameters
Figure 4.3 Microstructure near the interface of the Ti-6Al-4V - Inconel 718 joints diffusion bonded with 850°C and varying other process parameters.

(a) 850°C, 20 MPa, 3 h

(b) 850°C, 20 MPa, 2 h

(c) 850°C, 20 MPa, 1 h
4.2.4 Transverse Hardness Survey

The hardness survey carried out transverse to the diffusion bonded interface are shown in Figures 4.4 and 4.5. There is an increase in hardness value at the interface in the case of joints carried out at a temperature of 900°C. The hardness variation at the interface in the case of joints carried out at the temperature of 850°C is minimum.

(a) 900°C, 30 MPa and 4 h  (b) 900°C, 20 MPa and 4 h

Figure 4.4 Transverse hardness survey across the interface of the diffusion bonded Ti-6Al-4V - Inconel 718 joints with 900°C and varying other process parameters
Figure 4.5 Transverse hardness survey across the interface of the diffusion bonded Ti-6Al-4V - Inconel 718 joints with 850°C and varying other process parameters
4.2.5 SEM Micrographs and EDS Analysis

SEM micrographs were taken and EDS analysis was carried out on the samples for elemental distribution, elemental mapping and point scan analysis. The SEM micrographs are based on the compositional contrast of back scattered electron signal. The EDS results of the diffusion bonded Ti-6Al-4V - Inconel 718 samples along with the respective SEM micrographs are given in Figures 4.6 to 4.10. From the micrographs, different layers were observed at the interface zone of the diffusion bonded joint. The thickness of the interface zone was 5 to 7 µm.

The concentration profiles of the elements across the interface of the joint were obtained by EDS elemental mapping and the elemental distribution analysis. The elemental mapping showed the inter-diffusion of the elements from both the sides. The diffusion of titanium of Ti-6Al-4V into Inconel 718 and the diffusion of nickel and iron of Inconel 718 into Ti-6Al-4V were higher when compared to other elements.

EDS point analysis was carried out to determine the average composition of the different layers by taking on number of points in each layer. In the case of samples of the experiments carried out at the temperature of 900°C, there were two layers at the interface with the average composition: (1) 62% Ti, 5% Fe, 26% Ni and (2) 81% Ti, 1.5% Fe, 8% Ni. In the case of samples of the experiments carried out at the temperature of 850°C, and stress 20 MPa, there were four layers at the interface with the average composition: (1) 17% Ti, 21% Fe, 32% Ni, (2) 42% Ti, 20% Fe, 32% Ni, (3) 73% Ti, 5.5% Fe, 16.5% Ni and (4) 82.5% Ti, 2.5% Fe, 6.5% Ni.
Figure 4.6  EDS analysis of the Ti-6Al-4V - Inconel 718 joint diffusion bonded at $900^\circ\text{C}$, 30 MPa, 4 h
Figure 4.7 EDS analysis of the Ti-6Al-4V - Inconel 718 joint diffusion bonded at 900°C, 20 MPa, 4 h
Figure 4.8  EDS analysis of the Ti-6Al-4V - Inconel 718 joint diffusion bonded at 850°C, 20 MPa, 3 h
Figure 4.9  EDS analysis of the Ti-6Al-4V - Inconel 718 joint diffusion bonded at 850°C, 20 MPa, 2 h
Figure 4.10  EDS analysis of the Ti-6Al-4V - Inconel 718 joint diffusion bonded at 850°C, 20 MPa, 1 h
4.2.6 Summary of results

Both the tension test and the hardness test conducted on the diffusion bonded samples reveal a characteristic behaviour related to the bonding temperature. Tension test showed that the samples diffusion bonded at 900°C give rise to a tensile strength in the range of 250 to 292 MPa, whereas the samples diffusion bonded at 850°C give rise to a tensile strength in the range of 298 to 471 MPa. Thus the lower bonding temperature of 850°C has resulted in a higher strength compared to higher bonding temperature of 900°C. The transverse hardness survey also shows that the samples diffusion bonded at 900°C contained hard zones at the interface whereas the samples diffusion bonded at 850°C have not developed any such hard zones. Lower strength and higher hardness at the interface are due to the formation of certain inter-metallic phases which is predominantly formed at higher temperature of 900°C, but not at 850°C.

As per the binary phase diagram of Ni-Ti (given in Appendix II), the possible intermetallics / phases between titanium and nickel are Ti$_2$Ni, TiNi, TiNi$_3$ and β-Ti with weight percent of nickel of 38, 54 - 62, 77 - 90 and 0 - 12 respectively. From the EDS analysis of the Ti-6Al-4V - Inconel 718 diffusion bonded joints, it is postulated that Ti$_2$Ni and β-Ti phases could be present at the interface in the samples joined at a temperature of 900°C and TiNi$_3$, TiNi and β-Ti phases could be present at the interface in the samples joined at a temperature of 850°C.
The above hypothesis may need further characterisation and more detailed experimental work for confirmation.

Hence, based on the above results obtained, it is concluded that good bonding was achieved for Ti-6Al-4V - Inconel 718 joints from the diffusion bonding experiments carried out at the bonding parameters of temperature $850^\circ$C, stress 20 MPa and 2 hours.

4.3 CHARACTERISATION OF DIFFUSION BONDED Ti-6Al-4V WITH SS 304L JOINTS WITHOUT INTERLAYERS

4.3.1 Ultrasonic C-Scan Analysis

The C-scan images of the joints corresponding to different process parameters are shown in Figure 4.11. The ultrasonic C-scan images were taken by fixing the gate region to include the interface of the Ti-6Al-4V - SS 304L diffusion bonded joint. The variation in the intensity of the ultrasonic waves that is reflected from the surface depends on the quality of the bonding. The intensity is represented in colour scale in the C-scan image. In the image, red colour indicates the minimum reflection of ultrasonic wave and purple colour indicates the maximum reflection of ultrasonic wave.
Figure 4.11 The ultrasonic C-scan images at the interface of the diffusion bonded Ti-6Al-4V - SS 304L joints

a) 850°C, 20MPa, 3h  b) 850°C, 20MPa, 2h

c) 850°C, 20MPa, 1h  d) 800°C, 20MPa, 3h

e) 800°C, 20MPa, 2h  f) 800°C, 20MPa, 1h
Table 4.3  The percentage of area of higher reflection determined by C-scan analysis - Ti-6Al-4V - SS 304L diffusion bonded joints

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Diffusion bonding parameters used</th>
<th>Percentage of area of higher reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850°C, 20MPa, 3h</td>
<td>14.52</td>
</tr>
<tr>
<td>2</td>
<td>850°C, 20MPa, 2h</td>
<td>27.94</td>
</tr>
<tr>
<td>3</td>
<td>850°C, 20MPa, 1h</td>
<td>93.67</td>
</tr>
<tr>
<td>4</td>
<td>800°C, 20MPa, 3h</td>
<td>33.18</td>
</tr>
<tr>
<td>5</td>
<td>800°C, 20MPa, 2h</td>
<td>91.21</td>
</tr>
<tr>
<td>6</td>
<td>800°C, 20MPa, 1h</td>
<td>96.73</td>
</tr>
</tbody>
</table>

The percentage of area of higher reflection was determined from the images obtained from the ultrasonic C-scan system after processed by image processing and analysis software. The results are as shown in Table 4.3. It is seen that the Ti-6Al-4V - SS 304L joint diffusion bonded under the condition of 800°C, 20 MPa and 3 h shows less percentage of area of higher reflection.

4.3.2  Tension Test

The tension test was carried out on diffusion bonded samples of Ti-6Al-4V - SS 304L joints to find out the ultimate tensile strength of the bonds. The average UTS values obtained are given in Table 4.4. The joint efficiency of the bonds was also calculated. Ultimate Tensile Strength (UTS) of the lower strength metal (i.e. SS 304L alloy) in the dissimilar combination was used for the calculating the joint efficiency.
Table 4.4 Ultimate tensile strength of diffusion bonded samples - Ti-6Al-4V - SS 304L joints

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Diffusion bonding parameters used</th>
<th>Average UTS (MPa)</th>
<th>Joint efficiency* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850°C, 20MPa, 3h</td>
<td>294</td>
<td>56.6</td>
</tr>
<tr>
<td>2</td>
<td>850°C, 20MPa, 2h</td>
<td>235</td>
<td>45.3</td>
</tr>
<tr>
<td>3</td>
<td>850°C, 20MPa, 1h</td>
<td>182</td>
<td>35.1</td>
</tr>
<tr>
<td>4</td>
<td>800°C, 20MPa, 3h</td>
<td>334</td>
<td>64.4</td>
</tr>
<tr>
<td>5</td>
<td>800°C, 20MPa, 2h</td>
<td>176</td>
<td>33.9</td>
</tr>
<tr>
<td>6</td>
<td>800°C, 20MPa, 1h</td>
<td>120</td>
<td>23.1</td>
</tr>
</tbody>
</table>

* Joint efficiency is calculated as percentage of the UTS of the lower strength metal (i.e., SS 304L alloy) in the dissimilar combination.

4.3.3 Optical Microscopy

The optical metallographic microstructures near the interface of the diffusion bonded Ti-6Al-4V - SS 304L joints are shown in Figures 4.12 and 4.13. As seen from the micrographs, the specimens exhibit good bonding with no voids or porosities at the interface of the joint. Also the microstructures of the base metals Ti-6Al-4V and SS 304L near to the interface were not affected by the diffusion bonding.
Figure 4.12 Microstructure near the interface of the Ti-6Al-4V - SS 304L joints diffusion bonded with 850°C and varying other process parameters
Figure 4.13 Microstructure near the interface of the Ti-6Al-4V - SS 304L joints diffusion bonded with $800^\circ$C and varying other process parameters.
4.3.4 Transverse Hardness Survey

The hardness survey carried out transverse to the diffusion bonded interface is shown in Figures 4.14 and 4.15. The hardness variation at the interface in the case of joints carried out at the temperature of $800^\circ\text{C}$ is minimum.

(a) $850^\circ\text{C}$, 20 MPa, 3 h  
(b) $850^\circ\text{C}$, 20 MPa, 2 h  
(c) $850^\circ\text{C}$, 20 MPa, 1 h

Figure 4.14 Transverse hardness survey across the interface of the diffusion bonded Ti-6Al-4V - SS 304L joints with $850^\circ\text{C}$ and varying other process parameters
Figure 4.15 Transverse hardness survey across the interface of the diffusion bonded Ti-6Al-4V - SS 304L joints with 800°C and varying other process parameters.
4.3.5 SEM Micrographs and EDS Analysis

SEM micrographs were taken and EDS analysis was carried out on the samples for elemental distribution, elemental mapping and point scan analysis. The SEM micrographs are based on the compositional contrast of back scattered electron signal. The EDS results of the diffusion bonded Ti-6Al-4V - SS 304L samples along with the respective SEM micrographs are given in Figures 4.16 to 4.19. From the micrographs, different layers were observed at the interface zone of the diffusion bonded joint. The thickness of the interface zone was between 4 and 6 µm.

The concentration profiles of the elements across the interface of the joint were obtained by EDS elemental mapping and the elemental distribution analysis. The elemental mapping showed the inter-diffusion of the elements from both the sides. The diffusion of titanium of Ti-6Al-4V into SS 304L and the diffusion of nickel and iron of SS 304L into Ti-6Al-4V were higher when compared to other elements.

EDS point analysis was carried out to determine the average composition of the different layers by taking on number of points in each layer. In the case of samples of the experiments carried out at the temperature of 850°C, there were three layers at the interface with the average composition: (1) 77% Ti, 11% Fe, 1.45% Cr, 2%Ni, (2) 40% Ti, 43%Fe, 12% Cr, 3%Ni and (3) 3% Ti, 70.5%Fe, 21% Cr, 5%Ni. In the case of samples of the experiments carried out at the temperature of 800°C, there were five layers at the interface with the average composition: (1) 83%Ti, 5.5%Fe,
1%Cr, 1%Ni, (2) 72.5%Ti, 13.5%Fe, 3%Cr, 1.5%Ni, (3) 58%Ti, 25.5%Fe, 8% Cr, 2.5%Ni,(4) 17%Ti, 58.5%Fe, 14%Cr ,7.5%Ni and (5) 2.5%Ti, 70.5%Fe, 18%Cr , 8.5%Ni.

4.3.6 Summary of Results

Both the tension test and the hardness test conducted on the diffusion bonded samples revealed a characteristic behaviour related to the bonding temperature. Tension test showed that the samples diffusion bonded at 850°C gave rise to a tensile strength in the range of 182 to 294 MPa, whereas the samples diffusion bonded at 800°C for 3 h gave rise to a tensile strength of 334 MPa. Thus the bonding temperature of 800°C has resulted in a higher strength compared to higher bonding temperature of 850°C. The transverse hardness survey also showed that the samples diffusion bonded at 850°C contained hard zones at the interface whereas the samples diffusion bonded at 800°C had not developed any such hard zones. Lower strength and high hardness at the interface is due to the formation of certain inter-metallic phases which is predominantly formed at higher temperature of 850°C, but not at 800°C.

As per the binary phase diagram of Fe-Ti (given in Appendix II), the possible intermetallics / phases between Titanium and Iron are β-Ti, TiFe, TiFe$_2$ and α-Fe with weight percent of iron of 0 - 24, 51 - 54, 68 - 75 and 91 - 100 respectively. From the EDS analysis of the Ti-6Al-4V - SS 304L diffusion bonded joints, it is postulated that β-Ti, TiFe and α-Fe phases could be present at the interface in the samples joined at a temperature of 850°C.
and $\beta$-Ti, TiFe$_2$ and $\alpha$-Fe phases could be present at the interface in the samples joined at a temperature of 800°C.

This hypothesis needs further characterisation and more detailed experimental work for confirmation.

Hence, based on the above results obtained, it is concluded that good bonding was achieved for Ti-6Al-4V - SS 304L joints from the diffusion bonding experiments carried out at the bonding parameters of temperature 800°C, stress 20 MPa and time 3 hours.
Figure 4.16 EDS analysis of the Ti-6Al-4V - SS 304L joint diffusion bonded at $850^\circ$C, 20 MPa, 3 h
Figure 4.17  EDS analysis of the Ti-6Al-4V - SS 304L joint diffusion bonded at 850°C, 20 MPa, 2 h
Figure 4.18 EDS analysis of the Ti-6Al-4V - SS 304L joint diffusion bonded at 800°C, 20 MPa, 3 h
Figure 4.19  EDS analysis of the Ti-6Al-4V - SS 304L joint diffusion bonded at 800°C, 20 MPa, 2 h
4.4 CHARACTERISATION OF FRICTION WELDED Ti-6Al-4V WITH INCONEL 718 JOINTS WITHOUT INTERLAYERS

4.4.1 Ultrasonic C-Scan Analysis

Attempts were made to take ultrasonic C-scan images on the Ti-6Al-4V - Inconel 718 friction welded joints obtained by maintaining two different process parameters, RS = 1000 rpm; UL = 6 ton; FL = 2 ton and RS = 800 rpm; UL = 6 ton; FL = 3 ton. The C-scan images corresponding to those two friction welded joints were shown in Figure 4.20.

![C-scan image 1](image1)

(a) RS = 1000 rpm ; UL = 6 ton; FL = 2ton

![C-scan image 2](image2)

(b) RS = 1000 rpm ; UL = 5 ton; FL = 3ton

Figure 4.20 The ultrasonic C-scan images at the interface of the Ti-6Al-4V - Inconel 718 friction welded joints
The variation in the intensity of the ultrasonic waves that is reflected from the surface depends on the quality of the joint. The intensity is represented in colour scale in the C-scan image. In the image, blue indicates good welding due to the minimum reflection of ultrasonic wave and red indicates poor welding due to the maximum reflection of ultrasonic wave.

While performing C-scan analysis on different samples, it was observed that the images obtained were not proper. This is due to the problem in fixing the gate for the scans near the interface of the joints. As the interface region in friction welded components is not flat and parallel to the top surface, the signals received cannot be grouped for different gates. Hence, it was felt that further ultrasonic testing would not be useful.

4.4.2 Tension Test

Tension test was carried out on Ti-6Al-4V - Inconel 718 friction welded samples to find out the ultimate tensile strength of the bonds. The average UTS values obtained are given in Table 4.5. The joint efficiency of the bonds was calculated. Ultimate Tensile Strength (UTS) of the lower strength metal (i.e. Ti-6Al-4V alloy) in the dissimilar combination was used for the calculating the joint efficiency. Out of the number of experiments carried out with varying process parameters, the samples friction welded with RS = 1000 rpm; UL = 6 ton; FL = 2 ton, RS = 1000 rpm; UL = 6 ton; FL = 2 ton and with RS = 800 rpm; UL = 6 ton; FL = 3 ton had led to maximum joint efficiency of more than 20%.
Table 4.5  Ultimate tensile strength of friction welded samples - Ti-6Al-4V - Inconel 718 joints

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Friction welding parameters used</th>
<th>Average UTS (MPa)</th>
<th>Joint efficiency* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn-off-length = 2 mm</td>
<td>Speed (rpm)</td>
<td>Upset load (ton)</td>
<td>Friction load (ton)</td>
</tr>
<tr>
<td>1</td>
<td>1800</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1800</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>8</td>
<td>2</td>
</tr>
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<td>4</td>
<td>1200</td>
<td>6</td>
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<td>5</td>
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</tr>
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<td>7</td>
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</tr>
<tr>
<td>9</td>
<td>800</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

* Joint efficiency is calculated as percentage of the UTS of the lower strength metal (i.e., Ti-6Al-4V alloy) in the dissimilar combination.

4.4.3  Optical Microscopy

The optical microstructures around the interface of the Ti-6Al-4V - Inconel 718 friction welded joints are shown in Figures 4.21 to 4.25. An interface of non-uniform thickness with the presence of voids is seen in almost all joints of Ti-6Al-4V - Inconel 718 irrespective of the selected process parameters. Out of all the micrographs, the one corresponding to the welding parameters RS = 1000 rpm; UL = 6 ton, FL = 3 ton (Figure 4.24) shows fairly better interface with uniform thickness and negligible voids.
(a) RS = 1800 rpm; UL = 8 ton; FL = 2 ton

(b) RS = 1800 rpm; UL = 6 ton; FL = 2 ton

Figure 4.21 Microstructure near the interface of the friction welded Ti-6Al-4V - Inconel 718 with RS = 1800 rpm and varying other process parameters
Figure 4.22  Microstructure near the interface of the friction welded Ti-6Al-4V - Inconel 718 with $RS = 1500$ rpm; $UL = 8$ ton; $FL = 2$ ton

$RS = 1200$ rpm; $UL = 6$ ton; $FL = 2$ ton

Figure 4.23  Microstructure near the interface of the friction welded Ti-6Al-4V - Inconel 718 with $RS = 1200$ rpm and varying other process parameters
Figure 4.24 Microstructure near the interface of the friction welded Ti-6Al-4V - Inconel 718 with RS = 1000 rpm and varying other process parameters

(a) RS = 1000 rpm; UL = 6 ton; FL = 3 ton

(b) RS = 1000 rpm; UL = 6 ton; FL = 2 ton
Figure 4.25  Microstructure near the interface of the friction welded Ti-6Al-4V - Inconel 718 with RS = 800 rpm and varying other process parameters.
4.4.4 Transverse Hardness Survey

The hardness survey carried out transverse to the friction welded interface is shown in Figures 4.26 to 4.30. In the case of friction welding performed at higher rotational speeds 1800 and 1500 rpm, the increase in hardness values is more when compared to that at the rotational speeds of 1200, 1000 and 800 rpm. However, one experiment done at 800 rpm (RS = 800 rpm; UL = 5 ton; FL = 3 ton) speed resulted in lesser hardness than that of parent metal giving an indication of poor bonding and pores at the interface.

![Graphs showing hardness survey](image)

(a) RS = 1800 rpm; UL = 8 ton; FL = 2 ton  
(b) RS = 1800 rpm; UL = 6 ton; FL = 2 ton

Figure 4.26 Transverse hardness survey across the interface of Ti-6Al-4V - Inconel 718 joints friction welded with RS = 1800 rpm and varying other process parameters
Figure 4.27 Transverse hardness survey across the interface of Ti-6Al-4V - Inconel 718 joints friction welded with RS = 1500 rpm; UL = 8 ton; FL = 2 ton

Figure 4.28 Transverse hardness survey across the interface of Ti-6Al-4V - Inconel 718 joints friction welded with RS = 1200 rpm; UL = 6 ton; FL = 2 ton
Figure 4.29 Transverse hardness survey across the interface of Ti-6Al-4V - Inconel 718 joints friction welded with RS = 1000 rpm and varying other process parameters

(a) RS = 1000 rpm; UL = 6 ton; FL = 3 ton
(b) RS = 1000 rpm; UL = 6 ton; FL = 2 ton

Figure 4.30 (Continued)
Figure 4.30  Transverse hardness survey across the interface of Ti-6Al-4V - Inconel 718 joints friction welded with RS = 800 rpm and varying other process parameters

4.4.5  SEM Micrographs and EDS Analysis

SEM micrographs were taken and EDS analysis was carried out on the samples for elemental distribution, elemental mapping and point scan analysis. The SEM micrographs are based on the compositional contrast of back scattered electron signal. The EDS results of the Ti-6Al-4V - Inconel 718 friction welded samples along with the respective SEM micrographs are given in Figures 4.31 to 4.38. From the micrographs, different layers were observed at the interface zone of the friction welded joint. The thickness of the interface zone was varying for different samples from 25 to 100 µm.
The concentration profiles of the elements across the interface of the joint were obtained by EDS elemental mapping and the elemental distribution analysis. The elemental mapping showed the inter-diffusion of the elements from both the sides. The diffusion of titanium of Ti-6Al-4V into Inconel 718 and the diffusion of nickel and iron of Inconel 718 into Ti-6Al-4V were higher when compared to other elements.

The SEM micrographs of the joints friction welded with rotating speed of 1800 rpm, 1500 rpm and 1200 rpm show an interface of thickness of more than 100µm with non-uniform diffusion of elements forming two different layers with different chemical composition. The joint friction welded with rotating speed of 1200 rpm also shows discontinuity at the Ti-6Al-4V side. The SEM micrographs of the joints friction welded with rotating speed of 1000 rpm show relatively lesser interface thickness of less than 50 µm. The interface has two phases with the average composition of (1) 58.7% Ti, 7.0% Fe, 2.8% Cr, 28.7% Ni and (2) 81.6% Ti, 2.4% Fe, 1.7% Cr, 5.0% Ni. The distribution of these phases was also uniform at the interface. The joint prepared with RS = 800 rpm; UL = 5 ton; FL = 3 ton shows a number of voids at the interface.
Figure 4.31 EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 1800 rpm; UL = 8 ton; FL = 2 ton
Figure 4.32  EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 1800 rpm; UL = 6 ton; FL = 2 ton
Figure 4.33 EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 1500 rpm; UL = 8 ton; FL = 2 ton
Figure 4.34 EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 1200 rpm; UL = 6 ton; FL = 2 ton
Figure 4.35  EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 1000 rpm; UL = 6 ton; FL = 3 ton
Figure 4.36 EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 1000 rpm; UL = 6 ton; FL = 2 ton
Figure 4.37  EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 800 rpm; UL = 6 ton; FL = 3 ton
Figure 4.38  EDS analysis of the Ti-6Al-4V - Inconel 718 joint friction welded at RS = 800 rpm; UL = 5 ton; FL = 3 ton
4.4.6 Summary of Results

Both the tension test and the hardness test conducted on the friction welded samples reveal a characteristic behaviour related to the rotating speed used for friction welding. Tension test shows that the joint efficiency of samples friction welded at higher speeds 1800, 1500 and 1200 rpm was in the range from 11.8 to 16.2%. Joint efficiency of samples friction welded at the speed of 1000 rpm was in the higher range from 21 to 28%.

The SEM micrographs and EDS analysis on the samples reveal uniform distribution of phases at the interface. The transverse hardness survey also shows that the samples friction welded at higher speeds contain hard zones at the interface whereas the samples welded at 1000 rpm have not developed any such hard zones. However, still lowering the speed to 800 rpm, the results show similar to that of samples friction welded at higher speed. This may be due to increased friction load. Moreover, the joint prepared with process parameters RS = 800 rpm; UL = 5 ton; FL = 3 ton shows very poor joint efficiency. This joint had a number of micro voids which was evident from SEM micrograph.

Lower strength and higher hardness at the interface is due to the formation of certain inter-metallic phases which is predominantly formed at higher speeds, but not at lower speeds. Comparing the binary phase diagram of Ni - Ti and the EDS analysis of the Ti-6Al-4V - Inconel 718 friction welded joints, it is postulated that, TiNi$_3$ and Ti$_2$Ni phases could be present at the interface in the samples joined at RS = 1800 rpm and TiNi$_3$, TiNi and β-Ti phases could be present at the interface in the samples joined at RS = 1200 rpm. But the distribution of the intermetallics is not uniform. The SEM
micrograph and EDS analysis of the samples joined at RS = 1000 rpm show uniformly distributed Ti$_2$Ni and β-Ti at the interface.

This hypothesis needs further characterisation and more detailed experimental work for confirmation.

Hence, based on the above results obtained, it is concluded that good joint was achieved for Ti-6Al-4V - Inconel 718 joints from the friction welding experiments carried out at the welding parameters of rotational speed of 1000 rpm, upset load of 6 ton, friction load of 2 ton for which the joint efficiency obtained was 28%.

4.5 CHARACTERISATION OF FRICTION WELDED Ti-6Al-4V WITH SS 304L JOINTS WITHOUT INTERLAYER

4.5.1 Ultrasonic C-Scan Analysis

The ultrasonic C-scan images were taken by fixing the gate region to include the interface of the Ti-6Al-4V - SS 304L welded joint. The C-scan images corresponding to the four joints friction welded with different process parameters are shown in Figure 4.39. As mentioned in 4.4.1, it was felt that further ultrasonic testing would not be useful as the interface region in friction welded components is not flat and parallel to the top surface.

4.5.2 Tension Test

Tension test was carried out on of Ti-6Al-4V - SS 304L friction welded samples to find out the ultimate tensile strength of the bonds. The average UTS values obtained were given in Table 4.6. The joint efficiency of
the bonds was calculated. The joint efficiency of the bonds was also calculated. Ultimate Tensile Strength (UTS) of the lower strength metal (i.e. SS 304L alloy) in the dissimilar combination was used for the calculating the joint efficiency.

Friction welding was carried out at three different rotational speed 1500, 1200 and 1000 rpm. It was observed that the UTS of joints obtained at same rotational speed increases with decrease in upset load. Out of the number of experiments carried out with varying process parameters, the samples friction welded with RS = 1500 rpm; UL = 8 ton; FL = 4 ton and with RS = 1500 rpm; UL = 6 ton; FL = 4 ton had maximum joint efficiency of more than 50%.

Figure 4.39 The ultrasonic C-scan images at the interface of the Ti-6Al-4V - SS 304L friction welded joints
Table 4.6 Ultimate tensile strength of friction welded samples - Ti-6Al-4V - SS 304L joints

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>Friction welding parameters used</th>
<th>Average UTS (MPa)</th>
<th>Joint efficiency* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burn-off-length = 2 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speed (rpm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upset load (ton)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Friction load (ton)</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1500</td>
<td>5</td>
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</tr>
<tr>
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<td>1500</td>
<td>4</td>
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</tr>
<tr>
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<td>1500</td>
<td>4</td>
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<tr>
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<td>4</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
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</tr>
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</tr>
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</tr>
<tr>
<td>15</td>
<td>1000</td>
<td>4</td>
<td>208</td>
</tr>
</tbody>
</table>

*Joint efficiency is calculated as percentage of the UTS of the lower strength metal (i.e., SS 304L alloy) in the dissimilar combination.

4.5.3 Optical Microscopy

The optical microstructures near the interface of the Ti-6Al-4V - SS 304L friction welded joints are shown in Figures 4.40 to 4.45. An interface of uniform thickness with no voids or porosities is seen in almost all joints of Ti-6Al-4V - SS 304L. Also the microstructures of the base metals Ti-6Al-4V and SS 304L near to the interface were not much affected by diffusion bonding.
(a) RS = 1500 rpm; UL = 10 ton; FL = 5 ton

(b) RS = 1500 rpm; UL = 10 ton; FL = 4 ton

Figure 4.40 Microstructure near the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1500 rpm; UL = 10 ton and varying FL
Figure 4.41 Microstructure near the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1500 rpm and varying UL and FL

(a) RS = 1500 rpm; UL = 9 ton; FL = 4 ton

(b) RS = 1500 rpm; UL = 8 ton; FL = 4 ton

(c) RS = 1500 rpm; UL = 6 ton; FL = 4 ton
Figure 4.42 Microstructure near the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1200 rpm; UL = 10 ton and varying FL
Figure 4.43 Microstructure near the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1200 rpm and varying UL and FL.
Figure 4.44 Microstructure near the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1000 rpm; UL = 10 ton and varying FL
Figure 4.45  Microstructure near the interface of the friction welded 
Ti-6Al-4V - SS 304L with RS = 1000 rpm and varying UL and FL
4.5.4 Transverse Hardness Survey

The hardness survey carried out transverse to the friction welded interface is shown in Figures 4.46 to 4.51. The hardness at the interface is lesser for the joints obtained with higher upset loads. This behavior is observed for all the rotational speeds. The joints with an interface of higher hardness correlates with the better bond strength as observed from the tension tests.

(a) RS = 1500 rpm; UL = 10 ton; FL = 5 ton
(b) RS = 1500 rpm; UL = 10 ton; FL = 4 ton

Figure 4.46 Transverse hardness survey across the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1500 rpm; UL = 10 ton and varying FL
Figure 4.47 Transverse hardness survey across the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1500 rpm and varying UL and FL
(a) RS = 1200 rpm; UL = 10 ton; FL = 5 ton

(b) RS = 1200 rpm; UL = 10 ton; FL = 4 ton

Figure 4.48 Transverse hardness survey across the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1200 rpm; UL = 10 ton and varying FL

(a) RS = 1200 rpm; UL = 9 ton; FL = 4 ton

Figure 4.49 (Continued)
(b) RS = 1200 rpm; UL = 8 ton; FL = 4 ton  
(c) RS = 1200 rpm; UL = 6 ton; FL = 4 ton

Figure 4.49 Transverse hardness survey across the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1200 rpm and varying UL and FL

(a) RS = 1000 rpm; UL = 10 ton; FL = 5 ton  
(b) RS = 1000 rpm; UL = 10 ton; FL = 4 ton

Figure 4.50 Transverse hardness survey across the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1000 rpm; UL = 10 ton and varying FL
(a) RS = 1000 rpm; UL = 9 ton; FL = 4 ton
(b) RS = 1000 rpm; UL = 8 ton; FL = 4 ton
(c) RS = 1000 rpm; UL = 6 ton; FL = 4 ton

Figure 4.51 Transverse hardness survey across the interface of the friction welded Ti-6Al-4V - SS 304L with RS = 1000 rpm and varying UL and FL
4.5.5  SEM Micrographs and EDS Analysis

SEM micrographs were taken and EDS analysis was carried out on the samples for elemental distribution, elemental mapping and point scan analysis. The SEM micrographs are based on the compositional contrast of back scattered electron signal. The EDS results of the friction welded Ti-6Al-4V - SS 304L samples along with the respective SEM micrographs are given in Figures 4.52 to 4.66. The concentration profiles of the elements across the interface of the joint were obtained by EDS elemental mapping and the elemental distribution analysis.

From the SEM micrographs, the thickness of the interface zone was found to be only less than 2 µm in all the joints. The elemental mapping showed the inter-diffusion of the elements from both the sides i.e., diffusion of titanium of Ti-6Al-4V into SS 304L and diffusion of nickel and iron of SS 304L into Ti-6Al-4V. But there is no evidence for the formation of different layers or any particular phase at the interface zone of the friction welded joint.

4.5.6  Summary of Results

The tension test conducted on the friction welded samples reveal a characteristic behaviour related to the rotational speed used for friction welding. Tension test shows that a decrease in the rotational speed increases the joint efficiency of samples with the other parameters being constant. The maximum joint efficiency of the samples obtained at the speeds of 1500, 1200 and 1000 rpm were 70.1%, 43.5% and 40.1% respectively. The joint efficiency increases with decrease in upset load for the same rotational speed.

From the SEM-EDS analysis, it is evident that merely inter-diffusion of the elements from both the sides i.e., diffusion of titanium of Ti-6Al-4V into SS 304L and diffusion of nickel and iron of SS 304L into Ti-6Al-4V had taken place without the formation of different layers or any particular phase at the interface zone of the friction welded joints. This is in correlation with the results of the tension test and transverse hardness survey across the interface of the joints.
Figure 4.52  EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1500 rpm; UL = 10 ton; FL = 5 ton
Figure 4.53 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at $RS = 1500$ rpm; $UL = 10$ ton; $FL = 4$ ton
Figure 4.54 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1500 rpm; UL = 9 ton; FL = 4 ton
Figure 4.55 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1500 rpm; UL = 8 ton; FL = 4 ton
Figure 4.56 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1500 rpm; UL = 5 ton; FL = 4 ton
Figure 4.57 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1200 rpm; UL = 10 ton; FL = 5 ton
Figure 4.58  EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1200 rpm; UL = 10 ton; FL = 4 ton
Figure 4.59  EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1200 rpm; UL = 9 ton; FL = 4 ton
Figure 4.60  EDS Analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1200 rpm; UL = 8 ton; FL = 4 ton
Figure 4.61 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1200 rpm; UL = 6 ton; FL = 4 ton
Figure 4.62 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1000 rpm; UL = 10 ton; FL = 5 ton
Figure 4.63 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1000 rpm; UL = 10 ton; FL = 4 ton
Figure 4.64 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1000 rpm; UL = 9 ton; FL = 4 ton
Figure 4.65 EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1000 rpm; UL = 8 ton; FL = 4 ton
Figure 4.66  EDS analysis of the Ti-6Al-4V - SS 304L joint friction welded at RS = 1000 rpm; UL = 6 ton; FL = 4 ton
4.6 CHARACTERISATION OF JOINTS WITH INTERLAYER

The joints of the two dissimilar combinations made by diffusion bonding and friction welding with nickel interlayer were successful only in a few experiments for which the optical micrographs and SEM-EDS test were taken.

4.6.1 Diffusion Bonded Ti-6Al-4V - Inconel 718 Joints with Interlayer

The results of the SEM-EDS analysis on the diffusion bonded Ti-6Al-4V - Inconel 718 joints with nickel interlayer of thickness of about 70 µm with process parameters of temperature $900^\circ$C, stress 20 MPa and time 2 hours are shown in Figures 4.67 to 4.69.

4.6.2 Diffusion Bonded Ti-6Al-4V - SS 304L Joints with Interlayer

The results of the SEM-EDS analysis on the diffusion bonded Ti-6Al-4V - SS 304L with nickel interlayer of thickness of about 70 µm with process parameters temperature $900^\circ$C, stress 20 MPa and time 3 hours are shown in Figures 4.70 to 4.71.
Figure 4.67  EDS analysis of the Ti-6Al-4V - Inconel 718 joint diffusion bonded at 900°C, 20 MPa, 2 h with nickel interlayer
Figure 4.68  EDS analysis of the Ti-6Al-4V side of Ti-6Al-4V - Inconel 718 joint diffusion bonded at 900°C, 20 MPa, 2 h with nickel interlayer
Figure 4.69  EDS analysis of the Inconel 718 side of Ti-6Al-4V - Inconel 718 joint diffusion bonded at $900^\circ$C, 20 MPa, 2 h with nickel interlayer
Figure 4.70  EDS analysis of the Ti-6Al-4V side of Ti-6Al-4V - SS 304L joint diffusion bonded at 900°C, 20 MPa, 3 h with nickel interlayer
Figure 4.71  EDS analysis of the SS 304L side of Ti-6Al-4V - SS 304L joint diffusion bonded at 900°C, 20 MPa, 3 h with nickel interlayer
4.6.3 Friction Welded Ti-6Al-4V - Inconel 718 Joints with Interlayer

The optical microstructures of two friction welded Ti-6Al-4V - Inconel 718 joints with nickel interlayer welded with process parameters RS of 1000 rpm, UL of 6 ton and FL of 2 ton and RS of 800 rpm, UL of 6 ton and FL of 3 ton are shown in Figure 4.72. The microstructure reveals there is no bonding of interface; only mechanical mixing up of the materials has taken place by the applied frictional force.

![Microstructure images](image)

**Figure 4.72** The optical microstructures of welded Ti-6Al-4V - Inconel 718 joints with nickel interlayer

- a) RS = 1000 rpm; UL = 6 ton; FL = 2 ton
- b) RS = 800 rpm; UL = 6 ton; FL = 3 ton
4.6.4 Friction Welded Ti-6Al-4V - SS 304L Joints with Interlayer

The optical microstructures of two friction welded Ti-6Al-4V - SS 304L joints with nickel interlayer welded with process parameters RS of 1200 rpm, UL of 8 ton and FL of 4 ton and RS of 1000 rpm, UL of 6 ton and FL of 4 ton are shown in Figure 4.73. The microstructure reveals there is no bonding of interface; only mechanical mixing up of the materials has taken place by the applied frictional force.

![Microstructure Images](image)

a) RS = 1200 rpm; UL = 8 ton; FL = 4 ton

c) RS = 1000 rpm; UL = 6 ton; FL = 4 ton

Figure 4.73 The optical microstructures of two friction welded Ti-6Al-4V - SS 304L joints with nickel interlayer welded with varying process parameters
4.6.5 Summary of Results

The tension test of the samples could not be carried out as they failed immediately after the start of loading in the universal testing machine. In the case of diffusion bonded samples, the interdiffusion of elements were observed at the interface of the joints. The EDS analysis of the Ti-6Al-4V - Inconel 718 diffusion bonded joint with nickel interlayer shows the presence of the intermetallics TiNi and TiNi$_3$ at the Ti-6Al-4V side and diffusion of nickel at the Inconel 718 side. Similarly, The EDS analysis of the Ti-6Al-4V - SS 304L diffusion bonded joint with nickel interlayer shows the presence of the intermetallics Ti$_2$Ni, TiNi and TiNi$_3$ at the Ti-6Al-4V side and interdiffusion of nickel and iron at the SS 304L side. In the case of friction welded samples, the interlayer placed at the centre had come out due to the force. No further investigation was taken up to study the functional value of interlayer material in controlling the intermetallic formation.