Corrosion behaviour of stainless steel–titanium alloy linear friction welded joints: Galvanic coupling

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Linear friction welding may be used to join titanium alloys to stainless steel for a variety of applications. After welding, a crevice is often observed close to the edges and, in aqueous wet environments, a galvanic couple is formed between the two materials. If corrosion resistance is a requirement, the combined presence of a crevice and a galvanic couple is a concern. In this study, the behaviour of galvanically coupled titanium alloy and stainless steel has been investigated, both for planar electrodes and under simulated crevice conditions. In both cases, it was found that a significant driving force between the two materials develops over time to progress corrosion on the stainless steel, but the high specific impedance of the titanium surface limits the current flow. Consequently, it is concluded that galvanic coupling between titanium and stainless steel is only of concern if the area of the titanium largely exceeds the area of the steel, and only under complete immersion conditions in a sufficiently conductive electrolyte.

1 Introduction

Emerging joining technologies, e.g. laser beam welding (LBW), friction stir welding (FSW) and linear friction welding (LFW), enable joining of a wide range of dissimilar materials for high performance applications [1,2]. Further, the capability of joining dissimilar materials enables the production of components of optimised design with reduced cost and weight [3]. LFW, for example, is used to weld aircraft engine blades (titanium) to discs (stainless steel) [4]. Steel–titanium coupling is also used in biomedical applications, for both dental implants and articulation replacement [5–7].

This work focuses on the evaluation of the corrosion resistance of joints obtained by linear friction welding. During LFW, heat is generated at the faying surfaces of two components under a specific pressure, amplitude and frequency of relative linear motion, resulting in plasticisation of the interfacial region, and consequent formation of a metallurgical bond upon cessation of the relative movement [8]. This process normally requires several seconds to be completed [9,10]. LFW is attractive for joining difficult-to-weld, high performance and/or dissimilar alloys [11]. To date, much of the LFW development has been driven by the aeroengine industry, with the requirement to obtain integrally bladed titanium alloy disks of reduced weight and improved performance compared with existing slotted blade/disk assemblies. LFW can also be used to join dissimilar alloys in order to employ the optimum alloys for the blade (exposed to high cycle fatigue and high temperature) and disk (exposed to low cycle fatigue) [12]. Typically, during the LFW process, bonding defects can be generated; in particular, due to inadequate material stirring and remixing, some crevices may occur [13].

When two dissimilar materials are joined, particular attention should be paid to the potential corrosion issues arising from the galvanic couple. Galvanic corrosion is an electrochemical process resulting in accelerated and preferential corrosion of one of the two metals. Dissimilar materials have different electrochemical potentials; this difference in electrochemical potential provides the thermodynamic driving force for the onset of galvanic corrosion. Galvanic corrosion can be more severe under crevice conditions, due to the generation of a microenvironment within the crevice that can be significantly more aggressive compared with the external environment. Crevice corrosion has been the subject of many investigations as a result of its widespread occurrence and its destructive nature [14]. Previous studies [15,16] have shown that, in chloride environments, the solution within the crevice undergoes hydrolysis reaction leading to increased acidity and chloride concentration in the occluded volume, which can eventually lead to rapid passive
film breakdown and consequent increase of corrosion rate. Metals, especially in the passive systems (e.g. stainless steels in sodium chloride solution and carbon steels in chloride solution containing dissolved metal species), suffer crevice corrosion when the crevice opening is sufficiently narrow (<0.5 mm) so that exchange of species between the inside and the outside solutions is difficult and, therefore, the crevice solution becomes more aggressive over time (by acidification and enrichment of aggressive species) [17].

In order to assess the corrosion susceptibility due to the galvanic coupling of titanium and stainless steel, in this work electrochemical noise analysis has been employed. Electrochemical potential or current noise arises from anodic and/or cathodic events on the surface of corroding electrodes that are associated with the initiation or propagation of corrosion. Various methods are available for electrochemical noise analysis, each with specific advantages and limitations for the study or monitoring of a particular corroding system [18]. Whatever the approach for the analysis, if both current and potential noises need to be acquired, generally two working electrodes and a third reference electrode are employed. Among the other analysis techniques, estimation of the noise resistance, defined as the square root of the ratio between the potential variance and current variance, is generally applied to a couple of nominally identical electrodes [19–22]. Its wide use derives from the physical meaning of the noise resistance that is similar to that of the polarisation resistance, but it can be obtained without applying any probing signal to the corroding surface. With a conceptually similar approach, the noise impedance can be calculated by taking the square root of the ratio between the potential power spectral density and the current power spectral density, obtained by fast Fourier transform. Although the strength of this approach is to extract parameters that directly relate to the corrosion rate, a relatively severe limitation arises from the requirement to use two nominally identical electrodes. However, recently, it has been shown that it is possible to extend the two-electrode analysis to an array of dissimilar electrodes [23] by using the concept of virtual electrodes. For a given array of electrodes, after the individual currents flowing across each electrode are acquired and the experiment is terminated, it is always possible to numerically generate a couple of virtual electrodes by adding in the time domain of the individual electrode currents for a subset of electrodes. Thus, the analysis of any electrode array can be reduced to the analysis of a single pair of non-identical virtual electrodes.

The present research activity is founded on the previous premises. The joining of stainless steel with titanium alloys for high performance applications requires understanding of the galvanic coupling. Further, it is important to study the evolution of the corrosive phenomena with time and the importance of the presence of a crevice defect on the galvanic coupling between the two dissimilar materials.

2 Experimental

In this work, the corrosion behaviour of linear friction welded A316 stainless steel and the titanium alloy Ti6Al4V was investigated. The linear friction weld joints were obtained by using an electromechanical LFW machine at TWI Ltd., Cambridge, UK. Preparation of the sawn ends, which would form the faying surfaces (welding faces), was limited to degreasing with acetone prior to welding. The oscillating component was the Ti6Al4V alloy.

For electronoptical observations, a Zeiss EVO 50 scanning electron microscope (SEM) was used. Potentiodynamic polarisation tests were carried out in a three-electrode cell using a SCE reference electrode, and graphite rod as the counter electrode in a 3.5 wt% NaCl solution. The polarisations were carried out on both the base materials of the joints, after sandblasting.

Electrochemical noise tests were carried out on the base materials of the joints using the following configurations:

- A two nominally identical electrode configuration on steel (Fig. 1a).

![Figure 1. Schematic diagram showing the electrochemical cells used: (a) electrochemical noise immersion test in two nominally identical electrode configuration; (b) electrochemical noise immersion test in the four electrodes configuration (WE2, WE4 titanium and WE1, WE3 stainless steel, two dissimilar pairs of identical electrodes); (c) electrochemical noise test in the simulated crevice condition](image-url)
A two nominally identical electrode configuration on titanium (Fig. 1a).

A two dissimilar pair (titanium and stainless steel) of identical electrodes (four-electrode configuration, Fig. 1b).

The tests were undertaken in naturally aerated 3.5 wt% NaCl solution using a SCE reference electrode. The specimens were sandblasted before the test and were masked with beeswax in order to define the exposed electrode area. Both potential and current were measured using a Concerto multichannel electrochemical setup. The electrochemical noise data were used to calculate the time evolution of the low-frequency impedance obtained by using in-house developed software with the procedure described in detail in Ref. [23]. Specifically, the following parameters were used for the calculation of low-frequency impedance: segment length for fast Fourier transform of 8192 points, overlap between the subsequent segment of 75%, and Hanning window.

Complementing the work on the galvanically coupled materials, attention was paid to the study of galvanic coupling under crevice conditions, similar to those generated on the weld. The crevice was simulated using two nominally identical plates separated by means of two 0.1 mm thick polymeric films at the plate extremities in order to create an artificial crevice between the two plates. A schematic diagram of the cross section of the configuration employed is depicted in Fig. 1c. Beeswax was applied to the external surfaces in order to expose only the crevice to the solution. Three different crevice conditions were studied (Fig. 1c):

- Steel–steel coupling.
- Titanium–titanium coupling.
- Titanium–steel coupling.

In order to obtain a crevice with a well-defined geometry, the coupled surfaces of the plates were mechanically polished and mirror-finished. The behaviour of the simulated crevice was studied by the electrochemical noise approach as described above for the base materials. At the end of the test, the plate surfaces were observed by SEM in order to evaluate the progress of the corrosion process.

3 Results

Figure 2 displays the flash resulting from the plastic flow of the titanium alloy during the welding process with stainless steel. The figure also reveals that a crevice has been generated between the titanium and the stainless steel. This defect is common following the LFW process and has been described previously [13]. From Figure 2, it is evident that the crevice extended approximately 1 mm into the metal and was approximately 10 µm wide. Figure 3 shows that the welding process has resulted in the formation of cracks, and alterations of the microstructure due to material mixing which occurred in that zone are noticeable. Figure 4 displays the weld region near to the crevice after immersion in 3.5% NaCl for 21 days. Some superficial corrosion attack is evident in the proximity of the crevice and corrosion products are revealed both in the crevice and in the surrounding areas.

Typical polarisation curves from −0.75 to 2.125 V SCE for both the titanium alloy and the steel base material are shown in Figure 5. The cathodic activities were similar for both materials; the steel displayed a pitting potential close to 0 V while, for the titanium alloy, the pitting potential was approximately 1.5 V (SCE).

Figure 6 displays both the potential and the current noises recorded during immersion of the identical stainless steel and titanium specimens in the 3.5% NaCl electrolyte, and the low-frequency noise impedance obtained by the described
Concerning the titanium alloy, a transient from $-280$ to $-80$ mV (SCE) was observed initially; subsequently, the potential increased to a value of approximately $-100$ mV over 1 day and, finally, approached a steady potential of 0 V (SCE). Between 2 and 7 days, relatively large oscillations in the potential were revealed, but such oscillations were less significant for increased immersion times. Conversely, the stainless steel displayed an initial potential value of $-220$ mV (SCE) and, after a rapid transient, approached a value of $-160$ mV (SCE) that was maintained until the end of the test with some oscillations revealed.

Concerning the current noise data, the values recorded for titanium were of the order of $10^{-1}$ μA, which were about one order of magnitude lower than those revealed for stainless steel; occasionally, significant fluctuations in the current were revealed, and such fluctuations correlated with the fluctuations in potential. The values recorded for steel were of the order of microamps, with a mean value of roughly 3 μA with some very marked fluctuations; as evident for titanium, it is possible to correlate these fluctuations with fluctuations in the potential. The low-frequency noise impedance data calculated from the potential and current noise for the two experiments are presented in Figure 6c. Initially, the impedance of titanium was in the region of $10^6$ Ohm cm² and this value did not change significantly until the end of the test. Similarly, the steel impedance was steady, but approximately one order of magnitude lower ($10^5$ Ohm cm²) than that of the titanium alloy.

Figure 7 displays the results of a similar experiment where two pairs of nominally identical titanium electrodes were coupled with two nominally identical stainless steel electrodes. The potential of the coupled electrodes was initially close to $-220$ mV (SCE) and displayed several oscillations during the first day of immersion. After the initial transients, the potential approached that recorded for stainless steel alone (Fig. 6), being close to $-160$ mV (SCE). Concerning the currents, it is evident from Figure 7, that the two titanium electrodes have a similar behaviour, and exchange minimal current with the stainless steel electrodes. In particular, the current recorded from the steel was about one order of magnitude lower than that recorded for the titanium alloy. Furthermore, it is evident that one of the two steel specimens behaved as a preferential cathode, with the other as the preferential anode, with little current provided by the titanium electrodes.

Lastly, the low-frequency noise impedance calculated from the potential and current noises for all the electrodes are reported.
Both titanium electrodes displayed impedances in the region of $10^6$ Ohm cm$^2$ for the test duration, while the impedance from the stainless steel was close to $10^5$ Ohm cm$^2$ during the test duration. Three different crevices were tested, steel–steel, titanium–titanium and steel–titanium. Figure 8 reports both the potential and the current noises recorded during immersion in the 3.5% NaCl, and the low-frequency noise impedance and the resistance obtained by the previously mentioned method.

The steel potential was initially close to $-200$ mV (SCE) and it progressively drifted toward more negative values, reaching approximately $-300$ mV (SCE) at the termination of the experiment. Upon immersion, titanium displayed a potential of approximately 0 V SCE that suddenly dropped to $-350$ mV (SCE) after approximately one-half day of immersion. After the sudden drop to $-300$ mV (SCE), the potential recovered to a value of $-100$ mV (SCE) after immersion for 1 day. Subsequently, the potential progressively increased to approach a steady value of 0 V (SCE) at the end of the test. Several minor potential transients were evident after immersion for 7, 8, 9 and 11 days. The titanium alloy–stainless steel (Ti–SS) crevice showed a very low current, of the order of $10^{-1}$ mA, that was relatively stable for all the test duration. Finally, the stainless steel–titanium alloy crevice showed a similar current level of the order of $10^{-1}$ mA. The low-frequency noise impedances calculated from the potential and current noises for both stainless steel and the titanium alloy are presented in Figure 8. The steel impedance was stable for all the test duration with values of about $8 	imes 10^5$ Ohm cm$^2$. The titanium–titanium crevice displayed a low-frequency impedance that was slightly higher than $10^6$ Ohm cm$^2$, with significant oscillations during the later stages of the test. After the artificial crevice test, selected specimens were observed by SEM in order to evaluate the resulting corrosive phenomena. Scanning electron micrographs of both titanium alloy and stainless steel crevices are displayed in Figure 9. Pits were evident, both on the steel and titanium surfaces of the artificial crevices generated from the identical materials.
4 Discussion

During linear friction welding, a crevice can be generated close to the edge of the workpiece between the two dissimilar materials, and some microscopic material mixing is occasionally revealed on both sides of the crevice. The presence of such a crevice, formed by dissimilar metals, is of some concern in terms of corrosion resistance since a particularly aggressive microenvironment can be generated within the crevice, and the galvanic coupling effect between stainless steel and titanium may be potentially harmful.

From the polarisation curves acquired on single electrodes, it is evident that, in the short-term, the galvanic coupling effect between stainless steel and titanium alloy is not a significant issue, considering that shortly after immersion the two materials display similar corrosion potentials and similar cathodic activities. Furthermore titanium exhibits a well-extended passive region above the corrosion potential. However, on a longer term experiment, such as the 7-day test of Figure 6, it is evident that the potential of the titanium alloy tends naturally to increase with immersion time, while the potential of the steel is relatively stable. As a result, after 7 days of immersion, a potential difference of about 150 mV is available to drive corrosion on the stainless steel. However, if stainless steel and the titanium alloy are coupled together and the two materials have comparable areas, the high impedance of the titanium surface prevents a significant contribution to the cathodic current and the corrosion process on stainless steel should be little affected by the galvanic coupling with the titanium alloy. This is clearly evident from the experiment where a pair of stainless steel electrodes was coupled to a pair of titanium electrodes; the coupling current between the two nominally identical stainless steel electrodes was about one order of magnitude higher than the current due to the galvanic coupling with the titanium alloy electrodes. Accordingly, when galvanically coupled, the low-frequency noise impedances of both the titanium alloy and stainless steel were relatively close to the values measured for the individual materials alone. In summary, from the long-term galvanic coupling tests, it is disclosed that, over time, a significant driving force, in the region of 150 mV, can develop between stainless steel and titanium alloy. However, in the case of electrodes with comparable areas this does not increase significantly the corrosion rate of steel due to the high impedance of the passive titanium alloy. It should be noted, however, that galvanic corrosion issues might be possible if the area of the titanium exceeded largely the area of the stainless steel. In this case, the available driving force for galvanic corrosion remains unchanged, but the galvanic current increases proportionally with the exposed area of the titanium alloy surface.

Similar arguments apply to the simulated crevice experiments. Here, the coupling current between the two nominally identical steel electrodes largely exceeds the coupling current between the nominally identical titanium alloy electrodes and between the dissimilar titanium alloy and stainless steel electrodes. Thus, it can be concluded that, as in the case of separated electrodes, the galvanic coupling between stainless steel and the titanium alloy does not induce particularly severe corrosion on the stainless steel. Conversely, within the crevice, more significant

Figure 9. Scanning electron micrographs of the corroded zone in the simulated crevice. After the immersion test, some pits are evident for both stainless steel (a and b) and the titanium alloy (c and d)
corrosion compared with the case of a flat electrode is expected on both materials due to the generation of a more aggressive microenvironment of reduced pH and increased chloride concentration. This is confirmed by the micrographs of Figure 9, showing pitting on both the stainless steel and the titanium alloy within the crevice. Translating the findings to the practical case of a crevice generated during linear friction welding, it should be noted that the areas of the titanium alloy and stainless steel exposed to the crevice environment are always comparable as a result of the crevice geometry. Thus, considering the high specific impedance of the titanium alloy compared with stainless steel, it is expected that, for the crevice condition, the contribution to the corrosion of the stainless steel arising from the galvanic coupling with the titanium is negligible in most solutions. In practice, for the specific case of linear friction stir weld joints, concerns regarding corrosion susceptibility arise primarily from the presence of the crevice itself rather than from the two dissimilar materials being galvanically coupled and exposed to the crevice environment. On the other hand, a large titanium alloy/stainless steel surface area ratio could be an issue both for the corrosion within the crevice and for the corrosion of the macroscopic stainless steel electrode surface, but only under conditions where the part is immersed completely in a conductive electrolyte or a film of conductive electrolyte is continuously present on the surfaces of the parts.

5 Conclusions

The corrosion behaviour of a Ti6Al4V–A316 joint obtained by linear friction welding was investigated. It was found that both stainless steel and titanium show high corrosion resistance under coupled and uncoupled conditions over the time window inspected. The corrosion potential of stainless steel is relatively stable with time, while the corrosion potential of the titanium alloy increases progressively with time. This generates a potential difference that could potentially promote galvanic corrosion. The low-frequency noise impedance of the titanium alloy is generally at least one order of magnitude higher than that of stainless steel. As a result, although a potential difference is available, the contribution due to the titanium alloy on the corrosion of a stainless steel electrode of similar size is negligible. However, if the area of the titanium alloy electrode largely exceeds the area of the stainless steel electrode then such a contribution may become significant. The main potential corrosion issue associated with the presence of a crevice as the result of the linear friction welding process is the crevice itself, not that the materials forming the crevice are dissimilar. This is a consequence of the higher specific impedance of titanium and of the fact that the two sides of the crevice are, necessarily, of comparable areas.

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6 References

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