Adhesive Transfer operates during Galling

Samuel R. Rogers\textsuperscript{a,}\textsuperscript{*}, Jaimie Daure\textsuperscript{b}, Philip Shipway\textsuperscript{b}, David Stewart\textsuperscript{c}, David Dye\textsuperscript{a}

\textsuperscript{a}Imperial College, South Kensington, London SW7 2AZ, UK
\textsuperscript{b}University of Nottingham, University Park, Nottingham NG7 2RD, UK
\textsuperscript{c}Rolls-Royce plc, Raynesway, Derby DE21 7WA, UK

Abstract

In order to reduce cobalt within the primary circuit of pressurised water reactors (PWR’s), wear-resistant steels are being researched and developed. In particular interest is the understanding of galling mechanisms, an adhesive wear mechanism which is particularly prevalent in PWR valves. Here we show that large shear stresses and adhesive transfer occur during galling by exploiting the 2 wt.% manganese difference between 304L and 316L stainless steels, even at relatively low compressive stresses of 50 MPa. Through these findings, the galling mechanisms of stainless steels can be better understood, which may help with the development of galling resistant stainless steels.

There has been renewed interest in nuclear power generation in recent years, in an effort to reduce carbon emissions and reliance on fossil fuels. With new regulations and a desire to reduce cobalt in pressurised water reactor (PWR) primary circuits \cite{1} alternative materials are required. Of particular interest is the replacement of Stellite 6 (a cobalt hard-facing alloy) in valve seatings with a galling-resistant stainless steel alloy.

Galling is an adhesive wear mechanism which is known to result in severe surface degradation, and may result in sliding surfaces seizing \cite{2–4}. Whilst self-mated stainless steel is well documented to show poor galling resistance, particularly at elevated temperature, considerable efforts have been undertaken to develop a galling resistant stainless steel or iron-based hardfacing alloy \cite{2} \cite{5–17}.

Work has been produced which elucidates the galling mechanisms which may occur, many of these have been on self-mated test pairs, making adhesive transfer difficult to discern. Whilst a number of non self-mated tests have also been performed, the two materials are often found to differ quite considerably, be it through differing hardness, yield strengths, phases, microstructures or widely differing chemistries \cite{5} \cite{9} \cite{18} \cite{19}. This work seeks to address these issues, by performing non self-mated tests using two very mechanically similar stainless steels but which differ sufficiently in chemistry (namely molybdenum content) in order to observe any adhesive transfer which may have occurred.

Galling tests were performed using the ASTM G196 method, Figure \ref{fig:1}, under atmospheric conditions at the University of Nottingham. An applied compressive load of 50 MPa was used. 50 MPa was chosen since this would ensure that galling took place between the surfaces. Tests used non self-mated pairs of 314L/316L stainless steel. Virgin surfaces were used for each test. Surfaces had been ground to a finish of ± 10 μm.

Upon the completion of testing, the samples’ surfaces were scanned using white light interferometry.

Figure 1: (a) ASTM G196 galling rig, redrawn from \cite{4}; (b) ASTM G196 galling sample, with a section removed to enable a view of the radial cross-section; (c) top view of an ASTM G196 galling sample.

\*Corresponding author

Email address: srr13@ic.ac.uk (Samuel R. Rogers)
is seen to occur from surface (e) to (f), material has scars which are also seen. Although adhesive transfer galling scar, however, there are a number of smaller nal test, between surfaces (e) and (f) show a primary almost identical changes in volume, Figure 2. The fi- has also been lost from the system. When observing the rear of the galling peak, Figure 3(a) & (c), further portions of mechanically mixed 316L within the 304L peak can be seen. These are finer in width and longer, suggesting that they have undergone a greater extent of shear, and potentially mechanical mixing, than those towards the front of the galling peak, Figure 3(b). Flow lines are much more visible within both the galling peak and the substrate material at the peak rear.

When performing an EDX scan over the front portion of the galling peak, it can be seen that the predominant material of the peak is 304L stainless steel, as evidenced by its low Mo concentration, Figure 3(b), meaning that adhesive transfer of a significant volume has occurred. In addition, a portion of 316L appears to be mechanically mixed within the 304L peak, Figure 3(b). Whilst from this section alone, it is difficult to know how this material got there, by observing the mechanical mixing on the right of Figure 3(b), it can be seen that a small amount of the 316L substrate appears mixed into the 304L peak. It may therefore be that the larger portion of 316L within the peak has been mechanically mixed into the 304L. It is difficult to give certainty on this, however, since it could be that the 316L first transferred over to the 304L mating surface, before being mechanically mixed and transferred back to the the 316L mating surface.

When observing the rear of the galling peak, Figure 3(c) & (d), further portions of mechanically mixed 316L within the 304L peak can be seen. These are finer in width and longer, suggesting that they have undergone a greater extent of shear, and potentially mechanical mixing, than those towards the front of the galling peak, Figure 3(b). Flow lines are much more visible within both the galling peak and the substrate material at the peak rear.

With this information, we can refine the Archard adhesive wear mechanism [2], in order to include mechanical mixing within and between tribosurfaces, Figure 4. Two asperities come into contact and form an
Figure 2: White light interferometry height maps of 316L (a), (c) & (e) vs 304L (b), (d) & (f) stainless steel samples tested at various loads in the non-oxidised conditions, with their corresponding height scales and quantification measures. Tests were paired in the following way: (a) & (b), (c) & (d) and (e) & (f). The red dashed line on sample (c) denotes the cross-section which was used to image Figures 3 and 4.

| Sample | Applied Stress / MPa | Sample Height / μm | Galled Area / % | ∆V / mm³ |
|--------|----------------------|--------------------|-----------------|-----------|
| (a)    | 50                   | 257 -233           | 490             | 12.04     | -0.2440  |
| (b)    | 50                   | 162 -182           | 344             | 18.61     | -0.0916  |
| (c)    | 75                   | 262 -126           | 388             | 19.75     | +0.3068  |
| (d)    | 75                   | 171 -219           | 390             | 18.87     | -0.3005  |
| (e)    | 100                  | 198 -237           | 435             | 21.69     | -0.2533  |
| (f)    | 100                  | 270 -175           | 445             | 16.82     | +0.0121  |

adhesive junction, Figure 4(a), subsequent shearing of this junction results in wedge formation (this can also occur through the shearing of two flat surfaces that have adhered), Figure 4(b). At this point, the mechanism can continue in one of two ways: Figure 4(c), material from both tribosurfaces causes wedge growth to such an extent that excess material ahead of the prow folds over, whilst shear failure occurs behind the prow, resulting in the formation of lips, or; Figure 4(d) material from one tribosurface preferentially supplies material for wedge growth, resulting in a very large wedge on one tribosurface and a considerably smaller wedge on the opposing surface. The mechanism as shown in Figure 4(d) was found to primarily occur in this work. Whilst appearing consistent for the stainless steel pairings tested in this work and in [2], this mechanism may be one of a number of galling mechanisms. In addition, further work is needed to fully understand galling initiation.

Across the circumferential cross-section viewed in Figure 3, an additional smaller galling peak can be also be seen, Figure 5. If this small peak is mapped using EDX, it can be seen that unlike in Figures 3, the entirety of the peak appears to be made up of a number of mechanically mixed regions of 304L and 316L stainless steels, Figure 5. Given that the regions of 304L seem to be isolated within the 316L material within the peak, that all regions of 304L appear relatively thin and long, and that the volume of 316L material within the peak does not appear to have all come from this galling trough, it appears an alternative explanation for the galling peak morphology is required. The most likely possibility is that multiple instances of galling and adhesive transfer have
Figure 3: A circumferential cross-section of a galling peak of 316L stainless steel, Figure 2(c), from a non self-mated test of 304 vs 316L stainless steel sample tested at a normal load of 75 MPa. (a) The whole peak as viewed using SE imaging; (b) Mo EDX map of the peak front; (c) peak rear as viewed using SE imaging; (d) Mo EDX map of the peak rear.

Figure 4: A refinement of the Archard adhesive wear mechanism (wedge formation and growth mechanism) \[2\], with the addition of material flow, as described using colour co-ordinated arrows based on the observation from this work.

occurred, resulting in a galling peak with a layered internal structure, Figure 5(d), and when considering the volume of 316L, a peak which is considerably larger than the associated trough size would suggest.

In summary, as with self-mated 316L stainless steel, non self-mated 304L vs 316L galling pairs appear to gall via the wedge formation and growth, or Archard adhesive wear, mechanism. Due to chemical variations between the two alloys (namely the incorporation of molybdenum in 304L), adhesive transfer was observed between surfaces. Mechanical mixing between surfaces was also observed, in addition to the previously observed mechanical mixing in a single surface. A series of smaller galling peaks were observed to have formed, likely through successive galling and adhesive transfer events.

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