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Effects of temperature and contact stress on the sliding wear of Ni-base Deloro 50 hardfacing alloy

Seon–Jin Kim, Jun–Ki Kim [*]

Department of Materials Science and Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul, 133-791, South Korea

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Abstract

The sliding wear behavior of Ni-base Deloro 50 hardfacing alloy was investigated in air in the temperature range from room temperature to 350°C under contact stresses of 55, 103 and 207 MPa. At temperatures below 100°C, Deloro 50 showed severe adhesive wear and as a result the amount of wear loss was very large regardless of contact stress. With increasing temperature over 100°C, however, the amount of wear loss decreased and reached eventually to near zero value at temperatures of 200°C, 225°C and 250°C under the corresponding contact stresses of 55, 103 and 207 MPa, respectively. It was found that the decrease of the amount of wear loss was due to the wear transition from severe adhesive to mild oxidative wear which was caused by the formation of wear protective oxide layers on wear surfaces. It was considered that if the temperature was high enough to meet the oxidative wear condition, Deloro 50 could be used as hardfacing material for nuclear power plants valves even under the high contact stress of 207 MPa. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Co-base Stellite alloys have traditionally been used as hardfacing materials for nuclear power plant valves owing to their high corrosion resistance and superior wear resistance under sliding conditions [1]. However, it was found that the Stellite used in valve hardfacing is one of the main sources of Co which is the major contributor of the radiation exposures in nuclear power plants [2,3]. Thereafter, cobalt-free hardfacing alloys, such as Fe-base and Ni-base alloys, have been developed to replace Stellite [2–7].

It has been reported that Ni-base hardfacing alloys exhibited lower wear resistance than Stellite and Fe-base hardfacing alloys in general [3–6]. Thus, their use in nuclear power plant valves was restricted to the low contact stress level, below 103 MPa, while Fe-base hardfacing alloys were being considered as candidates for the higher stress level valves [3].

However, it was reported that the field performance of valves hardfaced with Ni-base alloys was generally acceptable [5]. Moreover, Ni-base hardfacing alloys have shown better wear resistance than Stellite and Fe-base hardfacing alloys under a contact stress of up to 207 MPa in 280°C BWR condition [7]. Therefore, it is expected that Ni-base hardfacing alloys could be more appropriate substitutes for Stellite alloys than Fe-base alloys at the elevated temperature.

Unfortunately, however, little has been known about the wear mechanism of Ni-base hardfacing alloys to explain their extraordinary wear behavior at the elevated temperature. In this study, the effects of temperature and contact stress on the wear of Deloro 50™, which is a representative Ni-base hardfacing alloy having been used as Stellite substitute in some nuclear power plants, were investigated in air at the temperature ranging from room temperature to 350°C under contact stresses from 55 to 207 MPa.

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[*] Corresponding author. Tel.: +82-2 2290 0406; fax: +82-2 2293 7844.

E-mail address: alloylab@email.hanyang.ac.kr (J.-K. Kim).

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2. Experimental procedure

2.1. Specimen

Deloro 50 was deposited on 12 mm thick 304 stainless steel plate by gas tungsten arc welding (GTAW). The GTAW condition was described elsewhere [6]. After two-layer deposition, weld specimens were machined into test specimens as presented in Fig. 1. Wear test surfaces were polished to a roughness value R_a less than 0.02 μm by grinding with 2000 grit SiC abrasive paper. The thickness of weld overlays remained after final grinding was about 2.5–3 mm. The chemical composition of wear test specimen was measured by ARD 3460 optical emission spectroscopy and is presented in Table 1. As presented in Fig. 2, the wear test specimen had a typical microstructure of Deloro 50 having chromium boride phases in the microstructure [6]. The Rockwell hardness of the wear test specimen was 46 HRC.

2.2. Sliding wear test

The block-on-block type sliding friction machine supplied by Plint & Partners was used for high load sliding tests. The self-mated tests were performed in air in the temperature range from room temperature to 350°C under contact stresses of 55, 103 and 207 MPa. These contact stresses were chosen to cover the overall contact stress between a disk and seat in gate valves in nuclear power plants [8]. The sliding speed was 3 mm/s and the sliding stroke was 9 mm. The total weight loss of the moving disk and the fixed plate was measured after 100 cycles of sliding test. More than three replicate tests were performed to obtain reliable data. The relative deviation of the amount of wear loss between tests was about ±10% under adhesive wear conditions and about ±5% under oxidative wear conditions.

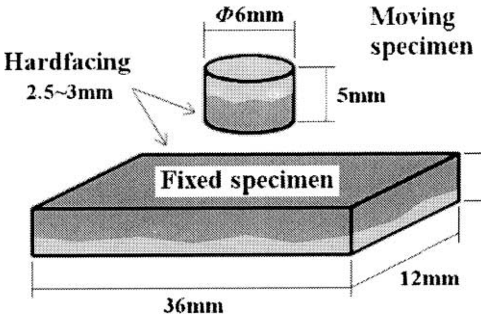

Fig. 1. Geometry of wear test specimens.

Table 1
The chemical composition of Deloro 50 wear test specimen (wt%)

Chemical composition	Ni	Cr	Fe	Si	C	B
Nominal	bal.	12	3.5	3.5	0.6	2.0
Analyzed	bal.	11.58	4.02	3.73	0.47	2.12

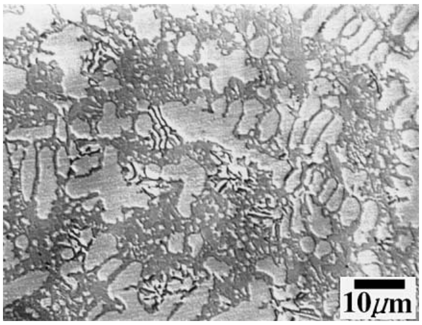

Fig. 2. Microstructure of Deloro 50 wear test specimen.

2.3. Examination of worn surfaces

The worn surfaces of Deloro 50 tested at various temperatures under various contact stresses were examined by scanning electron microscope (SEM) and wavelength dispersive spectroscopy (WDS). Cross-sections of worn surface and wear debris particles were examined by optical microscope, SEM and WDS.

3. Results and discussion

3.1. The effect of temperature

Wear losses of Deloro 50 as a function of temperature after 100 cycles sliding tests under contact stresses of 55, 103 and 207 MPa are presented in Fig. 3. As shown in Fig. 3, under all the contact stresses the amount of wear loss was very large at room temperature and increased slightly with increasing temperature up to 100°C. With further increase of temperature above 100°C, however, the amount of wear loss decreased and reached eventually to near zero value. The temperature at which Deloro 50 began to show no wear loss was about 200°C under a contact stress of 55 MPa and increased to 225°C and 250°C with increasing contact stress to 103 and 207 MPa, respectively.

The worn surfaces of Deloro 50 tested at various temperatures under a contact stress of 103 MPa are presented in Fig. 4. As shown in Figs. 4(a)–(c), worn surfaces tested at temperatures below 200°C were severely damaged by adhesive wear. Above 225°C, however, the worn surfaces were very smooth and covered partially by flat layers as shown in Figs. 4(d)–(f). These layers were identified as Ni-base oxides from WDS an-

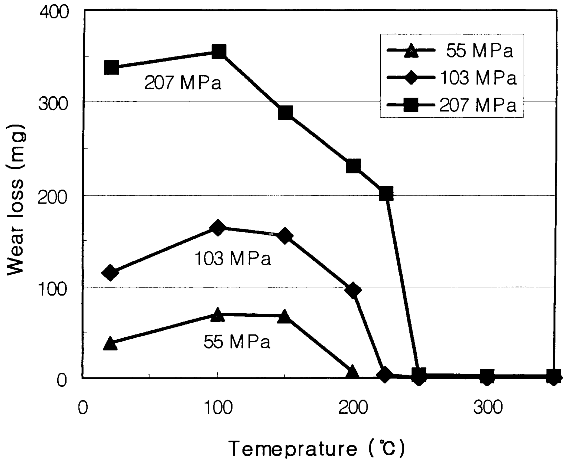

Fig. 3. Wear losses of Deloro 50 as a function of temperature after 100 cycles sliding tests in air under contact stresses of 55, 103 and 207 MPa.

alyses as shown in Fig. 5. Scratch marks observed on these oxide layers indicate that oxide layers prevented wear surfaces from the direct metal-to-metal contact and consequently inhibited adhesive wear. Accordingly, it was considered that the near zero amount of wear loss of Deloro 50 at the elevated temperature is due to the formation of oxide layers on wear surfaces.

It is well-known that, during sliding wear of metals, a transition from severe to mild wear can occur due to the formation of wear protective oxide layers [9–11]. This phenomenon is known as oxidative wear. Recently, three mechanisms have been proposed to explain the oxidative wear at elevated temperature, namely, the 'metallic-debris' mechanism, the 'oxidation-scrape-reoxidation' mechanism and the 'total-oxidation' mechanism [9]. An important issue addressed by these models is that wear debris particles play an important role in the formation of wear protective oxide layers. According to Jiang et al. [10], the wear protective oxide layers are formed by following steps: the generation of large wear debris particles, fragmentation to small debris particles, oxidation, agglomeration and compaction on wear surfaces.

Cross-sections of wear debris particles generated during 100 cycles sliding test at various temperatures under a contact stress of 103 MPa are presented in Fig. 6. From the WDS analyses, it was found that wear debris particles generated at temperatures corresponding to near zero wear loss are composed of matrix metal and its oxide. These agglomerated features of wear debris particles can support the oxidative wear mechanism in which wear protective oxide layers are formed by the compaction of oxidized wear debris particles. Therefore, it was concluded that the decreased wear loss and the improved wear resistance of Deloro 50 at elevated temperature was due to the wear transition from adhesive to oxidative wear by the formation of wear protective oxide layers.

3.2. The effect of contact stress

As one can see in Fig. 3, the temperature at which Deloro 50 began to show near zero wear loss increased with increasing contact stress. Worn surfaces tested at various temperatures under contact stresses of 207 and 55 MPa are shown in Figs. 7 and 8, respectively. As

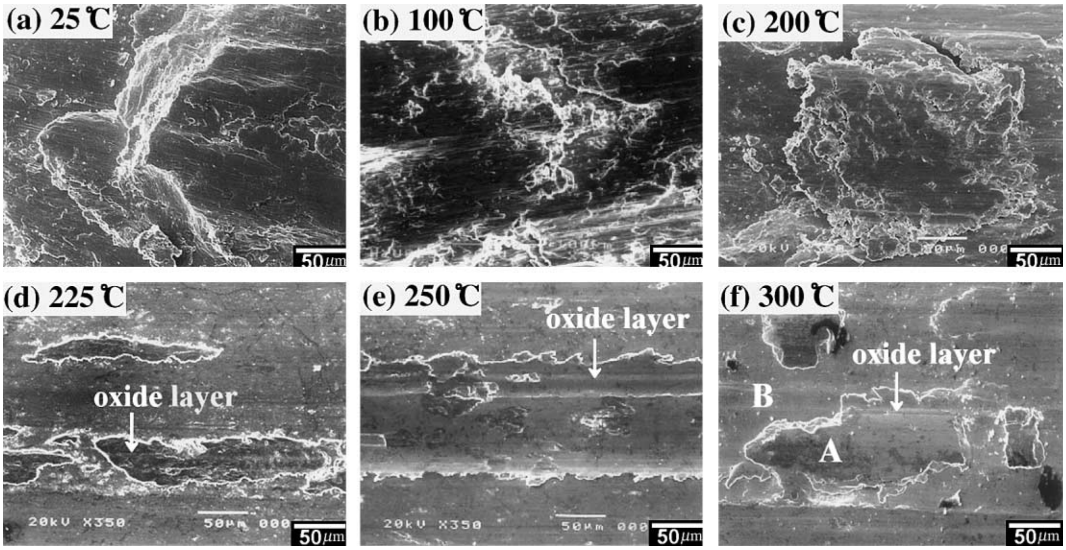

Fig. 4. SEM micrographs of worn surfaces of Deloro 50 after 100 cycles sliding tests at various temperatures under a contact stress of 103 MPa.

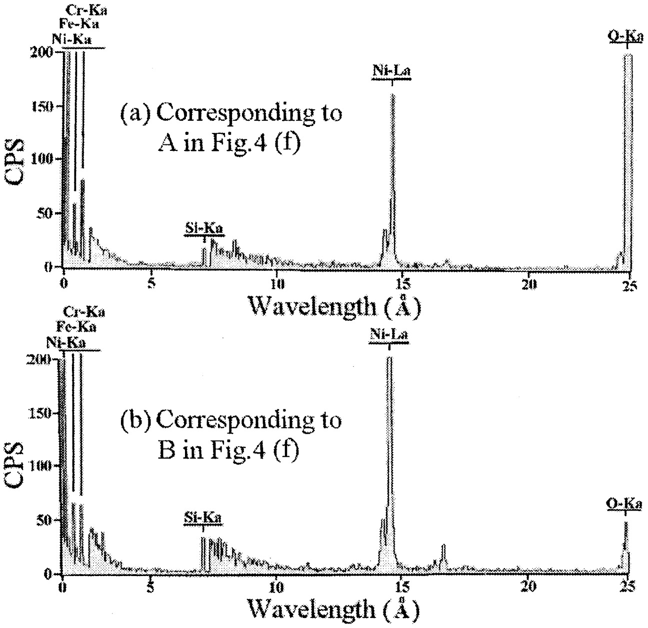

Fig. 5. WDS analyses of Deloro 50 worn surface tested at 300°C under a contact stress of 103 MPa, shown in Fig. 4(f).

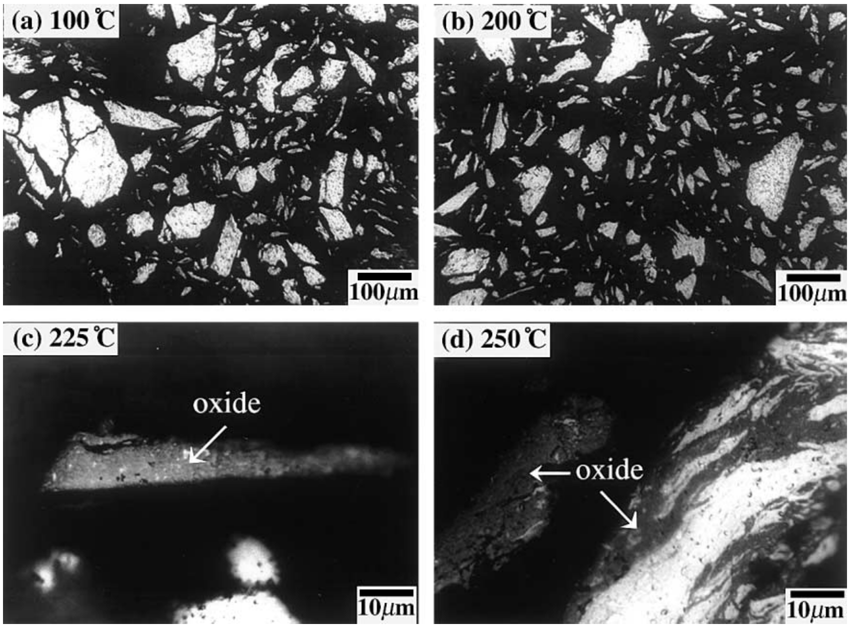

Fig. 6. Cross-sections of wear debris particles of Deloro 50 generated during sliding test at various temperatures under a contact stress of 103 MPa.

shown in Fig. 7, under the high contact stress of 207 MPa oxide layers began to be observed on the wear surface at the temperature of about 250°C. It is consistent with the temperature corresponding to near zero wear loss as shown in Fig. 3. Under the low contact stress of 55 MPa, the temperature, at which oxide layers were observed, decreased to about 200°C as shown in Fig. 8(c).

Cross-sections of wear debris particles generated during 100 cycles sliding test at various temperatures

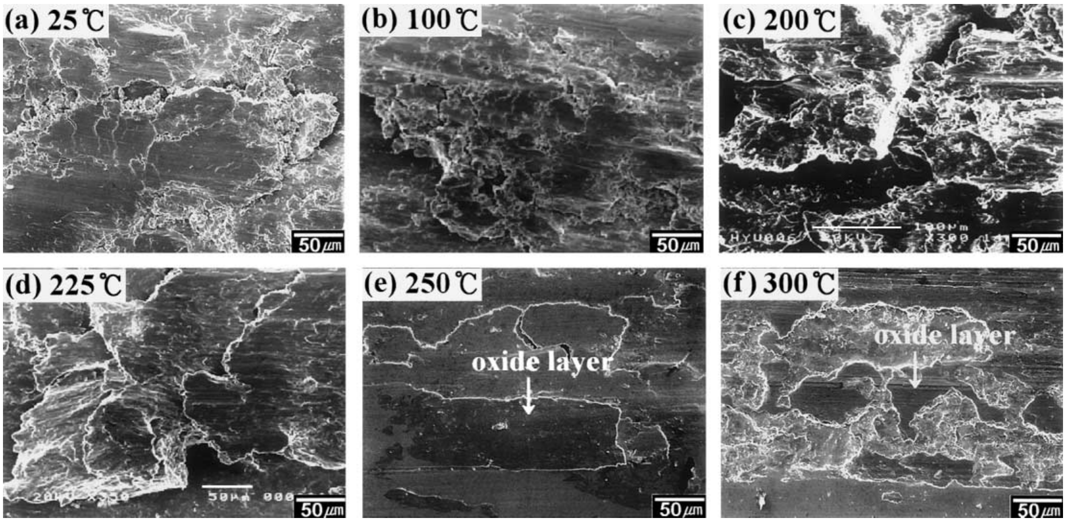

Fig. 7. SEM micrographs of Deloro 50 worn surfaces after 100 cycles sliding tests at various temperatures under a contact stress of 207 MPa.

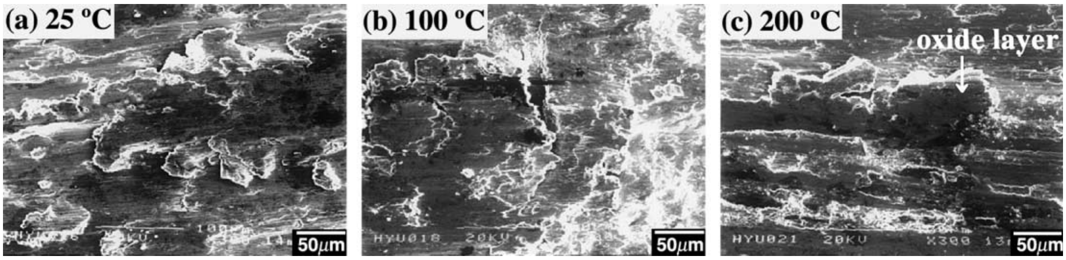

Fig. 8. SEM micrographs of Deloro 50 worn surfaces after 100 cycles sliding tests at various temperatures under a contact stress of 55 MPa.

under contact stresses of 207 and 55 MPa are presented in Figs. 9 and 10, respectively. As shown in Figs. 6, 9 and 10, the larger wear debris particles were generated with increasing contact stress. It is due to the increased depths of deformation layers on the wear surfaces [12]. Large wear debris particles are less likely to be entrapped within wear tracks and agglomerate to form compact wear protective layers [10]. The oxide wear debris particles observed after 100 cycles sliding test at 200°C under the contact stress of 103 MPa and at 225°C under the contact stress of 207 MPa, in which the adhesive wear was dominant, are presented in Fig. 11. It indicates that although the temperature was sufficiently high for the oxidation of wear debris particles, the stable wear protective compact oxide layers could not be formed under high contact stress. It was considered to be due to

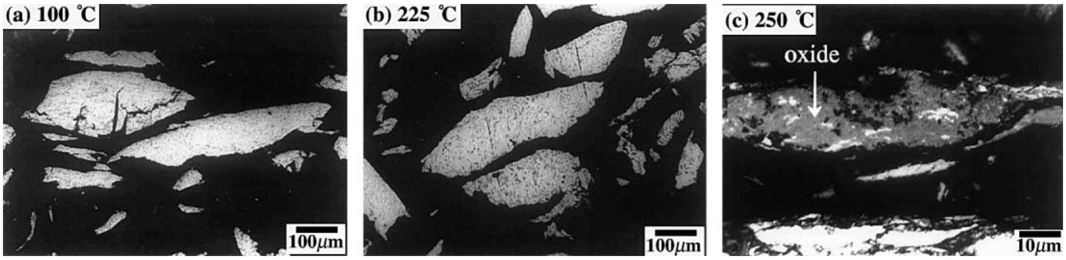

Fig. 9. Cross-sections of wear debris particles of Deloro 50 generated during sliding test at various temperatures under a contact stress of 207 MPa.

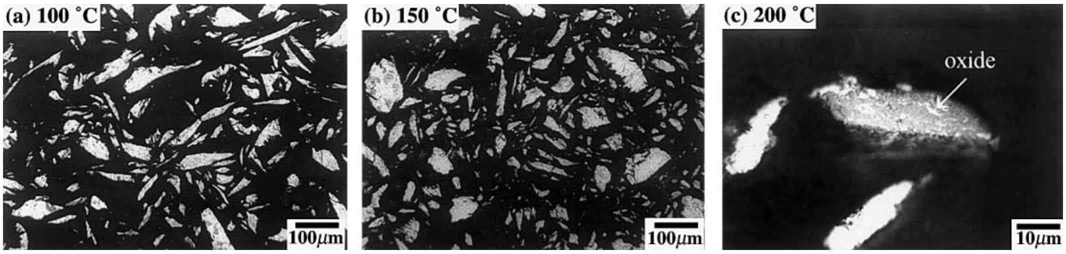

Fig. 10. Cross-sections of wear debris particles of Deloro 50 generated during sliding test at various temperatures under a contact stress of 55 MPa.

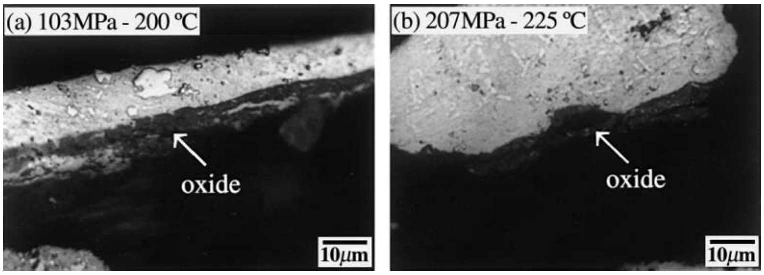

Fig. 11. Cross-sections of wear debris particles of Deloro 50 generated during sliding test at 200°C and 225°C under contact stresses of 103 and 207 MPa, respectively.

the fact that as the contact stress increases at a given temperature, the amount of oxide debris particles involved in forming wear protective oxide layers decreases.

According to the model proposed by Jiang et al. [10], the development of wear protective oxide layers is not controlled by oxidation processes but is closely related to the adhesion between wear debris particles within the wear surfaces. The major effect of increased temperature on wear is that more wear debris particles are involved in the development of the compact wear protective layers due to the increased physical adsorption interactions between solid surfaces [10]. Therefore, it was considered that the increase of the temperature corresponding to near zero wear loss of Deloro 50 with increasing contact stress is mainly due to the fact that the higher temperature is required under higher contact stress to make the more oxide debris particles involved in forming the compact oxide layers.

In general, there exists upper margin of oxidative wear that the amount of plastic shearing on wear surfaces is tolerable [11]. Under such a condition, if the contact stress is increased, the wear immediately becomes a severe adhesive wear. The fact that Deloro 50 maintained the mild oxidative wear up to 350°C under high contact stress of 207 MPa in air manifests that the amount of plastic shearing on wear surfaces is tolerable under that condition. In water environment, like in a light water reactor, the formation behavior and properties of oxide layers could be different from those found in air environment. Unfortunately, it has not been reported yet how the wear mechanism of Deloro 50 would be changed in the high temperature water. However, it can be expected from the experimental result by Wang et al. [7], in which Deloro 50 showed wear resistance as good as Stellite 6 at 280°C BWR condition under the contact stress of up to 207 MPa. This experimental result indicates that the water does not exert negative effect on the high temperature wear of Deloro 50. In addition, it is well-known that the water molecules prohibit the direct metal-to-metal contacts and, consequently, reduce the adhesive wear [13,14]. Therefore, it is concluded that if the temperature is high enough to meet the oxidative wear condition, Deloro 50 can be used as hardfacing material for nuclear power plants valves even under the high contact stress of 207 MPa.

4. Conclusions

1. Deloro 50 showed a large amount of wear loss at low temperatures even under a contact stress of 55 MPa. However, it showed near zero amount of wear loss at elevated temperature even under a contact stress of 207 MPa. The decrease of the wear loss of Deloro 50 with increasing temperature was considered to be due to the formation of wear protective oxide layers on wear surfaces.

2. The temperature at which Deloro 50 began to show near zero wear loss was increased from 200°C to 250°C with increasing contact stress from 55 to 207 MPa. It was considered mainly due to the fact that the higher temperature is required under higher contact stress to make the more oxide debris particles involved in forming the compact oxide layers.
3. The increase of temperature up to 350°C and contact stress up to 207 MPa in air did not corrupt the oxidative wear behavior of Deloro 50. Therefore, it is concluded that if the temperature is high enough to meet the oxidative wear condition, the Deloro 50 can be used as hardfacing material for nuclear power plants valves even under the high contact stress of 207 MPa.

Acknowledgements

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