Tribological behaviour of AFNOR grade Z6 NCT DV 25-15 precipitation hardening austenitic stainless steel with NiCr-B coating in high temperature liquid sodium

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Abstract

The sliding wear and friction behaviour between AFNOR Grade Z6 NCT DV 25-15 precipitation hardening austenitic stainless steel and NiCr-B hardface coating was investigated in high purity liquid sodium at 823 K employing an indigenously developed reciprocating-type tribometer. The specimens for testing were in the form of pins and disc, with two pins in contact with both the surfaces of a disc specimen. The pin and disc specimens were made from precipitation hardened Z6 NCT DV 25-15 alloy and NiCr-B alloy deposited on 316L stainless steel substrate using Plasma Transferred Arc (PTA) welding process respectively. Testing was carried out at sliding speeds of 2 mm/s for a total sliding distance of 200 m under contact stress of 10 and 20 MPa respectively. The static friction coefficient (μ_s) and dynamic friction coefficient (μ_d) were estimated from the maximum value of friction force at the start of the movement and from the friction force measured during movement respectively. In both the tests μ_d was found to be significantly lower than μ_s. Weight loss measured for both the pins and disc at the end of the tests were negligible and this indicates that wear is very low in both the tests carried out at contact stress of 10 and

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20 MPa. Worn scar profilometry on disc specimens was also carried out using Talysurf CLI 1000 Optical Profilometer with laser triangulation gauges, which revealed scars with larger scar depth on disc tested at 20 MPa stress level than on disc tested at stress level of 10 MPa. Scanning Electron Microscopy (SEM) on worn disc specimens revealed the presence of deformed and delaminated layer zone in both the cases. However this was significantly more in disc tested at 20 MPa, which is due to higher localized stress between rubbing surfaces at this stress level. It is concluded from this study that the static and dynamic friction coefficients (μ_s and μ_d) values are about 0.2 and 0.10 obtained at 20 MPa which are more than the friction coefficients values of about 0.11 and 0.05, respectively, at 10 MPa stress level. This is attributed to higher surface degradation caused by deformation and delamination at 20 MPa stress than at 10 MPa stress level. Results also indicate negligible wear loss in liquid sodium, which could be due to the lubricating action of liquid sodium.
Keywords: liquid sodium, reciprocating-type tribometer, friction coefficient, wear, pin-on-disc, optical profilometer.

1 Introduction

In Prototype Fast Breeder Reactor (PFBR), there are two types of absorber rods for control and shut down of the reactor. These are Control and Safety Rod (CSR) and Diverse Safety Rod (DSR). The mechanisms that handle the above two rods are Control and Safety Rod Drive Mechanism (CSRDM) and Diverse Safety Rod Drive Mechanism (DSRDM) respectively [1].

CSRDM consists of two parts, viz., upper part and lower part. The lower part is partially immersed in hot pool sodium and the upper part is in Reactor Containment Building (RCB) environment. The lower part consists of mobile translation tube with gripper body at its bottom end, gripper operating system and stationary sheath. The head of CSR is mechanically coupled with mobile assembly of CSRDM by gripper fingers. Gripper is operated manually from the top of CSRDM at a height of about 12 m. During normal operation and scram of the reactor, the mobile CSR is in coupled state with the gripper and before fuel handling operation, CSR is released from the gripper.

The gripper fingers (3 Nos.) hang from the fork and oscillate over the axle pins. They travel maximum by 120 mm while latching CSR head from gripper assembly. Due to the slot and pin arrangement, the fingers slide straight while translating from the top for the first 100 mm travel and open or close for the remaining 25 mm travel. The slotted fingers slide over the guide pins. The fingers and the pins are made of precipitation hardened austenitic stainless steel, Z6 NCT DV 25-15 and the bushes, provided between them, are made of NiCr-B deposits. There is oscillatory motion between the axle pin and bush and sliding motion between the finger and bush. During operation, these mating surfaces can experience frictional force that can influence the movement of the whole mechanism. This frictional force mainly depends on the materials in contact and the temperature of the sodium.

Various types of steels have been tested for wear and friction behaviour in sodium environment. Wild and Mach [2] carried out tribological tests on austenitic (1.4961) and ferritic (1.6770) steels in sodium. In their studies, coefficients of friction measured were less than 0.9 and 1.2 for austenitic and ferritic steels respectively. Also it was seen that the coefficients of friction was functions of temperature of the sodium and the contact stress. Studies by Radcliffe [3] showed low value of friction coefficients of about 0.7 and 0.45 in hot-trapped sodium and impure sodium for AISI 316 stainless steel. In another studies on 15Cr-15Ni-2Mo Titanium modified austenitic stainless steel by Kumar *et al.* [4] have shown that the friction coefficients are also dependant on sodium temperature.

Thus, it is of interest to study the friction and wear behaviour between Z6 NCT DV 25-15 precipitation hardened austenitic stainless steel and NiCr-B deposit in reactor-grade sodium under reactor operating conditions. This paper discusses the results of friction and wear test carried out on above material combination at 823K under contact stress of 10 and 20 MPa.

2 Materials investigated

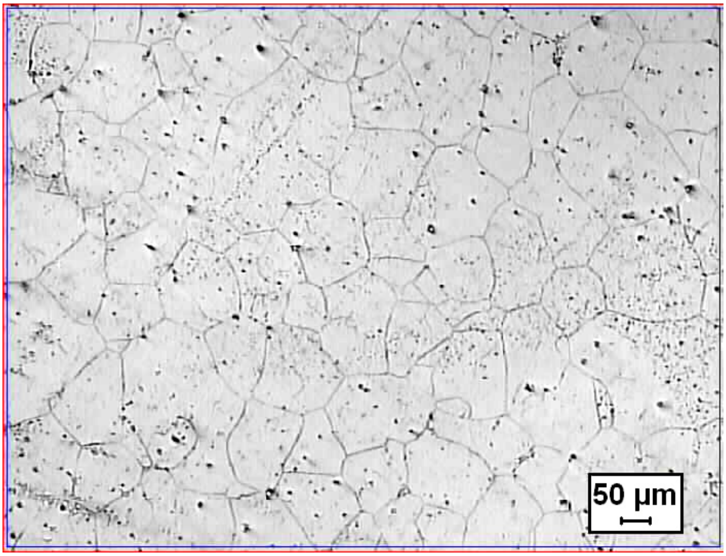
AFNOR Grade Z6 NCT DV 25-15 precipitation hardened stainless steel, which has similar coefficient of thermal expansion as that of austenitic stainless steels, has been chosen for fingers and pins in CSRDM. The chemical composition of this material is given in Table 1. This material is used in heat-treated condition as per French code RCC-MR [5]. Hence, disc specimens were made from heat treated rods of this material which were subjected to solution heat treatment at 980°C ± 10°C for 1 h, oil quenching, aging at 725°C ± 10°C for 4 h, cooling at 5°C/h to 575°C, holding at 575°C ± 10°C for 30 h, and cooling in still air. After this heat treatment, the room temperature hardness was found to be 316 VHN at 5 Kg load.

The pin specimens were prepared by depositing NiCr-B on 304L stainless steel substrate using gas tungsten arc welding (GTAW) process. The coating thickness on the pins was approximately 2 mm after machining. The room

Table 1: Chemical composition of Z6 NCT DV 25-15 alloy.

Elements	**wt %**
Ni	25.25
Cr	14.69
C	0.038
Mn	1.36
Mo	1.27
Si	0.48
V	0.26
Al	0.18
Ti	1.90
B	0.005
Fe	Bal

temperature hardness on the surface of the deposit was found to be 470 VHN at 5 Kg load. Table 2 shows the chemical composition of the NiCr-B rod employed for deposition. The welding parameters employed are given in Table 3. Figs 1(a) and 1(b) show the microstructures of the Z6 NCT DV 25-15 precipitation hardened stainless steel and NiCr-B deposit.



(a)

(b)

Figure 1: Microstructure of (a) Z6 NCT DV 25-15 precipitation harden alloy and (b) NiCr-B deposit used for wear and friction studies.

Table 2: Chemical composition of NiCr-B rod.

Elements	wt%
Cr	11.56
C	0.53
Si	3.87
B	2.03
Fe	3.97
Co	< 0.25
Ni	Bal

Table 3: GTAW welding parameters used for depositing NiCr-B alloy.

Welding current (A)	120-140
Welding voltage (V)	22
Shielding gas flow rate (lpm)	5-6
Electrode polarity	DC
2% thoriated tungsten electrode diameter (mm)	3

3 Parameters for in-sodium friction and wear test

The test parameters used for friction and wear studies are given in Table 4.

Table 4: Parameters for friction and wear test between Z6 NCT DV 25-15 alloy and NiCr-B deposit.

Material combination	Z6 NCT DV 25-15 alloy and NiCr-B deposit
Operating temperature	823 K
Contact stress	10 and 20 MPa
Sliding speed	2 mm/s
Sliding distance	200 m
Operating medium	Flowing Sodium (O_2 < 3 ppm)

4 Experimental procedure

The in-sodium friction and wear tests were carried out using a pin-on-disc, uniaxial reciprocating-type tribometer (Fig. 2). The static specimens, viz. the pins, were clamped to the specimen holder of the load lever. The reciprocating specimen, viz. the disc of 24 mm diameter and 8 mm thickness, was clamped to the lower specimen holder of reciprocating lever. For these tests, 10 MPa and 20 MPa stress and 6 mm stroke length were used. Testing was carried out at sliding velocity of 2 mm/s for a total travel distance of 200 m. The frictional forces between the pin and disc specimens were continuously measured by a load cell, and the friction coefficients were calculated by using equation:

$$\text{Friction coefficient } (\mu) = F/N \tag{1}$$

where F is the friction force (in Newtons) and N is the normal load [0.67 x load on pneumatic cylinder] (in Newtons). The static friction coefficient (μ_s) was estimated from the maximum value of frictional force at the start of movement, while the dynamic friction coefficient (μ_d) was estimated from the dynamic friction force measured during movement.

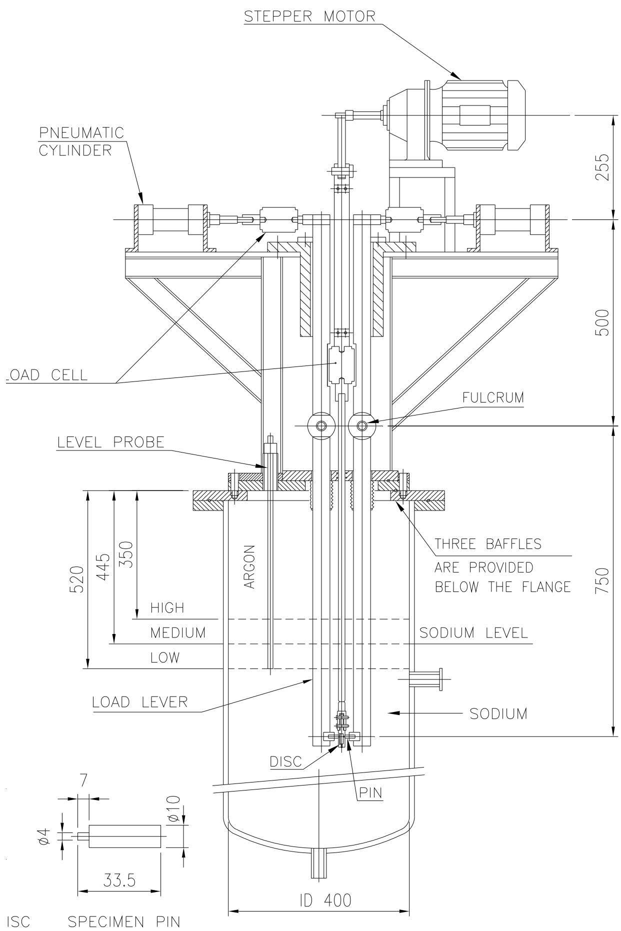


Figure 2: Reciprocating-type in-sodium tribometer.

Prior to assembling the disc and pin specimens in the in-sodium tribometer, all were properly cleaned with acetone and each was weighed using weighing machine of 1 mg (0.001 gm) accuracy. The frictional loads were measured using a calibrated load cell and the frictional forces were estimated from these loads. The static and dynamic friction coefficients were calculated using equation (1). After testing, all the disc and pins specimens were cleaned with alcohol, dried and weighed to estimate the weight loss due to wear.

5 Results and discussion

The results of in-sodium friction and wear test, along with wear loss data, for Z6 NCT DV 25-15 against NiCr-B coating are given in Table 5. The wear losses of both pin specimens are negligible at both the stress, while a small gain in discs weight are observed. This gain in discs weight is due to presence of chemical products on the disc surfaces, which formed during cleaning operation. With increasing stress, a slight increase in disc wear is observed. Fig. 3 shows the Z6 NCT DV 25-15 disc and NiCr-B pin specimens after testing at 10 MPa stress. In both the tests, the surface damage was low. This is due to high hardness of the material under investigation.

Table 5: Test parameters and wear loss in-sodium for disc and pins.

Specimen	Load (MPa)	Initial weight (gm)	Final weight (gm)	Weight loss (gm)
Disc 1	10	28.861	28.863	- 0.002
Pin 1 (Left)		17.110	NA	-
Pin 1 (Right)		17.185	17.185	0.000
Disc 2	20	28.048	28.053	- 0.005
Pin 2 (Left)		17.004	NA	-
Pin 2 (Right)		16.865	16.864	0.001

Figure 3: Disc and pins specimens of Z6 NCT DV 25-15 and NiCr-B after in-sodium testing at 10 MPa.

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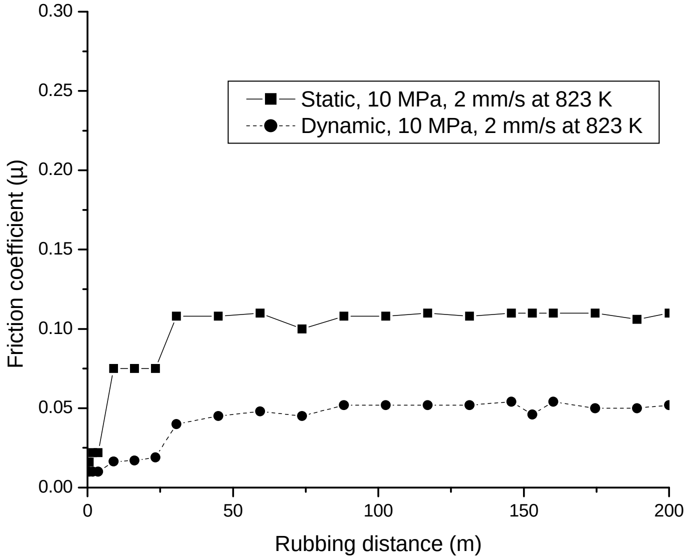
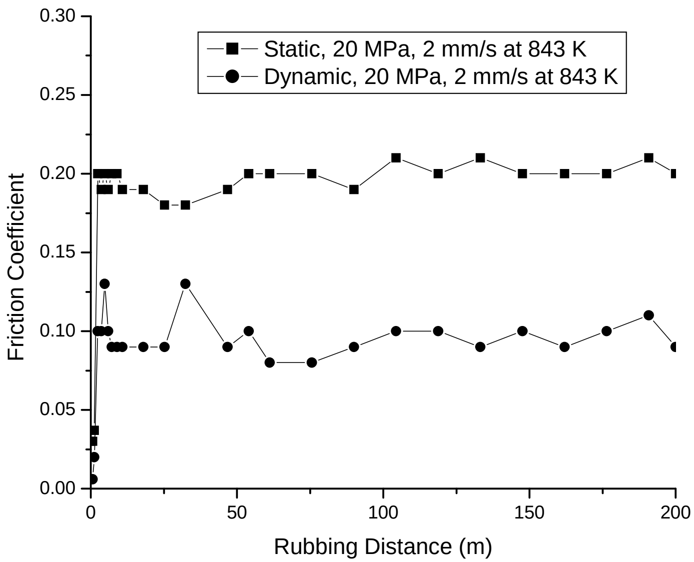


(a)



(b)

Figure 4: Friction coefficients of Z6 NCT DV 25-15 alloy vs. NiCr-B at (a) 10 MPa and (b) 20 MPa in sodium at 843 K.

The static and dynamic friction coefficients were calculated from the applied normal load and the measured frictional force. Fig. 4 (a) and Fig. 4 (b) show the variation of static and dynamic friction coefficients with rubbing distance for the present test conditions at 10 and 20 MPa contact stress respectively. As expected, the static friction coefficient μ_s is higher than the dynamic friction coefficient μ_d for tests conducted at both the stress level. The static and dynamic friction coefficients (μ_s and μ_d) are significantly higher at 20 MPa compared to friction coefficients obtained at 10 MPa. The average dynamic friction coefficient (μ_d) is 0.05 at 10 MPa and 0.10 at 20 MPa. This increase in friction coefficient is mainly due to increase in the load level, which allows asperities in contact to deform more and hence more resistance against rubbing. The variation in the friction coefficients with increasing rubbing distance and rubbing time is also marginal only. From Fig. 4(a) it is also observed that the friction coefficients, which are initially very low, stabilize only beyond 30 m of rubbing distance due to removal of the oxide layer and asperities during initial period of testing. In the present tests, the oxygen content in the sodium was not very high and hence it can be concluded from this study that adsorption and lubrication mechanism is the reason for low friction coefficients for this materials combination in the sodium environment.

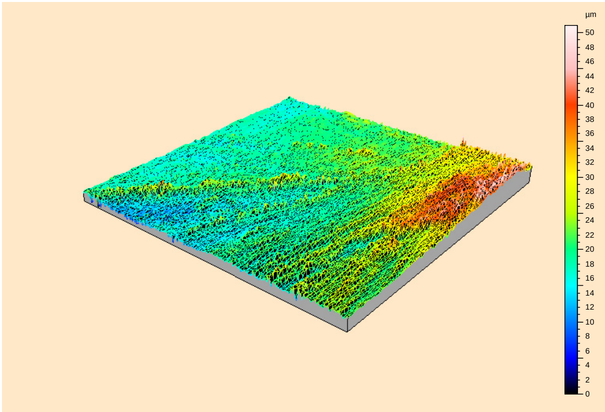
Surface damage due to wear was analysed by looking at the rubbed area on the disc specimens by Talysurf CLI 1000 Optical Profilometer with laser triangulation gauges. Less surface damage was observed in the disc specimen tested at 10 MPa stress level compared to the disc tested at 20 MPa stress level. Fig. 5(a) and Fig. 5(b) show images of the 2 mm^2 area of worn disc after 10 MPa and 20 MPa test, respectively. From these images, it is clear that the extent of disc damage is more in case of disc tested at 20 MPa. Also higher friction coefficients for test conducted at 20 MPa than the test at 10 MPa is supported by this damage in the former than the later.

Scanning electron microscopy (SEM) photographs of worn disc specimens (Figs 6 and 7) revealed the presence of deformed layer in both the discs tested at 10 and 20 MPa. Adherence of wear particles at few locations were seen in the disc tested at 10 MPa (Fig. 6), while evidence of more deformation and fracture due to rubbing at high contact stress was seen in the second disc (Fig. 7). Since, value of dynamic friction coefficient is not too high and also damage is much less than what observed in 316LN austenitic stainless steel by Kumar *et al.* [6], there will be no adverse affect on the behaviour of this material during service.

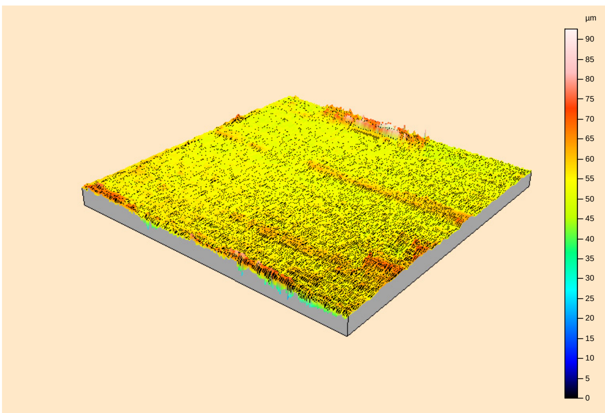
6 Conclusions

The following are the conclusions from the friction and wear tests between Z6 NCT DV 25-15 alloy and NiCr-B coating specimens, under simulated operating conditions, in reactor-grade flowing sodium at 823 K:

(1) The wear loss is found to be negligible (practically nil) for both disc and pins.
(2) The static and dynamic friction coefficients (μ_s and μ_d) values are about 0.11 and 0.05, respectively, at 10 MPa stress level, which is less than the friction coefficients values of about 0.2 and 0.10 obtained at 20 MPa.
(3) Friction coefficients of this material combination are low under tested condition.



(a)



(b)

Figure 5: 3D Talysurf CLI 1000 Optical Profilometer image of the worn disc after (a) 10 MPa and (b) 20 MPa tests.

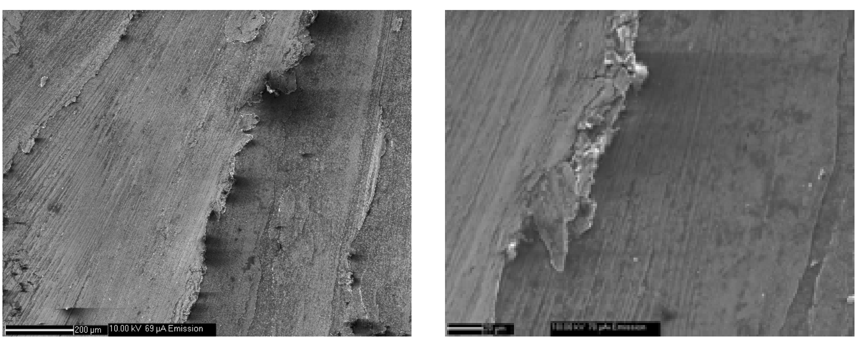


Figure 6: SEM pictures of worn disc specimen showing deformed zone and adherence of wear particles at few locations after test at 10 MPa.

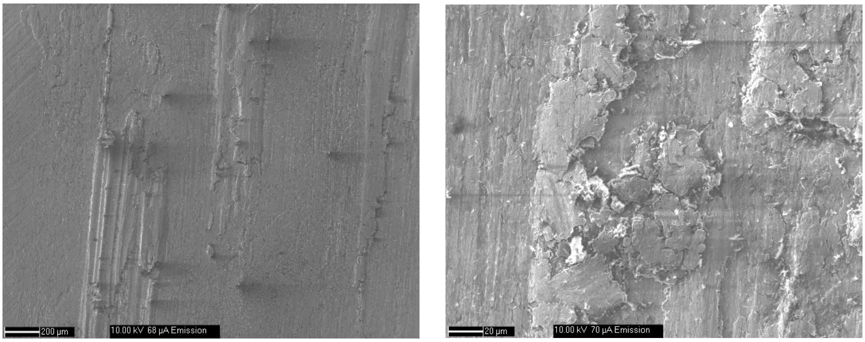


Figure 7: SEM pictures of worn disc specimen showing evidence of deformation and fracture after test at 20 MPa.

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