Test Methodology and Wear Characteristics of Austenitic Stainless Steel AISI Type 316 at Cryogenic Environment

G.H. Farrahi, V. Kazerani, and M.S. Ghorashi

Abstract— **Components in cryogenic milieu with relative motion, like seals and pumps cannot be lubricated by using oils or other lubricants. Therefore materials wear in cryogenic condition is a great concern. To earn valid data about the wear properties of common and super useful material in cryogenic tribosystems, reconstruction wear test apparatus at cryogenic temperature is needed. Investigations on metal-metal couple show that austenitic stainless steels have favorable and auspicious sliding properties at cryogenic temperature.**

This research provides the wear parameters of austenitic stainless steel AISI type 316 in cryogenic environment. For this purpose two sets of test environment are prepared, room temperature (273K) and 77K with the sample immersed in LN2 using designed Pin-On-Disk cryogenic simulator. Disk material is austenitic stainless steel AISI type 316L and pin is bearing steel SAE 52100. Test is chosen to have 20.1 m/s sliding speed and two pin normal forces, 10N and 20N.

Test results show reduction in friction coefficient (average $COF_{cryogenic}$: 0.15 - average $COF_{Room\ Temperature}$: 0.5) and lower wear rate in cryogenic environment. Better wear resistance properties is achieved, because austenitic stainless steels have higher mechanical strength in cryogenic condition and the forming of nitride layer at worn surfaces which enhances slipping of pin on the specimen. The wear rate in experiments reported to be approximately 4 – 10 (mm^3/Nm). Like friction coefficient, the same trend has been observed on wear rate between specimen in room temperature and cryogenic condition. The major mechanism of wear is severe abrasion in room temperature, by considering SEM micrographs of worn surfaces. Contrary, mild abrasive wear mechanism is observed in specimens tested under the cryogenic condition.

Index Terms— **Wear, Cryogenic, Stainless steel**

I. Introduction

GENERALLY, various types of lubricant exist, but nearly in most cryogenic applications lubricants are not used. In recent years many investigations in this field has been performed, and the major concerns among them are to find materials which suit better for tribosystems in cryogenic condition. A scrutiny on prime measurement of wear parameter in cryogenic environment is given by Kragelsky, in this survey they report the behavior of some different polymers as insulation material for wires [1]. In 1998, Gradt et al. studied HDPEs in cryogenic environments, in this experiment they use the HDPE disks and bearing steel as counter body material and showed that the HDPE has good resistance in the specified sliding condition [2]. In those years T.P Yukhno et al., using coating idea in cryogenic conditions, performed experiments in super hard coating for very low temperature applications. They focus in the bond layer condition effect on the efficiency of the sliding resistance of the coatings [3]. Many investigations on cryogenic tribosystem are performed for special application in superconducting systems. For a systematic study of a broad variety of conventional and advanced materials for cryogenic tribosystems special test device are developed in India, recently, Basu et al., using a designed cryogenic wear test stand, run several tests in cryogenic environment for different materials such as ceramics, composites and pure metals like copper and aluminum. They used submerged specimen in liquid nitrogen and 10, 15 and 20 N for normal forces, sliding resistance of the mentioned materials is the main target of their investigations [4]. Similarly El-Tayeb et al. do tests with titanium (Ti45) disks in 2012 [5].

The cryogenic wear tests have been conducted on sliding speeds 2.1 m/s, at a load of 10 N. The experiments results from cryogenic tests have been compared with the results of room temperature tests specimen on the same material. Finally, wear resistance properties of AISI 316L stainless steel is discussed predicated on experiment results.

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II. Experimental procedure

A. Pin-On-Disc test

To investigate the steady-state sliding wear of metal-metal pairs, friction and wear tests were run by using a Pin-On-Disk test stand with capability of cryogenic simulating developed during this survey. Two test environments were used: 1) at 293K in room temperature air without any coolant, 2) at 77K with the samples immersed in liquid nitrogen.

B. Wear test stand and procedure

Fig. 1 shows a schematic overview of the Pin-On-Disk test stand used during the sliding wear tests. The experiment details include a rotating stainless steel disk rotate against hemi-spherically ended metal pin. Pins are hold in a designed guide and several guides were used to permits testing of same specimen under different test conditions and achieve better accuracy in COF measurement.

The wear test stand was designed to work in air at RT and at cryogenic condition with the sliding surface immersed in the liquid nitrogen. The apparatus is able to work at disk sliding speed between 1 and 10 m/s by using a tree phase induction electro-motor with proper driver. Pneumatic jack with obtained compressed air used for preparing the normal load, jack course is 20mm and internal cylinder diameter is 25mm. These equipments bring us functional variable normal load between 10 and 100N. However, during the test the sliding speed at the pin was fixed at 2.1m/s and normal load at 10N and 20N.

During the test wear linear distance and sliding speed was calculated by a rotational optical encoder coupled to the test stand rotary shaft. All tests were performed for minimum sliding distance of 2 Km.

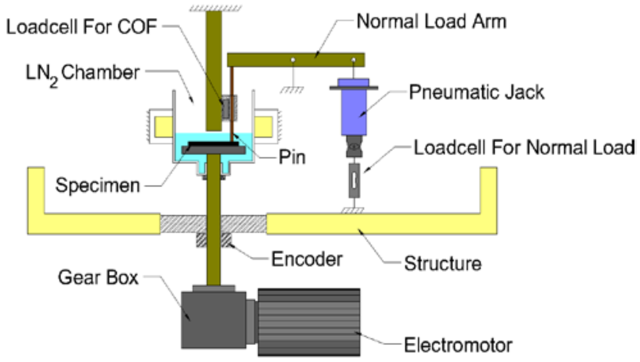

Fig. 1. Schematic diagram of Pin-on-disk wear test stand

Fig. 2. Setup of the cryogenic wear test simulator used in this research

The coefficient of friction is measured by strain gage load-cell which fixed the rotation of the pin guide in cryogenic environment assembly parts. These COF values, sliding speed and test temperature are monitored online during test using a design computer-based data logger system. Test stand designed and manufactured for this research is shown in Fig. 2.

TABLE I
TEST PARAMETERS

Specimen No.	Temperature	Normal force	Sliding Velocity	Duration
1	Room temp.	10 N	2.1 m/s	1 hour
2	Room temp.	20 N	2.1 m/s	1 hour
3	Cryogenic	10 N	2.1 m/s	1 hour
4	Cryogenic	20 N	2.1 m/s	1 hour

All specimen disk material is AISI 316 and pin material is bearing steel 52100.

C. *Preparation of specimens*

Disk of austenitic stainless steel (AISI type 316L) were cut from shaft stock with diameter of 80mm and faced with single point cutting tool to rub surface disorders. The disks were abraded against silicon carbide under running water, this operations done to clean the disk and to provide an isotope external face. Before the test, the surface roughness of the disk is measured by a commercial profilemeter which is ranged 1.2 – 1.5 μm for R_a. The disks are submerged in hexane for an overnight as to degrease their surfaces. Spherical steel balls (bearing grade: AISI 52100) of 5mm diameter are used as the counter body material. Test parameters are summarized and shown in table 1.

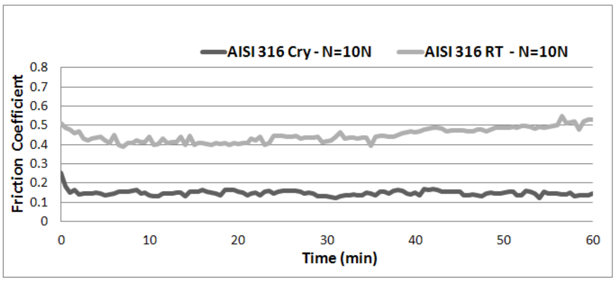

Fig. 3. Chart of steady-state COF vs. time. Data pursuant to 10 N load and RT and cryogenic environments

III. RESULTS

A. *Coefficient of friction*

Friction coefficient vs. time presented in Fig. 3 and Fig.4 shows that tests performed in cryogenic environment have lower COF than tests done in room temperature. The following result can be due to some reasons. One of the

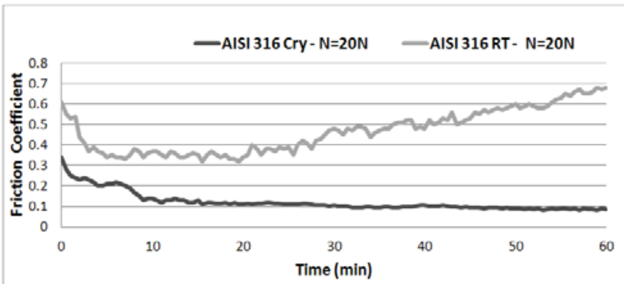

Fig. 4. Chart of steady-state COF vs. time. Data pursuant to 20 N load and RT and cryogenic environments

major reasons is phase change of austenitic stainless steel to martensite, which has higher hardness than previous phase. This results in lower COF. Further discussion on this matter is postponed to the results section. The average COF value for the experiments is summarized in table 2. It has a wide range from 0.15 to 0.5.

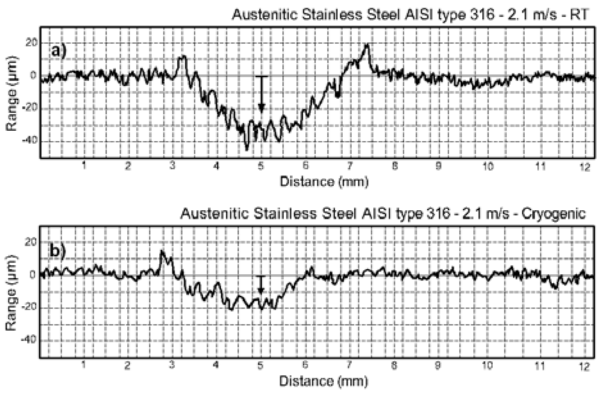

Fig 5. 2-D surface profiles of worn surface of austenitic stainless steel AISI type 316 samples after wear tests at a normal force of 10 N. (a) Wear track profiles at room temperature environment. (b) Wear track profiles sliding at cryogenic environment.

TABLE 2
SUMMARIZED RESULTS OF WEAR TESTS

Specimen No.	Average COF	Wear rate (mm^3/Nm)	Temperature
1	0.449	13.56	Room temp.
2	0.481	14.28	Room temp.
3	0.148	4.72	Cryogenic
4	0.120	4.23	Cryogenic

B. *Wear rate*

Wear tracks depth is measured by getting a number of two-dimensional (2-D) scans at various positions using commercial profilometer. Samples of 2-D profiles are shown in Fig. 5 which demonstrate the extremity of tracks at both sliding environment. For every tracks the area of such 2-D profiles are calculated and the wear volume data is computed using equation 1.

$$V_d\ .(mm^3) = 2 \times \pi \times TrackRadius \times TrackWidth \times WearDepth \qquad (1)$$
$$WearRate(mm^3 / Nm) = V_d /(NormalLoad \times SlidingDist.)$$

The computed wear rate and sliding speed is shown in table 2. The wear factor of experiment in room temperature has larger value than cryogenic environment. Based on the mentioned reason in the coefficient of friction section, it shows the better wear properties for austenitic stainless steel specimen in cryogenic conditions.

C. *SEM-EDS analysis*

A detailed morphological investigation is carried out using SEM micrographs. These micrographs can be seen in Fig. 6 and Fig. 7. Wear track marks in room temperature tests shows remarkable surface damage at that scale, while there are only faint line marks along sliding direction on specimens tested on cryogenic condition. These marks show mild abrasive wear mechanism for cryogenic environment, which is favorable for most applications. In specimens tested at room temperature three particle abrasive mechanisms is observed. Third particle is generated via delaminated oxide layers from the surface. Tests done at room temperature have higher COF compared to cryogenic condition due to severity of wear mechanism in room temperature. Cracks can also be seen on SEM micrographs, which prove existence of contact fatigue mechanism. This mechanism enhances generation of third loose particle in sliding interaction and increase the severity of wear damage. Plastic deformation is observed in morphology of surfaces worn at room temperature whereas it is not detected on worn surfaces in cryogenic condition.

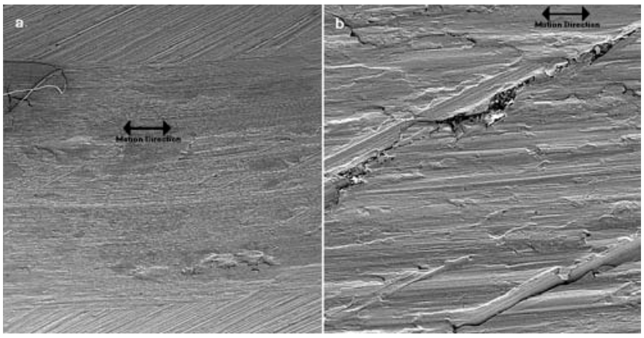

Fig. 6. SEM micrographs from surface morphology after wear test. (a) Specimen 1 in room temperature environment with 30x magnification (macroscopic view) abraded and worn surfaces can be seen. (b) Specimen 1 in room temperature environment with 400x magnification (semi-microscopic view) plastic deformation and effect of third abrasive particle can be seen.

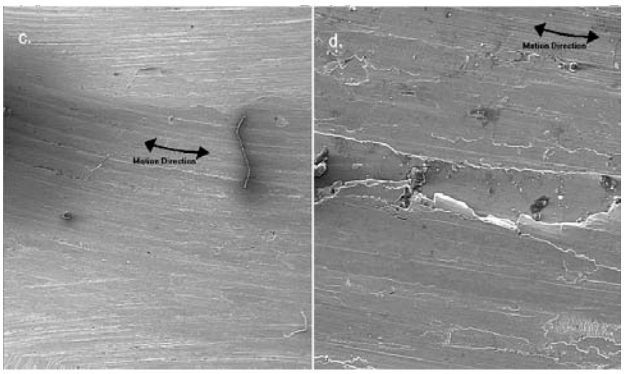

Fig. 7. SEM micrographs from surface morphology after wear test. (c) Specimen 3 in cryogenic environment with 30x magnification (macroscopic view) abraded and worn surfaces can be seen. (d) Specimen 3 in cryogenic environment with 400x magnification (semi-microscopic view) faint worn *tricks and fatigue cracks can be seen.*

EDS analysis on worn surfaces has been done to detect probable material composition which may be produced while wearing out. In Fig. 8 EDS analysis of a worn surface at cryogenic temperature is shown. This result reveals existence of nitride layer on surface. Existence of nitride

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layer clearly describes lower COF at cryogenic temperature based on its slippery properties.

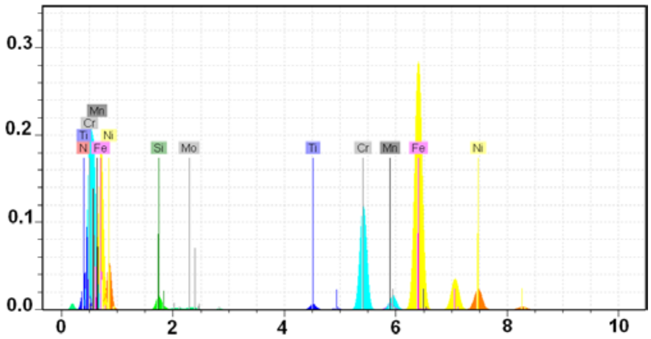

Fig. 8. EDS compositional analysis of the worn surface of specimen 3, existence of nitrogen in worn surface can be seen.

IV. Conclusion

Adhesion, plastic deformation, and delaminated oxide layer wear mechanism are observed on worn surfaces of austenitic stainless steels even at cryogenic temperatures. Although, higher hardness at cryogenic temperature due to phase change and other enhancing mechanism mentioned in results section (e.g. generation of nitride layer), makes these steels to have better performance in lower temperatures. This investigation shows that AISI type 316 has a brilliant sliding resistance which makes this group of metals to be used widely in cryogenic applications.

V. Abbreviations

SEM: Scanning electron microscope
COF: Coefficient of friction
LN: Liquid Nitrogen

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