Controlling Temperature Variations on the Disc Surface in High Temperature and High Vacuum Tribometers

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Abstract: We present design of a Pin-on-Disc type tribometer operating at 800°C, 1E-4 Torr vacuum. Temperature calibration tests were conducted in atmosphere, and optical pyrometer readings were matched to a thermocouple on a stationary disc surface, heated by inductive means. Maximum temperatures were attained in less than 18 min. Temperature variation at different locations on the disc surface were reduced by flush contact between surfaces, a coat of ceramic-based high-emissivity (>0.9) high-temperature rated paint, and, rotating the disc during heating. Surface contaminants changed emissivity and hence the zone viewed by the optical pyrometer itself was coated with the same paint, ultimately reducing temperature variations to ±3°C.

Keywords: Pin-on-Disc, Precision, Induction heating, High temperature, High vacuum

1. INTRODUCTION

High temperature resistant coatings and materials are used in several industries, as varied as nuclear, aerospace, energy and metal forming. The development process of such coatings and materials can be accelerated through testing and evaluation of their tribological parameters such as friction and wear under conditions simulating actual operations. These conditions often include temperatures as high at 800°C, under vacuum or controlled gas environments, or high pressures.

The loads and environmental conditions can be replicated using a pin-on-disc or ball-on-disc. These are standard laboratory methods for tribological testing of coatings and materials. In such tests the sample under test consists of both the pin or ball and the disc, and solid, fluid, or phase-changing lubricants. Results are presented for a particular combination of materials and lubricants under different contact, relative speeds, loads and environmental conditions.

1.1. Background

Various authors have reported results for high temperature tribological tests on different samples. Hardell et al, [1] reported friction and wear behaviour of high strength boron steel at temperatures up to 800°C. Furthermore, Stott et al [2] highlighted the effect of oxidation on sliding wear of metal alloys at 700°C. Similarly, several literatures on high temperature tribology studies are available [3].

However, it is hard to find the relevant literature that discuss instrumentation requirements like heating rate of the samples and its temperature stability of their samples during tests. Some of the tests are carried out by heating the samples under test in a furnace in order to reach the required test temperatures of up to 800°C. An average furnace with suitable insulation takes anywhere between 1 hour to 4 hours to reach 800°C. This represents a significant time before actual tests can be carried out. Therefore, some testing laboratories resort to starting the heating process while vacuum systems are running to reduce the time. However, this can lead to erroneous results in tribological measurements since partial oxidation can occur at elevated temperatures even at low vacuum.

Furthermore, furnace heating causes thermal expansions in all parts of the machine and thus measurements cannot be guaranteed to be accurate for all temperatures, especially for such parameters as the wear track, wear depth and loads applied by pneumatic, hydraulic, electronic means or combination thereof.

Hence, it becomes imperative to enable quick heating of the samples under test once desired environmental conditions have been reached. It also requires a minimization of the thermal expansions of key metrology elements.

Both these objectives can be achieved by supplying heat to only the samples under test, by electrical means, either directly to the samples or parts in close contact with them. This electrical means can be either inductive or resistive heating or combination thereof. The temperature of the samples can be measured and the feedback can be used to control power to the heat sources.

The objective of this study was to identify appropriate means of heating the samples in a short time, measure temperature with a high level of accuracy, use this to tightly control the heat supplied and hence the temperature of samples for tribological testing in a pin-on-disc set-up under high vacuum.

2. SYSTEM DESCRIPTION AND DESIGN CONSIDERATIONS

2.1. Description of entire system

The system consists of a standard pin-on-disc machine with several modifications. These modifications are introduced to provide quick heating of the samples under test, as well as to ensure minimal heating of other parts of the machine. A schematic of the arrangement is shown in Fig. 1. An induction heater is used to heat the disc holder and the disc is heated by conduction. The disc holder is mounted on a hollow shaft which is very rigid and is internally cooled by water. This shaft is connected to a motor.

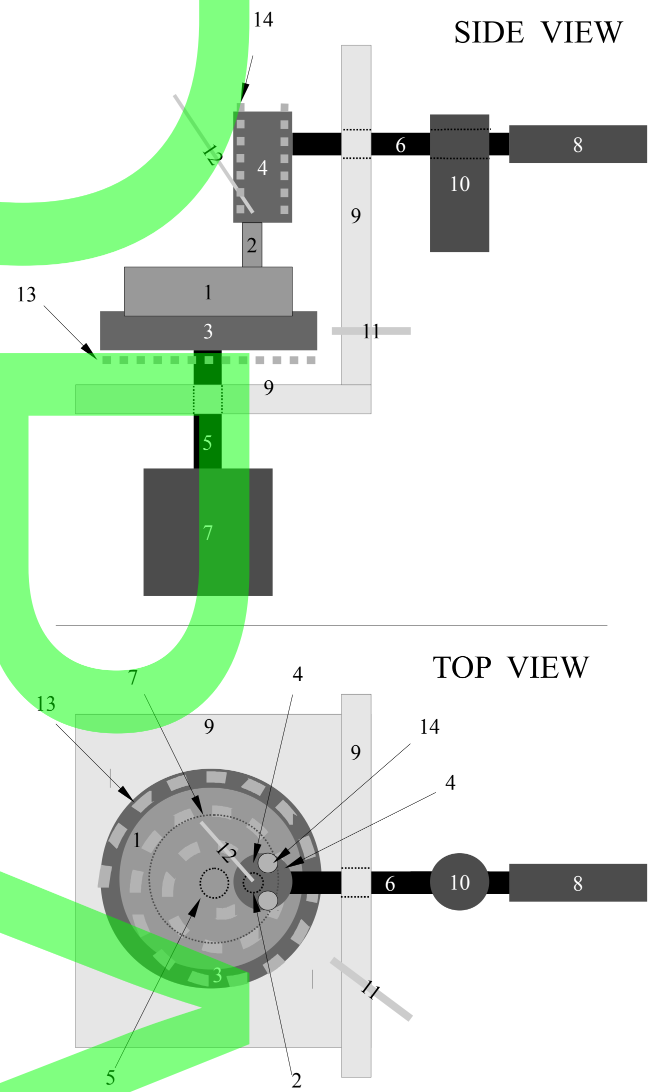

Figure 1: Schematic view of entire system in final configuration. Extraneous parts are not shown eg. supports, bolts, bearings, housing, wear depth sensor etc. Parts are consistently labelled and shaded in both Side and Top Views. Labelling: 1. Disc; 2. Pin (or Ball); 3. Disc holder; 4. Pin holder; 5. Shaft; 6. Pin holder support beam; 7. Motor; 8. Wear diameter actuator; 9. Cooling Baffles; 10. Loading actuator; 11. Non-contact optical pyrometer; 12. Thermocouple; 13. Induction heater; 14. Cartridge heaters

The pin holder is fixed to a stiff pin holder support beam which can be moved back and forth to adjust the wear track diameter. This adjustment can be manual or with a linear motor. Pin holder support beam is also attached to a loading means that can be used to control the load applied by the pin or ball on the disc. This mechanism is connected to a displacement measuring system to measure the wear.

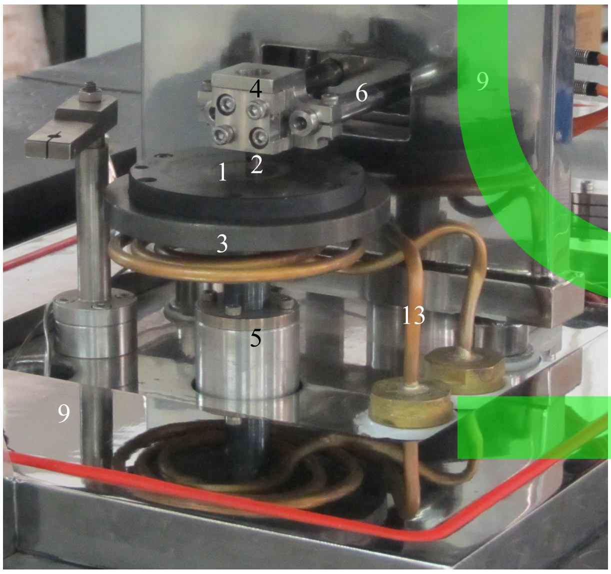

Figure 2: Photograph of actual pin-on-disc system, with few key parts clearly seen: 1. Disc; 2. Pin; 3. Disc holder; 4. Pin holder; 5. Shaft; 6. Pin holder support beam; 9. Cooling Baffles; 13. Induction heater

Several cooling systems are provided, the cooling system for the shaft has been described above. A hollow metallic baffle with continuous flow of chilled water is placed between the heated disc holder, shaft, pin holder assembly, and, the assembly to apply loads and change the wear track. Openings are provided in the baffle for the pin holder support beam, and to provide a clear line of sight for the optical pyrometer. The optical pyrometer is mounted directly on the baffle, ensuring it is cool at all times. Such arrangements ensures that motors, actuators, sensors and metrology structures remain cool at all times. Some key features can be seen in the photograph in Fig. 2.

The entire assembly is mounted inside a vacuum chamber with cooled walls to ensure minimal expansions and maximum reflection of energy back to the heated sample. All sensors, heaters, actuators and motors are connected to a data acquisition and control system running on a PC.

During actual tests the disc can rotate at speeds up to 2000 rpm for extended periods of time and heated to 800°C under high vacuum. Under such conditions both heating arrangement and temperature measurements become very difficult. Various alternatives were considered for each and these are discussed below.

2.2. Pin heating

The pin holder, has an independent heating arrangements using four customized cartridge heaters made by M/s NexThermal, Bangalore, India, of 150 W power each. The pin or ball is heated by conduction. An independent K-type calibrated thermocouple made by M/s Ajay Sensors, Bangalore, India, is provided in the pin or ball to measure and control the temperature. The heaters and thermocouple are all rated for vacuum at the operating temperatures. The temperature can be set independent of the disc. Since the movement of the pin holder is minimal, extra wire lengths were provided for heaters and the thermocouple.

2.3. Disc heating

Traditional zone heating was eliminated right away since the aim was to heat the disc and pin or ball independently. A cartridge heating arrangement was then considered for the disc holder. However, the thermal mass of the disc and disc holder is considerably more than the pin or ball and pin holder. This meant that the time required for heating would be unacceptably high for reasonable power requirements. Also, suitable high vacuum high temperature high power rated electrical slip-ring contacts were not available.

Hence the best alternative was to heat the disc holder by inductive means which in turn would heat the disc by contact conduction. An inductive heater model number SA-15A operating at 30-100 kHz made by M/s SATRA, Delhi, India, was selected. This meant that the disc holder had to be fabricated out of a paramagnetic metal or alloy capable of tolerating high loads and high temperatures. The alloy Inconel (R) – 625, made by M/s Special Metals Corporation, Huntington, WV, USA, was found to satisfy these requirements.

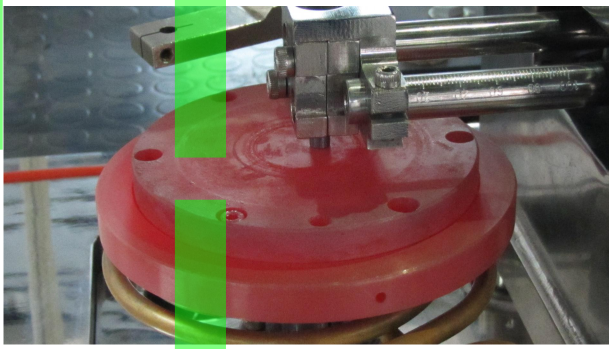

Figure 3: Photograph showing heated disc and disc holder in operations.

A hollow copper coil was wound in a spiral and placed below the disc holder as. The heating itself was carried out by supplying power in a pulsed mode (96 seconds power, 4 seconds dwell) till the desired temperature was reached. An image of the disc holder and disc is shown in Fig. 3. Once the set temperature was attained a software PID controller took over to maintain the set temperature within ±2%. For this, accurate measurement of temperature was essential.

2.4. Disc temperature measurements

Different methods are available for measuring temperature. Thermocouple is the traditional, most used, and most trusted means for this. However, since the disc needs to rotate at reasonably high speeds at high temperatures, using a contact type thermocouple proved very challenging primarily because relative motion between thermocouple and the disc at elevated temperature would cause either the disc or the thermocouple or both to wear out very quickly. This would require regular replacement of the thermocouple. Failure of the thermocouple during tests would also hamper test data integrity. Furthermore, the wear debris generated from this unwanted wear would interfere with the measurements of interest – friction between the pin or ball and the disc. Debris analysis would also be adversely affected. Hence, a contact type thermocouple was deemed unsuitable for this purpose.

A thermocouple embedded in the disc holder and enclosed by the shaft and rotating with it was also considered. However, this shared similar issues with getting the electrical signals to the non-rotating data acquisition system due to a non-availability of high precision slip rings or rotating contacts for high temperature high vacuum applications. Hence, even this alternative was rejected.

Yet another alternative was to embed the power supply, control electronics, data handling along with the thermocouple inside the shaft. However, significant difficulties in implementing such a system with sufficient stability were encountered. Hence, a non-contact optical pyrometer, model CTSF-22 made by M/s Micro-Epsilon, was selected. It is high vacuum compatible and has sufficient accuracy and range for this application.

2.5. Calibration thermocouple

A calibrated K-type thermocouple made by M/s Ajay Sensors, Bangalore, India, was used.

3. ESTIMATIONS AND METHODOLOGY

Calculations for time to heat the disc and the pin holder were carried out. Various parts were modelled in SolidWorks (R) Computer Aided Drafting (CAD) package and fabricated as per drawings.

3.1. Pin heating

It was determined that the cartridge heaters selected were able to heat the pin holder to various temperatures reasonably quickly. This was validated using the calibration thermocouple.

3.2. Disc heating

The skin depth can be calculated using Eq. (1).

$$\delta_s = \sqrt{\frac{\rho_e}{(\pi \cdot f \cdot \mu_r \cdot \mu_0)}} \quad (1)$$

where,
ρ_e is the electrical resistivity of the material,
f is the frequency of the inductive heater,
μ_r is the relative permittivity, and,
μ_0 is the permittivity of free space or vacuum.

Using values published in [4], for example the skin depth for Inconel (R) – 625 was estimated as 2.293 mm for 65 kHz at 500°C. From this, and parameters obtained from the CAD model and verified by actual measurements, the time taken for disc holder to be heated to different temperatures was estimated, based on [5], and the results were validated with actual measurements.

Using reasonable assumptions of surface contacts, it was estimated by calculation that the disc would be heated in 15 to 20 minutes to 800°C. This was validated experimentally in air. These results were not expected to change in vacuum since conduction is the main mode of heat transfer between the disc holder and the disc.

Eight locations on the same PCD on the disc were marked with spacing of 45°, disc temperature measurement was carried out using non-contact optical pyrometer pointing to the surface of the disc at each of these locations. The results were compared to the measurements made in the same location on the disc surface using the calibration thermocouple. The thermocouple had to be physically placed in close contact with the surface of the disc. This was done manually, hence all measurements with the calibration thermocouple were carried out in air with a stationary disc.

During tests it was found necessary to rotate the disc during the heating cycle. In such cases, the disc was heated to the desired temperature using the feedback of the non-contact optical pyrometer, the thermocouple was kept close to the disc, but not touching it. Then the motor was stopped and the temperature measurements at the same locations were made immediately. For all the tests the non-contact optical pyrometer was kept pointing at the top of the disc surface. After consistently accurate results were obtained the non-contact optical pyrometer was repositioned to point at the side of the disc holder as seen in Fig. 1. A final set of readings were taken to validate that the disc holder and disc were at the same temperature.

4. RESULTS

Time to heat the pin or ball with pin holder, and the disc with disc holder were found to be in close agreement with the estimated values as can be seen in Fig. 4

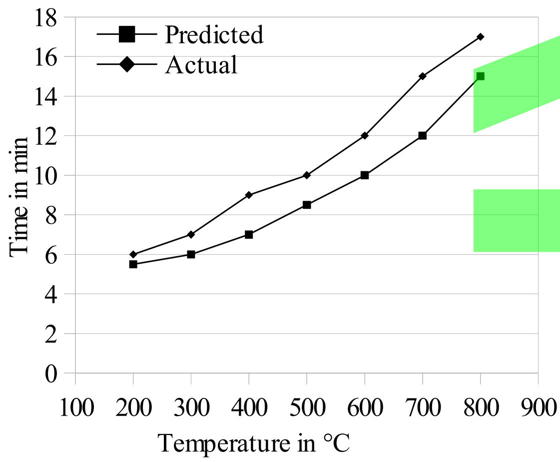

Figure 4: Time to reach set temperature for different set temperatures as predicted from calculations and as measured in actual conditions.

No anomalies were noted for pin or ball and pin holder temperature measurements. However, serious undesirable temperature variations were noted at the eight marked locations on the surface of the disc at different temperatures. The readings of the non-contact optical pyrometer matched the readings of the calibration thermocouple very closely to within ±15°C at 800°C at the same locations for the tests. These results are presented for different temperatures as measured by the non-contact optical pyrometer.

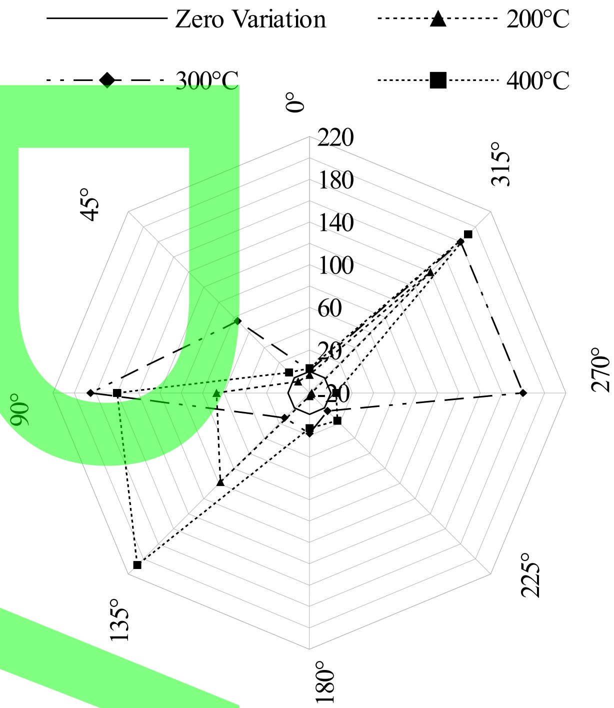

Figure 5: Variations in original condition at different set temperatures across different angular locations on disc surface from 0° to 360°.

As can be seen in Fig. 5, even at half the maximum operating temperature of 800°C variations of up to ±100°C at different locations on the disc surface were noted.

A series of steps were undertaken to ensure uniform heat transfer from disc holder to disc, and increase the rate as well as to accurately measure temperature. First, the top surface of the disc holder and bottom surface of the disc were ground to fine finish. Both the surfaces were thoroughly cleaned with alcohol for several minutes before assembly. The screws used to mount the disc to the disc holder were tightened using a torque wrench to a torque suitable for the respective screw sizes. This ensured flush and uniform contact. An immediate improvement was seen, with the variation reducing up to ±50°C as seen in Fig. 6. However, even these variations were found to be unacceptable.

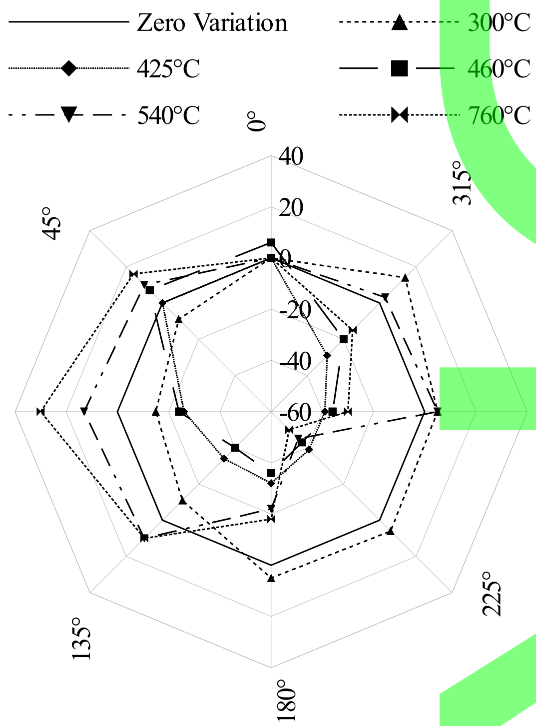

Figure 6: Variations after grinding contact surfaces and applying uniform torque on clamping screws at different set temperatures across different angular locations on disc surface from 0° to 360°.

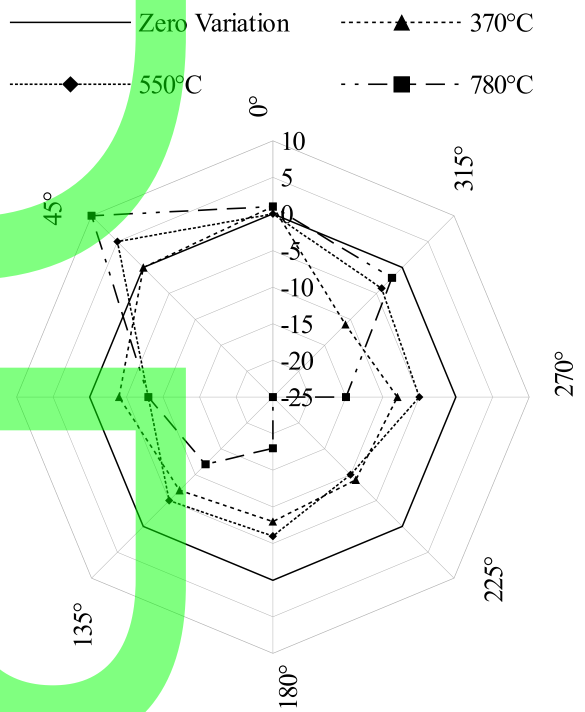

Figure 7: Variation after coating with ceramic based high emissivity high temperature rated paint, and flush mounting.

To improve heat transfer and uniformity of heat distribution, it was decided to reduce the contact area between the disc and disc holder by introducing a small step on the top surface of the disc holder. The area of the step was painted with a coat of ceramic-based high-emissivity (>0.9) high-temperature rated paint HIE COAT 840-M made by M/s Aremco Products, Inc., Valley Cottage, NY, USA. After appropriate stabilization, it was found that the temperature variations were reduced to ±20°C at 800°C and correspondingly lower variations were observed at other set temperatures as seen in Fig. 7.

However, even this was deemed to be unacceptably high. This was traced to the fact that the spiral inductive coils did not heat the disc holder itself uniformly since there had to be discontinuities at the entrance and exit points of the spiral.

Hence, it was decided to rotate the disc and disc holder with the motor at different speeds to ensure uniform heating of the disc holder. The maximum measured variations at 800°C at different rotation speeds are presented in Fig. 8. As is clear, 60 rpm provides the least variations of ±10°C.

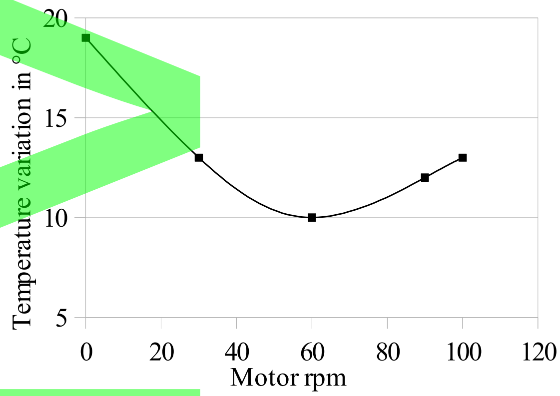

Figure 8: Variations in temperature about mean at different motor rotation speeds.

For all further tests, the disc was rotated at this speed till the desired temperature was reached and then the motor was stopped and the calibration thermocouple was used to measure actual disc surface temperature. However, it was found that this temperature variation was not observed by the thermocouple, which measured constant temperatures.

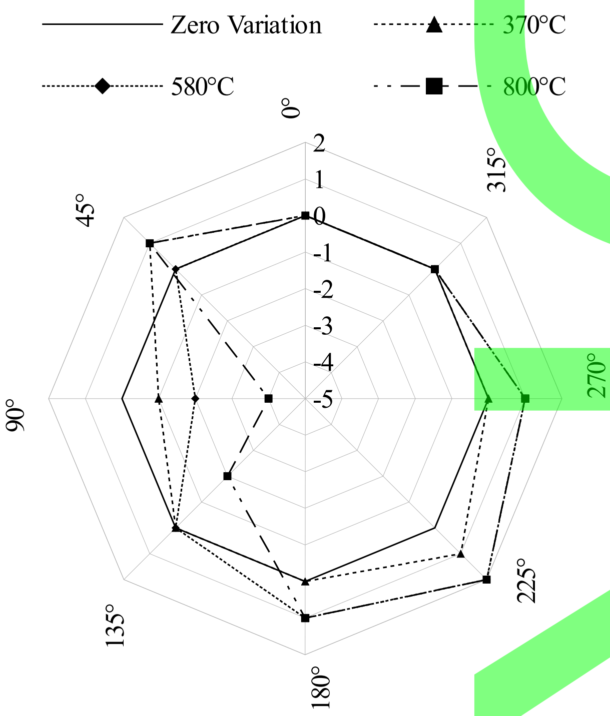

Figure 9: Variations in final configuration with optical pyrometer pointing to the side of the disc holder and thermocouple measuring on top of the disc for different temperatures at specific angular locations on the disc surface.

It was found that if the surface seen by the non-contact optical pyrometer was cleaned thoroughly these temperature variations were reduced. Hence, it was concluded that these temperature variations arose due to surface contaminants changing emissivity. It was not possible during tests to ensure that this surface remained clean since wear debris, lubricants etc. were likely to be deposited on this surface.

Hence, to provide a standard reference surface, the zone viewed by the optical pyrometer itself was coated uniformly with the same ceramic-based high-emissivity (>0.9) high-temperature rated paint. This reduced temperature variations to its minimum of ±3°C at 800°C. Correspondingly lower variations were observed at lower set temperatures as seen in Fig. 9.

To further minimize the effects of wear debris and lubricants during tests, it was decided to place the non-contact optical pyrometer such that it pointed to the side of the disc holder. This final arrangement is shown in Fig. 1. The side was painted with the same ceramic-based high-emissivity high-temperature rated paint. The temperatures measured by the calibration thermocouple on the disc surface were measured and found to be the same as those measured by the non-contact optical pyrometer placed in this manner, these results can be seen in Fig. 9.

5. CONCLUSIONS AND RECOMMENDATIONS

It was found that inductive heating of the disc holder and heating of the disc through a combination of contact conduction and surface radiation and absorption can significantly reduce the time for tribological tests.

It was also found that there are several issues with this type of heating which can be reduced by appropriate design and care for sample preparation and testing.

6. ACKNOWLEDGEMENTS

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