Estimation of thermal stress at the interface of sliding in a pin on disc tribometer using finite element approach

Renjish Vijay¹,², V N Aju Kumar¹, A Sadiq¹ and S B Sandeep³

¹Department of Mechanical Engineering, TKM College of Engineering, Kollam-691005, Kerala, India
²APJ Abdul Kalam Technological University, Kerala, India
³Advanced Tribology Research Centre, College of Engineering Trivandrum, Kerala, India
⁴Email-id: renjishvijay@gmail.com

Abstract. Finite Element Method (FEM), introduced at the end of sixties, is used for solving engineering problems by mathematical formulations. The present study estimates the thermal stresses and temperature distribution induced at the contact surface during frictional sliding. The pin on disc tribometer is modelled as per ASTM G99 in ANSYS Workbench simulation software with the help of User Defined Function (UDF). Aluminium alloy 6061 coated with Yttrium stabilized zirconia is used for the analysis where the alloy is subjected to continuous sliding motion against aluminium oxide disc material. User Defined Results are employed in this analysis for the determination of thermal stress generated at the contact surface during frictional sliding. Temperature distribution is determined and is represented in contours.

1. Introduction

Many mechanical systems are subjected to sliding and coating forms an inevitable element in order to improve tribological [1] and mechanical properties [2]. The coating also adds to the functionality of the material as well as its aesthetics [3]. Yttrium stabilized zirconia based Thermal Barrier Coating (TBC) is widely used in industries such as automobile, aerospace, etc. as it exhibits good mechanical as well as tribological characteristics [4-7]. This coating is subjected to thermal loads due to sliding and the determination of thermal stresses and temperature distribution is of interest. Estimation of mechanical properties due to frictional sliding conditions of Yttrium stabilized zirconia coated samples can be studied by analytical approach [8] and numerically by Finite Element Analysis (FEA) [9-13]. Finite element analysis gives approximate solution regarding the nonlinear analysis problem, by considering all the physics regarding the contact analysis. Since this contact pair analysis required certain thermal loading boundary conditions, User Defined Functions (UDF) or ANSYS Parametric Design Language (APDL) are encouraged in ANSYS workbench for the analysis. User Defined Results are employed to provide the temperature distribution at the sliding interface as ANSYS does not provide the analysis results directly. Various works have been conducted regarding the estimation of mechanical characteristics during frictional sliding, but this paper focuses on some of the modification and innovation in simulating the pin on disc model and application of boundary conditions. Transient structural Finite element method is used in the current study for determining the thermal stress, thermal strain, contact pressure, fatigue life and temperature distribution during frictional sliding in pin on disc tribometer.
2 Materials and Methods
Aluminium alloy 6061 coated with Yttrium stabilized zirconia is subjected to frictional sliding in pin on disc tribometer. Finite element method (FEM) is used for estimating thermal stress, thermal strain, contact pressure, temperature distribution, and fatigue life of coated sample during contact analysis. ANSYS Parametric Design Language (APDL) commands, also referred to as User Defined Functions (UDF), are used for setting up thermal and mechanical boundary conditions. The following section deals with finite element modelling of pin on disc tribometer and the methods employed for the analysis.

2.1 Finite Element Modelling
Yttrium stabilized zirconia coated aluminium alloy 6061 is slid over aluminium oxide disc and is modelled as per ASTM G99 for transient structural analysis. ANSYS three-dimensional Design Modeler is used for sketching the geometry. The rigid stiffness behaviour is assigned and the material properties like Elastic Modulus, Density, Poisson’s ratio, etc. are imported into the model to map the real conditions. User Defined Functions (UDF) are assigned to both geometries individually as “et,matid,226” and “keyopt,matid,1,11”. This UDF assigns element number and enables extra degree of freedom to the geometry. Figure 1(a) illustrates the friction between the Yttrium stabilized zirconia coated alloy and aluminium oxide disc material with friction coefficient of 0.25 [1]. Figure 1(b) describes the details of frictional contact where; the asymmetric behaviour is opted as it defines all contact elements on one surface and the target element on the other surface. Augmented Lagrange formulation and stiffness is maintained to update for each iteration, which enables the convergence of the solution. The Auto detection option in the connection tab is disabled as ANSYS cannot change the definition of the contact once defined. This is shown in Figure 1(c).

![Figure 1. (a) Frictional – Aluminium oxide to Yttrium stabilized zirconia (b) Frictional Input for transient structural analysis (c) Details of connection between contact surfaces](image)

To define the real constant for frictional contact, APDL commands are inserted in the “connection” tab. The commands are as follows; (i) “keyopt, cid, 1,1” is an element type number which enables the temperature degree of freedom (DOF) for transient structural analysis, (ii) “rmodif,cid,15,1!” specifies the fraction of frictional dissipated energy converted into heat i.e. FHTG from equation (1), (iii) “rmodif,cid,18,0.5!” specifies the weight factor (FWGT) for the distribution of heat between the contact and target surface for transient analysis as mentioned in equation (2) [14]. When the contact surface is in relative motion, friction come into effect and the contact interface is subjected to frictional heating. The transfer of heat is to be studied and represented. In coupled transient structural analysis of contact modelling, the rate of frictional
dissipation $Q$ is related to equivalent frictional stress $\tau$ and sliding velocity $V$ as represented in equation (1):

\begin{align}
Q &= FHTG\tau V \\
Q &= FHTG FWGT \tau V
\end{align}

Equation (2) represents the amount of frictional heat dissipation on contact and target surface [14]. The geometry is then divided to 346 number of elements and 2413 number of nodes by meshing operation with aspect ratio ranging from 1.03 to 2.92 with 1528 number of iteration. The mesh aspect ratio is defined from User Defined Results with an expression “MESH_ASPECT_RATIO”. The meshing operation is done with default element size, with dimensionally reduced rigid body behavior and is also provided with highly smoothened mesh with zero number of retries as shown in Figure 2(a) and (b).

![Figure 2. (a) Advanced details of mesh (b) Sizing details of mesh](image)

2.2 Finite Element Method.
This section deals with how the boundary conditions are being applied using User Defined Function (UDF) for transient analysis. The aluminum oxide disc of modeled pin on disc tribometer is grounded and the pin is tracing a circular path with an angular velocity of 26.17 rad/sec over the disc material with a wear track diameter of 80mm about z-axis. Figure 3(a) and (b) represent the details of revolute, where disc is maintained to be stationary and pin is mobile.

![Figure 3. (a) Details of revolute pair (b) Pressure and Rotational velocity applied to model](image)

The angular velocity and pressure applied on the top face of the pin is represented in Figure 4(a) and (b). Newton Raphson option in nonlinear controls of analysis settings is maintained to be unsymmetric; also the stabilization is maintained to be constant with an energy dissipation ratio of 0.1, as indicated in Figure 4(c). Thermal boundary conditions such as reference temperature, convective effects and thermo-mechanical properties like heat capacity, thermal expansion, thermal conductivity and Taylor-Quinney coefficient are imported for all the entities on the surface for
solving [make sure that friction and bulk coefficient is positive]. To make sure positive bulk coefficient, the heat capacity should be in MKS and the rest of boundary conditions in millimeter.

![Figure 4. Boundary conditions (a) Rotational velocity (b) Pressure (c) Analysis setting](image)

3. Results and Discussion

This section deals with the observation and interpretation of results obtained from nonlinear finite element analysis (FEA) of contact pair. The status of sliding, fatigue life, thermal stress, thermal strain, contact pressure and temperature distribution of frictional sliding of Yttrium stabilized zirconia over aluminium oxide disc are analyzed using ANSYS and discussed in the following section.

3.1 Status of Sliding and Contact Pressure

The status during frictional sliding of Yttrium stabilized zirconia coated sample over aluminium oxide disc is studied. From the section 2.2 it is clear that the pin is tracing a circular path on the disc material about z-axis. Figure 5(a) shows the status of sliding, and it is found that pure sliding is observed from the contour, but in actual practice the effect of heating at the contact surfaces result in local welding. Dual colour combination in the contour indicates the small percentage of unstable sticking phenomenon occurred during heated frictional sliding. Figure5(b) represents the contact pressure distribution at the interface between Yttrium stabilized zirconia and aluminium oxide disc modelled using ANSYS Workbench. The contact pressure at the interface greatly depends upon the load under consideration. It is found to be $3.44 \times 10^{-10} \text{MPa}$ which is significantly less due to reduced load applied upon the top surface of pin as seen in section 2.2.

3.2 Equivalent thermal stress and strain

Thermal stress and thermal strain induced during frictional sliding is evaluated and interpreted in this section. Apart from wear, stresses are also generated at the interface due to sliding phenomenon. The effect of thermal boundary conditions incorporated in frictional sliding is responsible for the development of equivalent thermal stress and strain at the contact interface of pin on disc tribometer. Figure 6(a) and (b) indicates the thermal stress and strain contour with a maximum value of $538.72 \text{MPa}$ and $2.69 \times 10^{-3}$ respectively. Both the contact pressure and thermal stress influence the mechanical properties of material to a great extent.
3.3 Temperature distribution
The reference temperature is defined by using User Defined Function (UDF) as boundary conditions for finite element transient structural analysis. Since distribution of temperature is not directly obtained from ANSYS workbench, User Defined Results are being used with an expression “TEMP”. This gives the temperature distribution during frictional sliding in pin on disc tribometer. Figure 7 shows the temperature distribution contour upon the disc material and is found to be ranging from 0 to a maximum of 43°C at the contact interface. The pin trace circular path and the temperature variation is shown with the help of various colours.

![Figure 5. (a) Status of Sliding (b) Contact Pressure](image1)

![Figure 6. (a) Equivalent Von-Mises Stress (b) Equivalent Strain](image2)

3.4 Fatigue life
Fatigue life of the sample is also an important factor to be considered from mechanical point of view. The analysis was done by keeping Good man mean stress theory and using equivalent von mises stress component. The fatigue life of above sample is found to be existing between a minimum of 1188 cycles to a maximum of 1x10⁶cycles. The endurance limit is found to be 86.2 MPa. Figure 8(a) and (b) shows the tabular data and graphical representation of stress vs number of cycles obtained from finite element analysis, and it is clear that beyond 1x10⁶ number of cycles the material may undergo fatigue failure.
4 Summary and Conclusions

Finite element analysis for estimation of various properties of Yttrium stabilized zirconia coated aluminium alloy was conducted. The samples are subjected to frictional sliding and the properties like thermal stress, thermal strain, contact pressure, temperature distribution, and fatigue life tabulated. Since the effect of frictional sliding is considered, the modelling is done as per ASTM G99 standard. The effect of pure sliding is observed at the contact interface. Contact pressure is significantly low due to the low applied load on the sample under study. Thermal stresses are developed at the contact interface due to friction between rubbing surface and the temperature distribution noted. Fatigue life and factor of safety with Goodman mean stress theory are also studied and it is found that the model doesn’t accurately predict the fatigue behaviour during sliding.

Acknowledgments

The authors kindly thank Dr. Mohammed Sajid N. K professor and Head of Mechanical Engineering department of TKM College of Engineering for providing facilities in computation. Special mention goes to research dean Dr. K A Shafi and Dr. Krishnakumar T S for the valuable suggestions and helps provided during the research. We thank Dr. V R Rajeev and Dr. Rani S from College of Engineering Trivandrum for the technical support provided in completion of work.
References

[1] Krishnamurthy N, Prashantha reddy M S, Raju H P and Manohar H S 2012 A study of parameters affecting wear resistance of alumina and yttria stabilized zirconia composite coatings on al-6061 substrate International Scholarly Research Notices 2012.

[2] Song C, Wang Y, Fan X J, Xie S M, Liu M, Zhou K S, Deng C M, Deng C G and Liao H L, 2020 Microstructure and mechanical property of dense yttria stabilized zirconia coating fabricated by an axial bi cathode plasma torch under very low-pressure Ceramics International, 46 (7) 9507-9511

[3] Camposilvan E, Leone R, Gremillard L, Sorrentino R, Zarone F, Ferrari M and Chevalier J 2018 Aging resistance, mechanical properties and translucency of different yttria stabilized zirconia ceramics for monolithic dental crown application Dental Materials 34(6) 879-890

[4] Ghasemi R, Shoja-Razavi R, Mozafarinia R and Jamali H 2013 Comparison of microstructure and mechanical properties of plasma-sprayed nanostructured and conventional yttria stabilized zirconia thermal barrier coatings Ceramics International 39(8) 8805-8813

[5] Brandon J R and Taylor R 1989 Thermal properties of ceria and yttria partially stabilized zirconia thermal barrier coatings Surface and coating technology 39 143-151

[6] Muratore C, Voevodin A A, Hu J J and Zabinski J S 2006 Tribology of adaptive nanocomposite yttria stabilized zirconia coatings containing silver and molybdenum from 25 to 7000°C Wear, 261 797-805

[7] Gao L, Guo H, Wei L, Li C, Gong S and Xu H 2015 Microstructure and mechanical properties of yttria stabilized zirconia coatings prepared by plasma spray physical vapor deposition Ceramics International 41(7) 8305-8311

[8] Ren X and Pan W 2014 Mechanical properties of high-temperature-degraded yttria-stabilized zirconia Acta materialia 69 397-406

[9] Abdullah O I and Schlattmann J 2016 Temperature analysis of a pin-on-disc tribology test using experimental and numerical approaches Friction 4 (2) 135-143

[10] Podra P and Andersson S 1999 Simulating sliding wear with finite element method Tribology international 32 (2) 71-81

[11] Suresh R, Kumar M P, Basavarajappa S, Kiran T S, Yeole M and Katare N 2017 Numerical simulation and experimental study of wear depth and contact pressure distribution of aluminium MMC pin on disc tribometer Materials Today: Proceedings 4 (10) 11218-11228

[12] Laraqi N, Alilat N, de Maria J G and Baïri A 2009 Temperature and division of heat in a pin on disc frictional device-Exact analytical solution Wear 266 768-770

[13] Straffelini G, Verlinski S, Verma P C, Valota G and Gialanella S 2016 Wear and contact temperature evolution in pin on disc tribotesting of low metallic friction material sliding against pearlitic cast iron Tribology Letters 62(3) 36

[14] Singh A K, Ranjan V, Tyagi R and Singh B N 2019 Numerical analysis of temperature distribution in sliding contacts of pin on disc model Vibroengineering PROCEEDIA 29 274-278