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FINITE ELEMENT STUDY OF EFFECT OF DISTANCE BETWEEN PLANES ON CONTACT HEAT TRANSFER

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ABSTRACT

Engineering surfaces can be characterized as more or less, randomly rough. The two solid surfaces apparently in contact touch each other only at a few individual spots and because of this the real area of contact is far less than nominal area of contact. The real area of contact depends on surface roughness, applied load, surface hardness and material properties like Young's modulus. Many theories and empirical relations based on experimental results are available in the literature for the computation of contact heat transfer. Computation of real area of contact and heat transfer is very important in the applications like cooling of electronic chip, wear studies etc. The distance between two contacting surfaces changes the contact area and this in turn affects the contact heat transfer. In the present work finite element study of effect of distance between planes on contact heat transfer is carried out.

Keywords*: Real area of contact, Contact Heat Transfer and Distance between planes*

1. Introduction

All practical solid surfaces have microscopic and macroscopic irregularities. Surface roughness is a measure of the microscopic irregularity, whereas the flatness deviations, waviness and out of roundness are the macroscopic errors. When two bodies are in contact, it appears that the contact is all over the cross sectional area of contacting bodies. This area is termed as nominal or apparent area of contact. However the solid surfaces apparently in contact touch each other only at a few individual spots and the sum of all these contact spot areas gives the real area of contact. Bowden et.al [1] showed that even at relatively high contact pressures of the order of 10 MPa, the actual area of contact for most metallic surfaces is only about 1 to 2% of the nominal contact area

The heat conduction between any two contacting bodies occurs through contact spots or through actual area of contact. In other words, the heat transfer between contacting bodies depends on actual area of contact rather than on the nominal area. When two solid bodies come in contact, such as 1 and 2 as shown in figure 1 (a), heat flows from the hotter body to the colder body. The temperature profile along the two bodies varies, approximately, as shown in the figure 1(b). A temperature drop is observed at the interface between the two bodies in contact. The temperature drop is due to imperfect contact interface and this drop, ΔT, is said to be a result of a thermal contact resistance existing between the contacting surfaces. Thermal contact resistance (TCR) is defined as the ratio of the temperature drop and the average heat flux across the interface.

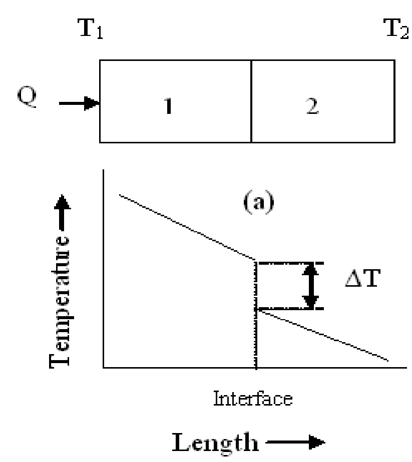

Fig. 1 Temperature Drop due to Imperfect Joint

$$R = \frac{\Delta T}{Q/A} \qquad (1)$$

Where R is thermal contact resistance, Q is heat flow; A is nominal area of contact. Thermal contact conductance, h_C, is defined as the reciprocal of thermal contact resistance.

$$h_c = \frac{Q}{A\Delta T} \qquad (2)$$

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Contact heat transfer is usually characterized by contact conductance and it is important wherever conduction heat transfer takes place between two bodies. The contact conductance plays significant role in many applications like aircraft structural joints subjected to aerodynamic heating, nuclear power appliances, bolted and riveted joints [2], cooling of electronic chip [3], etc. With the advent of computer technology most of the equipments are embedded with an electronic chip. According to Moore's [4] law, number of transistors in a chip is doubling every eighteen months and this is leading to more power requirements and consequently higher operating temperatures. It is a well-known fact that the reliability of circuits (transistors) is exponentially dependent on the operating temperature of the junction and as such, small differences in operating temperature (order of 10–15^{o}C) can result in doubling the lifespan of the devices. [5] Some of the other applications where thermal contact conductance plays a significant role are listed here.

i. Structural joints of machine tools. [6]
ii. Dry sliding contacts. [7]
iii. Injection molding [8]
iv. Aircraft structural joints subjected to aerodynamic heating. [9]

The study of different parameters affecting thermal contact conductance is carried out by Yovanovich et al [10] and the problem is expressed in the form of a triad for thermal contact conductance/ resistance. The triad consists of three basic problems: i) Geometry based ii) Mechanics based and iii) Thermal based. The intersection in the triad yield following problems to be addressed:

i. The geometry and mechanics constitutes the contact mechanics problem.
ii. The geometry and thermal lead to constriction (spreading) resistance problem.
iii. The mechanics and thermal constitutes the thermal elastoplasticity problem.

The intersection of geometry, mechanics and thermal constitutes the thermal contact resistance problem. The thermal contact resistance problem can be solved with reference to contact mechanics theory. There are three types of contact mechanics problems a) pure elastic contact, b) pure plastic contact, and c) the more complex elastoplastic contact. In the present work elastic contact is considered.

2. Objective and Solution Methodology

Mean plane separation is the distance between the two nominal contacting surfaces, which changes with the applied load. The variation in mean plane separation results in the change in number of peaks coming in contact with each other and this is responsible for the change in contact area. In the present research work the effect of change in mean plane separation on contact heat transfer for different surface roughness is studied

The objective of estimating the contact area and heat transfer is a complex, non linear problem due to the consideration of contact between two rough surfaces. The solutions to the problem obtained from theoretical models require independent validations. A comprehensive solution methodology which includes theoretical and numerical method (finite element analysis) is adopted in the present research work. The main objective of present research work is to study the variation in contact area and heat transfer due to change in distance between planes for a given set of work pieces. It is important to note here that the accuracy of calculation of contact area and heat transfer is not the focus of present work, but instead the amount of change in these parameters due to distance between planes is studied thoroughly. In this context the basic Greenwood and Williamson [11] and Cooper Mikic Yovanovich [12] models are employed to estimate the real area of contact and contact conductance for different distance between planes. The contact conductance is evaluated for different cases using finite element analysis and using GW and CMY models.

Few assumptions considered in the present work are as follows.

i. The elastic deformation of contacting summits is considered in the analysis as self weight of the bodies is the sole load acting.
ii. Contacting surfaces are isotropic. The variation in RMS roughness is considered.

The two methods used to study the research objectives are discussed in the following section.

2.1 Theoretical calculations

In the present research work the typical surface roughness values used by McCool [13] are considered and the 'Greenwood and Williamson' model is used to find the contact area between two contacting bodies for different distance between planes. The equation 3 is used to compute real area of contact between work pieces for various distances between planes.

$$\frac{A_C}{A_O} = \pi R_1 \sigma_S D_{SUM} F_1\left(\frac{d}{\sigma_S}\right) \quad (3)$$

$$h_C = \frac{2k_s na}{\left(1-\sqrt{\frac{Ac}{Ao}}\right)^{1.5}} \quad (4)$$

The equation 4 based on CMY model is used to find the contact conductance between the contacting surfaces. The results are evaluated against the objectives of research work. Computed contact areas for same set of work pieces in contact but with different mean plane separations are compared. The contact heat transfer depends on actual area of contact and the results obtained for contact area give an insight into the variation of contact heat transfer with distance between planes.

2.2 Numerical analysis (Finite Element Analysis)

The finite element study is carried out to understand the effect of distance between mean planes, on contact heat transfer. A proven finite element analysis platform, ANSYS has been used for the same. The finite element analysis yields the temperature distribution in the contacting work pieces for given boundary conditions. The surface roughness on the contacting surfaces of work pieces is carefully incorporated in the modeling stage. The inclusion of surface roughness which is in microns in the finite element model where other geometric dimensions are in millimeter is a significant part of present research work. Contact elements are used which help in replicating the actual contact present in contacting surfaces and this requires nonlinear solution. One dimensional steady state heat transfer is considered. The temperature distribution in a given set of work pieces which are in contact but with different distance between planes is obtained through finite element analysis. Simulation is carried out for number of cases with different RMS roughness values.

2.2.1 Analysis methodology

The two surfaces A and B having variations in surface parameters when come in contact, the contact area differs with distance between planes as the number of peaks in contact change. The finite element simulation, starts with the creation of two bodies with given surface roughness. The dimensions of bodies and surface roughness are of different order; body dimensions are usually in millimeter whereas surface roughness parameter is some fraction of millimeter. It is therefore, required to take substantial care in the modeling step. A number of different ways have been suggested to create rough surface using ANSYS software. In the present research work surface roughness is included in the initial stage of modeling. The simulation is carried out with the steps

i. Modeling
ii. Meshing
iii. Approach of Bodies
iv. Boundary conditions
v. Solution.

2.2.1.1 Modeling

The generation of rough surface is the most difficult part in the modeling. The surface roughness parameter is in microns whereas the geometric nominal dimensions are in millimeter. The different scales pose a great challenge in modeling a volume having typical nominal dimensions as well as incorporating surface roughness. The solid bodies are created with different roughness parameters on contacting surfaces. This variation in roughness parameter is included in the modeling at the generation of key point level. The modeling involves following steps.

i) Creation of key points in 3 dimensional space
ii) A set of random numbers are created which follow Gaussian distribution with given mean and standard deviation. The key points are created at specified X, Y locations and random numbers are used to specify Z co-ordinate. The Gaussian distribution is used in the generation of random numbers and therefore the key points based on these random numbers follow Gaussian distribution.
iii) The creation of areas with the already generated key points.
iv) A block having rough surface is generated by extruding the areas.
v) The subtraction of a small block from already created block having rough surfaces is carried out to get one side flat and another side rough surface.

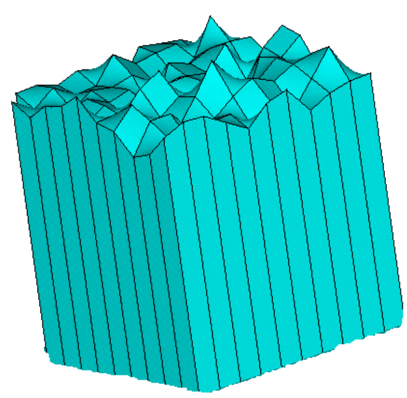

Fig. 2 Creation of Volume having One Rough Surface

2.2.1.2 Discritization

The contacting bodies are meshed with thermal solid element with appropriate material properties. Contact elements are created at the two surfaces of bodies where contact is going to occur. Solid 87 elements are used to mesh the volumes. Target 170 and Conta 174 elements employed to create contact pair between the two work pieces.

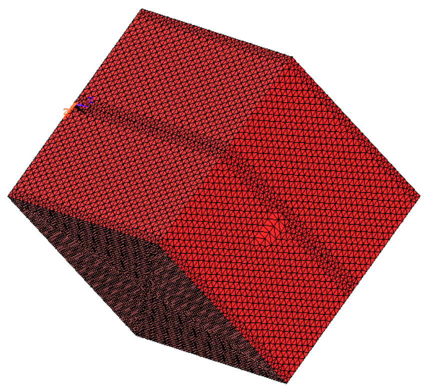

Fig.3 Meshing of Volumes

2.2.1.3 Contact between bodies

One contacting body is moved towards the other with a specified distance to achieve the contact pair between the two bodies. The variation in movement of one body relative to other, results in different mean plane separations.

2.2.1.4 Boundary conditions

Energy boundary conditions are applied.

2.2.1.5 Solution

The finite element equations are solved using the PCG (Programmed Conjugate Gradient) solver available in ANSYS tool. This step yields the temperature distribution in the contacting bodies.

The process is repeated for contact pairs with different distance between planes. Simulation is carried out for the contact of two surfaces with typical surface roughness parameters. The different steps of the simulation require significant amount of preparation, model building and running time.

2.2.2 Input data and assumptions

The finite element simulation starts with modeling of contacting bodies. Dimensions of contacting bodies and thermal conductivities are listed in the table 1.

The present finite element simulation uses RMS roughness (standard deviation of summit heights, σ_{S1} and σ_{S2}) and mean distance between two contacting surfaces as the input parameters. The finite element simulation as well as theoretical analysis using GW model is carried out for various roughness parameters and one set is listed in table 2. The numerical values of standard deviation of heights mean separation between two surfaces and density of summits are referred from literature [13] so that roughness parameters represent typical values. The values of one set of parameters used in the simulation are listed in the table 2.

Table 1: Modeling Data

Dimensions and material properties				
	Width mm	Breadth mm	Depth mm	Thermal Conductivity W/mK
Body 1	20	20	10	50
Body 2	20	20	10	50

Table 2: Surface Roughness Parameters

Surface parameters for roughness set 1	
Parameter	Value (mm)
Standard Deviation	0.00024
Mean separation between surfaces	0.0006,0.0004,0.0003,0.0002, 0.0001

A constant heat flux of 5W/m^2 is applied to one of surface of a contacting body and same heat flux is removed from the other contacting body. All lateral surfaces of contacting bodies are insulated.

3. Results and Discussion

The distance between contacting bodies is changed by moving the bodies with respect to each other and this result in the variation of number of peaks coming in contact with each other. The increase or decrease in number of peaks in contact is responsible for variation in the real area of contact as the distance between contacting surfaces change. The theoretical computations using GW model yield contact areas for a given set of work pieces for different distance between planes and for various roughness sets. Similarly finite element analysis gives temperature distribution for different cases and these temperature drops are utilized in finding contact conductance. The results of theoretical and finite element analysis are systematically represented with ‘Contact Area Variation Index’ and ‘Contact Conductance Ratio’. The ratio of contact area to the maximum contact area among various distances between planes for a given roughness set is defined as “Contact area Variation Index’. Similarly contact conductance ratio is used to represent variation of contact heat transfer with distance between planes for a set of surface roughness.

Figure 4 to Figure 7 show temperature distribution of lower work piece, as the distance between planes is varied from 0.0004 mm to 0.0001 mm. The red contours show the contact spots between the two work pieces through which heat flows. The lower work piece is in contact with upper hot work piece at these spots. It is evident from the temperature contours that, at larger gaps between two planes, contact occur at few points and as the gap reduces more number of summits comes in contact and the real area of contact increases. This variation of contact area with distance between two mean planes is manifested as the steep change in the temperature of lower work piece. The temperature in lower work piece for a gap of 0.0004 mm, varies between 59^0C to 101^0C where as for the same work piece, if the distance between planes is 0.0001 mm, the temperature ranges between 195^0C and 242^0C. This indicates clearly that, as distance between planes, decreases, the contact area increases.

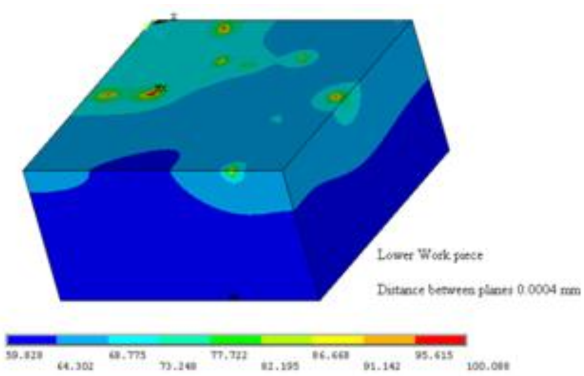

Fig. 4 Temperature Distribution for Distance between Planes 0.0004 mm

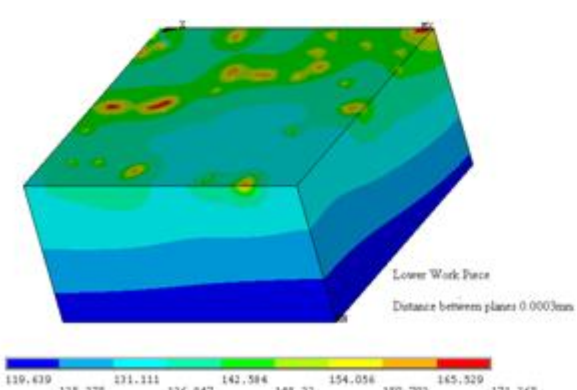

Fig. 5 Temperature Distribution for Distance between Planes 0.0003 mm

Figures 8 to 12 show variation of contact conductance against distance between planes for various roughness sets. The contact conductance increases with reduction in gap between planes for all options of surface parameters. This represents the significant effect of distance between planes on contact area and contact conductance

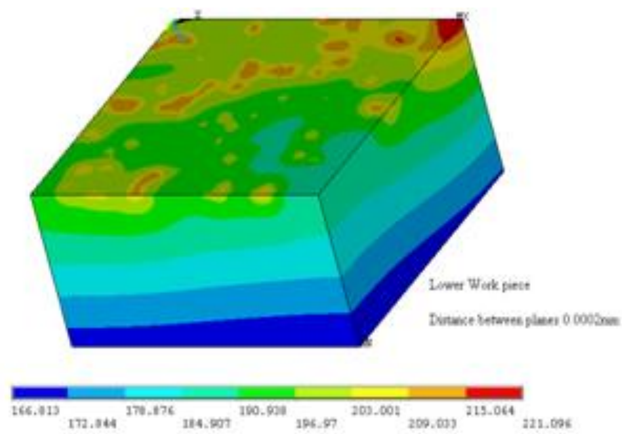

Fig. 6 Temperature Distribution for Distance between Planes 0.0002 mm

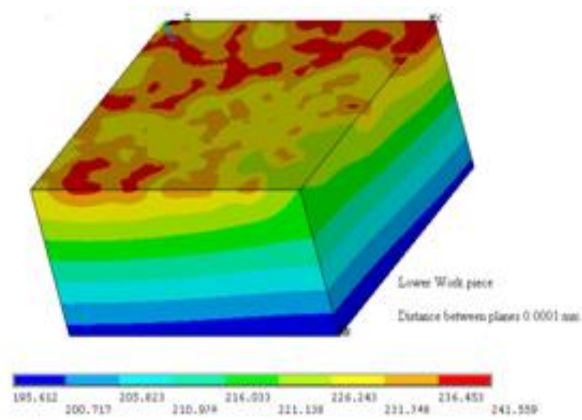

Fig. 7 Temperature Distribution for Distance between Planes 0.0001 mm

Figure 12 and 13 show the variation of contact area computed using GW model, with distance between planes for different distance between planes. It can be observed from the graphs that as the distance reduces the contact area increases

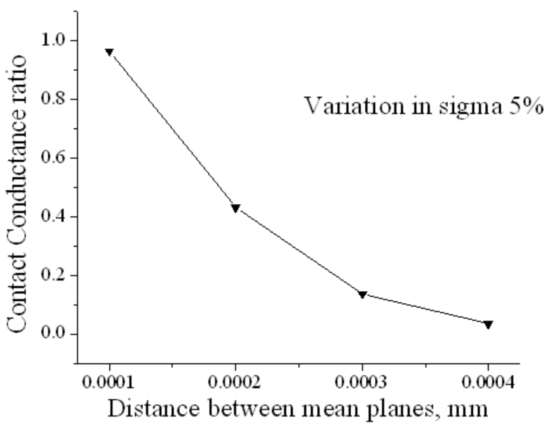

Fig. 8 Variation in Contact Conductance for Roughness set 1

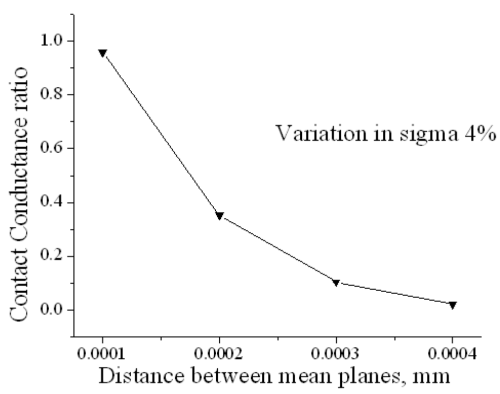

Fig. 9 Variation in Contact Conductance for Roughness set 2

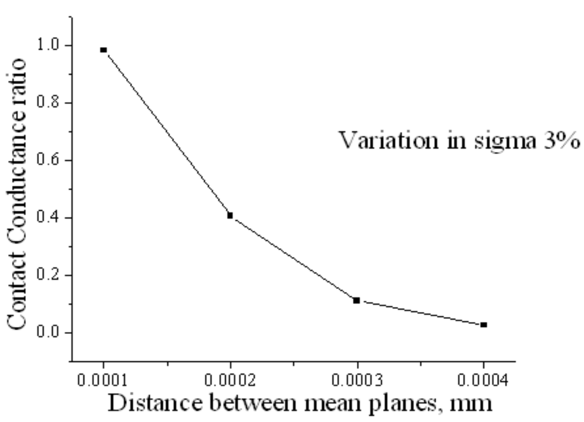

Fig. 10 Variation in Contact Conductance for Roughness set 3

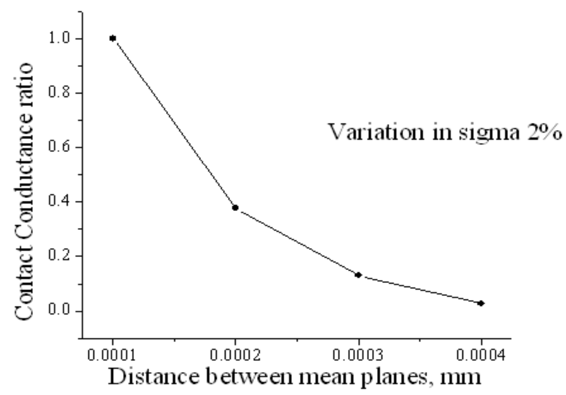

Fig. 11 Variation in Contact Conductance for Roughness Set 2

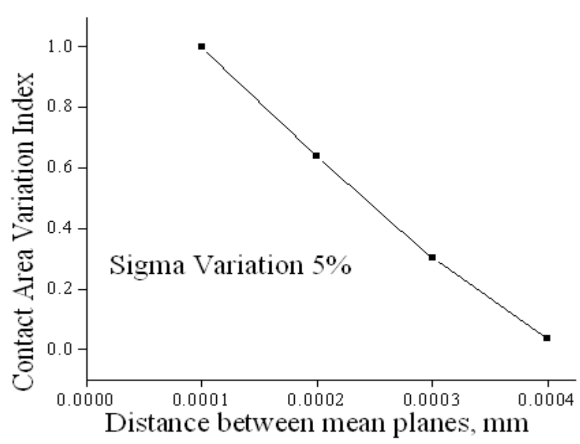

Fig. 12 Variation in Contact Area for Roughness set 1

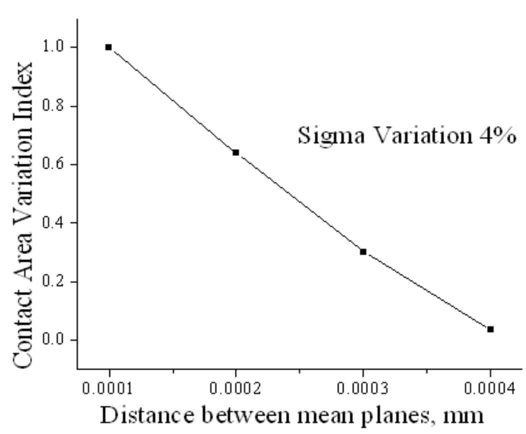

Fig. 13 Variation in Contact Area for Roughness Set 2

4. Conclusion

The theoretical and finite element study of effect of distance between mean planes, and variation in RMS roughness of given surfaces, on contact area and heat transfer is studied. The GW model is used to find the real area of contact between rough surfaces. A proven finite element analysis platform, ANSYS has been used for finite element analysis. The finite element analysis yields the temperature distribution in the contacting work pieces for given boundary conditions. As the contact heat transfer depends on the real area of contact, it is observed from finite element and theoretical results that the trends of contact heat transfer and contact area are same. It indicates clearly that the present finite element model which develops a realistic model of rough surface can be employed to study the effect of roughness and other parameters on contact heat transfer.

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Nomenclature

ΔT	Temperature drop	^oC
hc	Thermal contact conductance	$W/m^{2o}C$
A	Cross sectional Area	m^2
RMS	Root Mean Square Roughness	mm
A_c	Real area of Contact	mm^2
A_O	Nominal Area of Contact	mm^2
R_1	Radius of summits in surface profile	mm
σ	RMS surface roughness	mm
D_{SUM}	Density of summits	
F_1	Factor referred from tables	
d	Distance between planes	mm

