LLNL-TR-676929

Sensor 17 Thermal Isolation Mounting Structure (TIMS) Design Improvements

Ken Enstrom

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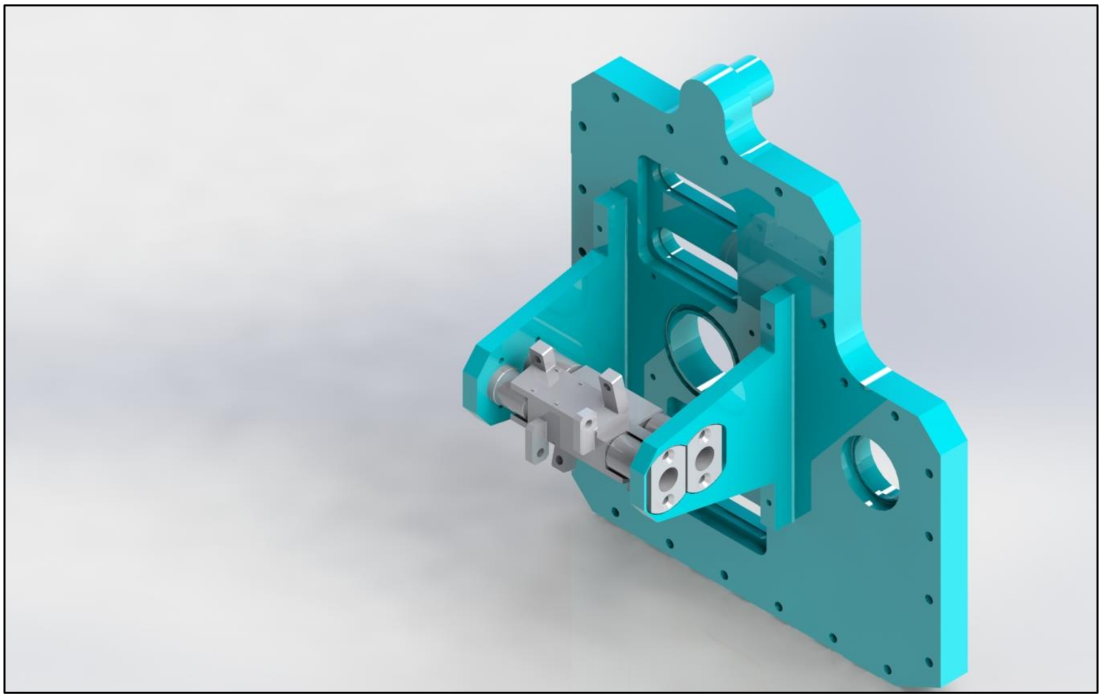

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Lawrence Livermore National Laboratory
NSED - Engineering

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1. Motivation

SENSOR 17 is used in airborne applications and may experience a loss of functionality on exceptionally hot days. The heat leakage into the system through the thermal isolation mounting structure (TIMS) can overwhelm the Stirling cycle cryocooler employed. No previous attempt to improve or optimize the TIMS beyond the initial design has been attempted. The work in this report describes a new design that improves performance dramatically, thereby addressing this potential loss of functionality.

A major benefit of this study is the direct translation to SENSOR 19, a new sensor under development with a more challenging TIMS problem due to increased size and weight relative to SENSOR 17. The proposed TIMS for SENSOR 19 is an extrapolation of the SENSOR 17 design. The components were approximately doubled in size to handle the mass of the larger 2.2lb SENSOR 19. This paper describes analytically predicted performance for a new, improved TIMS for SENSOR 17. Test articles are in fabrication. Tests are planned to quantify the thermal performance of this new thermal isolation system. If results are close to predictions, we will apply the new TIMS concept to a SENSOR 19 test article. If successful, we will have the capability of significantly reducing the heat load on the SENSOR 19.

Currently the SENSOR 19 heat load from the TIMS is approximately 2.5W. This loading drives cryocooling solutions that are highly undesirable (e.g. – use of two COTS Stirling cycle cryocoolers vs use of one, or incorporation of a large Gifford-McMahon cycle unit). If the new TIMS reduces heat leakage enough, the SENSOR 19 overall system Size, Weight and Power (SWaP) can be drastically reduced.

2. Introduction

The SENSOR 17 thermographic camera weighs approximately 0.5lbs, has a fundamental mode of 167 Hz, and experiences 0.75W of heat leakage in through the TIMS. The configuration, shown in Figure 1, is comprised of four 300 Series SST washers paired in tandem with P.E.I (Ultem 100) washers.

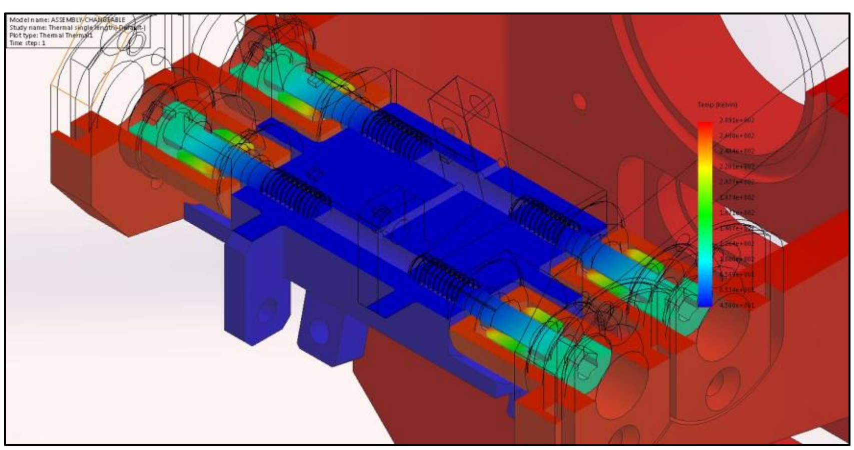


Figure 1. Horizontal cross-section of SENSOR 17 heat model generated using SolidWorks Simulation.The thermal isolation mounting system (TIMS) is shown in teal/green/yellow. The warm mounting arms are shown in red (ambient temperature). The IR Mount structure for SENSOR 17 is shown in blue.

The SENSOR 17 sensor is mounted to a 300 series stainless plate with A-shaped arms. The Plate can be assumed to be at ambient temperatures (≈293K) and the I.R. Mount needs to be cooled to 45K. It is attached to the tip of a cryocooler by a ‘cold strap’ and is assumed to be at the temperature of the cold-strap (≈45K).

During flights SENSOR 17 experiences excitations at frequencies centered around 10-30Hz, 60Hz, and 120Hz from the aircraft flight environment. The temporal progression described below depicts the 1st Modal shape at the systems resonant frequency.

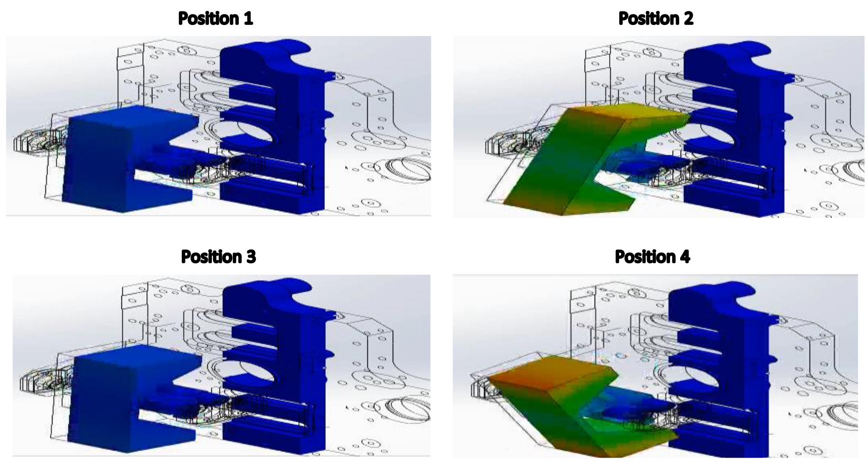


Figure 2. SENSOR 171st node articulation shape.

This simulation indicates Modal articulation will cause a pitch rate of the camera with respect to the body axis of the airplane. This articulation shows up as flutter in the camera.

3. Investigation

For a preliminary analysis of our system the thermal resistance network technique was utilized to understand the mounting structure at a basic level. The method utilizes an analogy between conduction heat transfer and electrical conductance. The analog of current is heat flux, the analog of voltage is a temperature gradient, and the analog of electrical resistance is thermal resistance. The following figure is the conduction analog of ohm’s law. Delta T (K) is the temperature differential across an element experiencing steady state heat flux, Q (W) is the heat flux, and R (K/W) is thermal resistance.

$$\dot{Q} = \frac{\Delta T}{R}$$

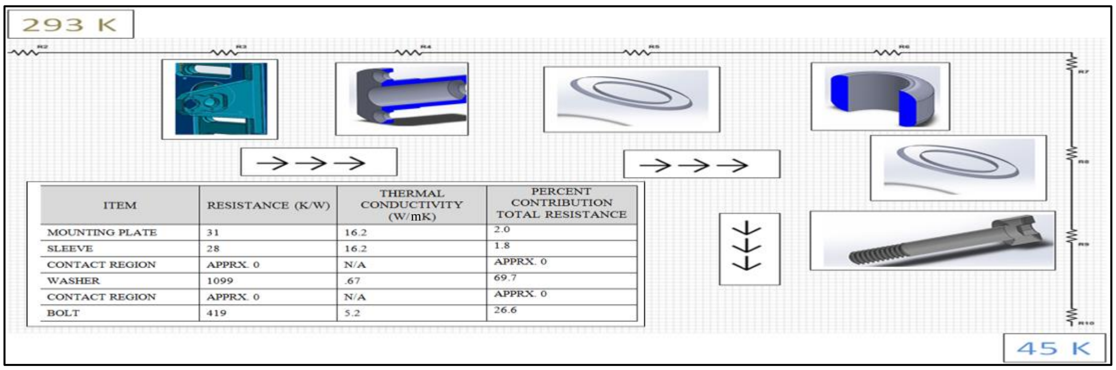
Figure 3. Conduction analogy to Ohm's law.

Thermal resistance (R), in units of K/W, is calculated in the case of conduction using the the equation in Figure 4.

$$R = \frac{L}{K * A}$$

Figure 4. Thermal resistance to conduction calculation.

In Figure 4 L is the length of the material, K is the material thermal conductivity (W/meter*K), and A is the cross sectional area normal to the flow of heat flux through the material. From this basic analogy a network for the SENSOR 17 mounting system was developed and visualized in Figure 5 below.



ITEM	RESISTANCE (K/W)	THERMAL CONDUCTIVITY (W/mK)	PERCENT CONTRIBUTION TOTAL RESISTANCE
MOUNTING PLATE	31	16.2	2.0
SLEEVE	28	16.2	1.8
CONTACT REGION	APPRX. 0	N/A	APPRX. 0
WASHER	1099	.67	69.7
CONTACT REGION	APPRX. 0	N/A	APPRX. 0
BOLT	419	5.2	26.6

Figure 5. SENSOR 17 thermal resistance network pre-modification.

Figure 5 includes a table showing the approximate contribution to total thermal resistance of the system. Upon first inspection, the Ultem 1000 washer was proven to be our primary contributor to thermal isolation at 70% of overall system resistance. In order to progress into a full-fledged F.E.A model some boundary conditions and material properties must be defined. William Hunt provided the following experimental observations in an attempt to accurately define the SENSOR 17 system. The observations are shown in Table 1 below.

Table 1. Experimental conditions and gathered data.

Experimental Condition	Value
Mounting Arm Temp	293 K
Assumed Cold Strap Temp. And bordering components	45 K.
System 1st Modal Frequency	167 Hz.
Mock I.R. Mass	265 g
Heat Flux Through Mounting Structure	¾ Watt

Thermal conductivities of the 300 series stainless as well as the titanium alloy to be used in the design modification were taken from a study carried out by the University of Colorado, Boulder. The thermal conductivities of metals changes orders of magnitude as the temperature is cooled to 100K and below from atmospheric conditions. The following table is from the study and highlights how the thermal conductivities were calculated.

Table 2 Thermal conductivities of a selection of metals from 4-300K.

Coeff.	6061 -T6 Aluminum	304 SS	718 Inconel	Beryllium copper	Ti-6Al-4V
a	0.07918	-1.4087	-8.28921	-0.50015	-5107.8774
b	1.09570	1.3982	39.4470	1.93190	19240.422
c	-0.07277	0.2543	-83.4353	-1.69540	-30789.064
d	0.08084	-0.6260	98.1690	0.71218	27134.756
e	0.02803	0.2334	-67.2088	1.27880	-14226.379
f	-0.09464	0.4256	26.7082	-1.61450	4438.2154
g	0.04179	-0.4658	-5.72050	0.68722	-763.07767
h	-0.00571	0.1650	0.51115	-0.10501	55.796592
I	0	-0.0199	0	0	0
data range	4-300 K	4-300 K	4-300 K	4-300 K	20-300 K

$$\log(k) = a + b\log T + c(\log T)^2 + d(\log T)^3 + e(\log T)^4 + f(\log T)^5 + g(\log T)^6 + h(\log T)^7 + i(\log T)^8,$$

Due to the fact that no temperature measurements were made with respect to the individual components in the mounting structure of the SENSOR 17, this selection of material temperature became an iterative process in order to hone in on experimental conditions. The thermal conductivity of the Ultem 1000 washer material was also a large unknown. It was approximated to be on the order of less than 1 W/mK but not cryogenic data existed for reference. In order to understand how Ultem behaves at cryogenic temperatures, boundary conditions and experimental data was used to back solve the thermal conductivity of the Ultem. In Figure 6 a distribution of temperature probe points in an F.E.A model were taken as a preliminary step of analysis.

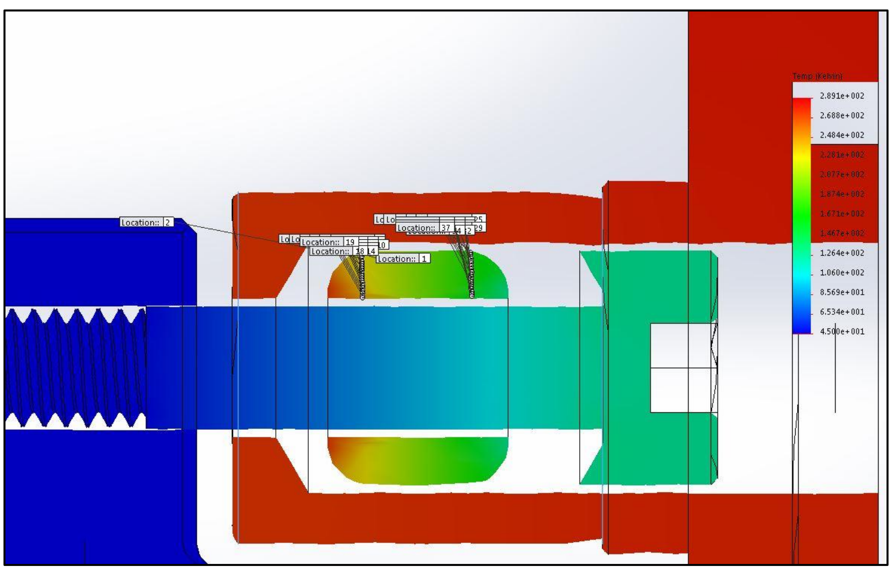


Figure 6. Calibration points for Ultem 1000 washer.

Referring back to the Ohm's law analogy shown in Figures 3 and 4, it can be readily understood how the Thermal conductivity was calculated. Our system knowns from experimentation and observation are the heat flux through the washer, 0.75W total or .1875W per bolt, as well as the physical length and cross sectional area of the washer. The F.E.A generated temperature differential now allows us to calculate the only unknown, thermal conductivity. The calculated value after an iterative process to this problem was applied was 0.67 W/mK. All experimental thermal conductivities have been compiled into Table 3.

Table 3. Compiled thermal conductivities.

Component	Thermal Conductivity (W/mK)
300 Series SST Back Plate at ambient	16
Titanium Alloy Ball Bearing at100K	≈3
Titanium Alloy Ball Bearing at 293K	≈6
300 Series SST at 45 K	≈5
300 Series SST at 100K	≈8
Ultem 1000 at 180K	≈0.7

This determination of thermal conductivity concluded the investigation into the SENSOR 17 system and provided a solid base for future modification. With a working thermal and nodal model we could now determine how modifications to existing components would alter system properties such as heat leakage and stiffness. Contact conductance between the washer and adjoining surfaces was shown to be negligible using the methods laid out in the conceptual realization of this report.

It should be known that a change in original contact patch thickness was noted by Will after this analysis was done. It can be theorized that this contact patch provided additional system resistance to the original design and may slightly overstate the improvement from our design modification. The original estimated width of the contact patch was 1 millimeter with an approximate diameter of .22”. The newly measured contact patch may be half the width or less. As contact width decreases, overall system resistance increases.

4. Design Modification

Noting the minimal contact conductance as well as the large conical contact plane between the washer and adjoining surfaces, a new design was proposed to enhance the SENSOR 17 thermal isolation system. The proper materials for cryogenic isolation are well known. A low thermal conductivity metal alloy and plastic have already been utilized in tandem. From here, contact resistance and thermal channeling must be used in order to further optimize the system. A design using Titanium balls was conceived in order to increase Brinnel hardness and therefore reduce contact plane surface area. In Figure 7 below, the proposed design is visualized.

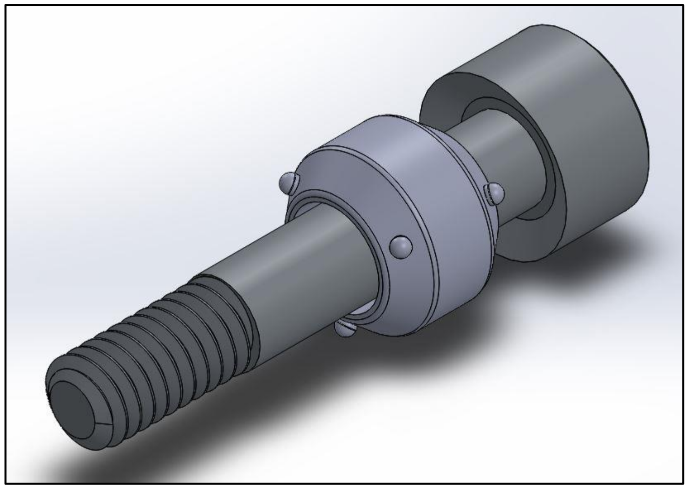


Figure 7. Design modification.

The small point contacts, created by the .0268" diameter balls, target heat flux. The three distinct points along the periphery of the washer channel heat flow to a greatly reduced cross sectional area and improve the overall resistance of the washer while providing an additional thermal break in themselves.

5. Conceptual Design Verification

In order to understand contact resistance, a Hertzian stress analysis was performed to determine circular contact area between the sphere surface and the plane it rests. In appendix A the process is captured in an Excel Worksheet. The two primary equations utilized to determine contact resistance are shown below in Figure 8.

SPHERE/PLANE EQUATION

$$a = \sqrt[3]{\frac{3F}{8}\frac{(1-\nu_1^2)/E_1+(1-\nu_2^2)/E_2}{1/d_1+1/d_2}}$$

$$h_c = 4200 k_s R_a^{-.257}\left(\frac{P}{H}\right)^{0.95}$$

Figure 8. Contact Resistance Equations.

The units and exact procedure are laid out in the thoroughly laid out in Appendix A. The equations show a correlation between Brinnel hardness, pressure, surface roughness, mean thermal conductivity, to contact resistance.

It was determined that the overall contact resistance per 3 ball pair was on the order of 5 K/W. It was also determined that the conical contact strip of the current SENSOR 17 design provided negligible contact resistance to the system.

Through the same analysis method demonstrated in the investigation section of this report the new design was found to reduce overall heat leakage to 250mW while leaving system stiffness unaltered. The modified resistance network is visualized in Figure 9 below.

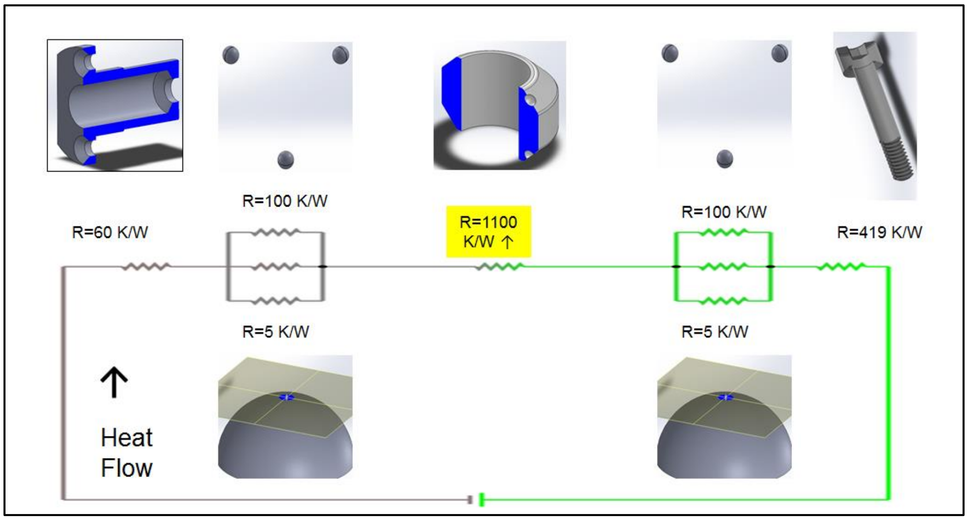


Figure 9. Modified resistance network.

The additional contact resistances have been added and the improvement to the washer resistance highlighted. The exact improvement to washer resistance should be verified through measurement, but can be approximated to be on the order of a 50% improvement to the original washer resistance. The other 17% improvement comes from calculated contact patch resistance and the thermal resistance through the titanium ball. The improvements to system properties are documented in Table 4.

Table 4. SENSOR 17 Design improvements.

ITEM	VALUE (UNIT)	PERCENT IMPROVEMENT
OVERALL HEAT FLUX (**3-BALL** LATHE WASHER)	250 (mW) Vs. 750mW	66.6%
SYSTEM STIFFNESS (**3-BALL** LATHE WASHER)	167 (Hz)	N/A

In order to confirm system stiffness remains unaltered a static deformation analysis was preformed using the known bolt loading. The deformation shown in Figure 10 below is less than 0.0007".

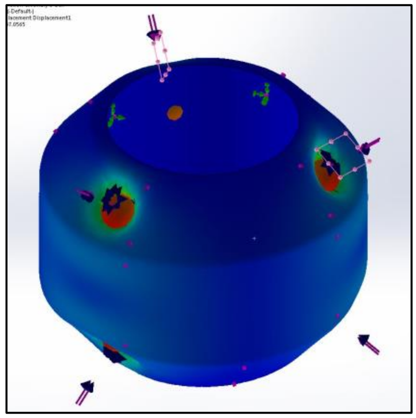


Figure 10. Washer deformation under load.

6. Design Realization

In order to confirm the theory applied to the analysis of the SENSOR 17 design, as well as modifications made, laboratory tests will be performed to verify the Ultem thermal conductivity, measure the thermal isolation system heat flux and temperature drop, and measure the system natural frequency,.

3/8" Ultem stock has been obtained in order to manufacture the modified SENSOR 17 washer as well as semi-precision .0268" diameter Titanium balls. Figure 11, taken from Bal-tec, describes the tolerances on a grade 100 semi-precision ball.

Surface Integrity is defined as the surface smoothness and freedom from defects such as flats, pits, soft spots and cuts. Semi-precision balls must be free of such defects when inspected without magnification.

Size is the mean diameter, measured between two parallel planes on the ball surface. Tolerances for semi-precision balls are ±0.0005 (grade 100) up to ±0.005 (grade 1000).

Sphericity is defined as the deviation (out-of-round condition) from a true spherical form. The normal range of sphericity for semi-precision balls is between ±0.0001 (grade 100) and ±0.001 (grade 1000).

Figure 11. Semi-Precision ball tolerances.

Raymond Visceral from LLNL's precision machine shop has been briefed on our needs and a manufacturing plan has been determined. Approximately 8 hours of machine time is needed to manufacture four of the modified SENSOR 17 washers. A .028" bull nose end mill has been obtained for use when drilling the ball pockets. The manufacturing plan proposed and approved by Ray is visualized by the blue tooling lines in Figure 13. Tests set up and results will be described in a separate report.

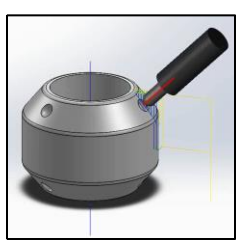


Figure 12. Tooling path visualization for modified washer.

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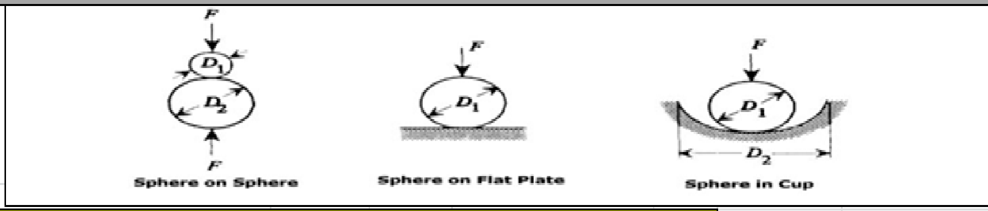
Appendices

Hertzian Contact Stress Calculation



INPUT PARAMETERS

PARAMETER	SYMBOL	OBJECT 1	OBJECT 2	UNIT
SHAPE		SPHERE	PLANE	
POISSON'S RATIO	v	0.305	0.305	#
ELASTIC MODULUS	E	28500	28500	ksi
DIAMETER	d	0.0258	INFINITY	inch
FORCE	F	50	50	lbf
NOT APPLICABLE FOR SPHERE	l	1	N/A	inch
NUMBER OF BALLS IN WASHER	3	←←← ITERATION		
CONTACT ANGLE	45			

CONVERTED VALUE		
OBJECT 1	OBJECT 2	UNIT
0.305	0.305	#
28500000	28500000	psi
0.0258	INFINITY	inch
50	50	lbf
1	N/A	inch

FORCE PER BALL	23.57022604

RESULTS

PARAMETER	SYMBOL	OBJECT 1	OBJECT 2	UNIT
CONTACT RADIUS	a	0.002439299		inch
CONTACT AREA		1.8693E-05		sq. in.
		1.206E-08		sq. m

SPHERE/PLANE EQUATION

$$a = \sqrt[3]{\frac{3F}{8}\frac{(1-v_1^2)/E_1 + (1-v_2^2)/E_2}{1/d_1 + 1/d_2}}$$

CYLINER/PLANE EQUATION

$$b = \sqrt{\frac{2F}{\pi l}\frac{(1-v_1^2)/E_1 + (1-v_2^2)/E_2}{1/d_1 + 1/d_2}}$$

CONTACT RESISTANCE CALCULATION

THERMAL CONTACT CONDUCTACE CORRELATION

$$h_c = 4200 k_s R_a^{-.257}\left(\frac{P}{H}\right)^{0.95}$$

where:

SYMBOL	DEFINITION	UNITS	EQUATION
ks	harmonic mean thermal conductivity	(W/mK)	$k_s = \frac{2k_1k_2}{k_1+k_2}$
Ra	combined average roughness	(m)	$R_a = \sqrt{R_{a1}^2 + R_{a2}^2}$
P	Pressure	Mpa	
H	Hardness	brinnel	

INPUTS

Ks	3.09
Ra	1.25E-05
P	8693.661829
H	100

RESULTS

	VALUE	UNITS
250	0.198103397	W/K
	5.0	K/W

←← ANSWER