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Re-entry Survivability Analysis of Aluminum Oxide with Surface Roughness Considerations

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Abstract

Reentry survivability is important in the minimization of the risk of space object to human populations. An accurate re-entry survivability needs to consider the importance of surface roughness. A preliminary study of re-entry survivability with the surface roughness consideration is carried out based on its effect on the surface heat transfer due to the catalytic properties. Two different levels of surface roughness for aluminum oxide materials are considered in the present study. The catalytic properties of these materials are measured from the heat transfer measurement at the shock tube end-wall combined with the catalytic heat transfer theory. From the experimental measurement, it is found that the catalytic property increases for the roughened material. With the catalytic efficiency values obtained from the experimental condition, the re-entry survivability analysis shows that a material with a high level of surface roughness exhibits a low survivability rate.

Keywords: *re-entry survivability, surface roughness, shock tube, aluminum oxide*

1. Introduction

During the atmospheric re-entry of space debris, bow shocks form upstream of any blunt-shaped body, and majority of the kinetic energy is quickly converted into thermal energy, leading to high temperatures on the vicinity of the surface. Therefore, dissociation, ionization, and excitation of molecular vibration within the shock layer are produced. On the surface, the flow can re-accelerate, and recombination may occur. The exothermic surface catalytic recombination has a major impact on surface heat transfers via the diffusive heat transfer, which is usually greater than the conductive heat flux. It has previously been observed that the surface catalytic recombination effect can bring up to two-thirds of the total heat flux, consequently causing an increase in the wall temperature and eventually leading to ablation, which induces low survivability during re-entry. Due to this situation, the catalytic recombination makes it difficult to predict the heat flux of space debris, as well as its survivability.

Considering the substantial impact of surface roughness and catalycity in the surface heat transfer estimation, the present study targets to investigate these factors and their effects on re-entry survivability of aluminum oxide (Al_2O_3). Following the previous approach by Kim et al. [1], catalytic heat transfer theory is used to determine the surface catalytic recombination activity using a shock tube. The influence of surface roughness is investigated by controlled grinding the material surface with different levels of sandpaper. The obtained recombination efficiency values for Al_2O_3 are used as the input parameter in the re-entry trajectory analysis code. Two different types of surface roughness material are considered and labelled as smooth and rough surfaces. The influence of surface roughness on the re-entry survivability of the material is elaborated in the discussion section.

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2. Re-entry Survivability Analysis

To carry out the re-entry analysis, an object-oriented based tool called `ATD Trajectory Tool (ATDTT)' is utilized in the present study. This tool can analyse individual simple-shaped parts (sphere, box, cylinder, and flat plate) of re-entry satellites or the upper stages of launch vehicles. One of the main features of these tools is their fast simulation, which gives users the ability to quickly perform a wide range of analyses. This tool has been validated by comparing it with other existing tools in previous studies [2-3].

The trajectory module estimates a 3DOF trajectory assuming the object regarded as a point mass. The Earth is assumed to be a rotating sphere and equations based on an Earth-fixed reference frame are elucidated using a 4th-Order Runge-Kutta method. For the atmosphere module, the NRLMSISE00 model is used, and temperature, pressure, and density are considered. The aerodynamics module estimates the average drag coefficient according to the shape and motion of the object. In this calculation, flow regimes are divided into free transitional, molecular, and continuum flow, in accordance with the Knudsen number (Kn), a dimensionless number (ratio of mean-free path and characteristic length). The aerodynamic coefficient is determined for each flow regime. The net heat flux is computed from the aerothermodynamics module. In common with the aerodynamics module, the net heat flux is obtained for each flow regime. The resulting value comprises the convective, oxidation, catalytic, and re-radiation heat fluxes. The convective heating is calculated as the stagnation-point heat flux multiplied by averaging factors that represent the mean heating of the object considering its configuration and attitude motion. The wall enthalpy ratio is considered to determine the hot wall convective heating. The catalytic heating is defined as the diffusive heat transfer resulted from the wall catalytic recombination. The oxidation heating is estimated as the mass flux of oxygen flow to a surface multiplied by the oxidation heat. The re-radiation heat loss is calculated by using the Stephan-Boltzmann equation.

3. Experimental Details

The experiments were performed using a conventional pressure-driven shock tube facility, this facility has been described in detail by Kim et al. [1]. The facility has been widely used for catalytic efficiency measurements. It consists of an 86-cm-long driver tube and a 330-cm-long driven tube, separated by a thin polyethylene diaphragm. The test campaign was initiated by passive bursting of a polyethylene diaphragm due to highly-pressurized drive gas, creating an incident shock wave that propagated toward the driven tube. Then, the shock wave reflected off the end-wall of the driven tube, generating a high-temperature stagnant region near the end-wall relevant to flows around the stagnation-blunt body in a hypersonic regime. The experimental heat transfer measurement is carried out using thin-film gauges. Detailed explanations of the reflected-shock wave testings are available in previous studies [1]. Table 1 provides the summary of the flow condition considered in the present study.

Table 1. Flow Condition

Property	Experiment	Calculation
Driver Gas	He	
Driven Gas	21%O_2 – 79%Ar by volume	
	Condition 2	
p_2 [kPa]	52.7	51.3
u_{shock} [km/s]	1.96	2.01
	Condition 5	
p_5 [kPa]	276	266
T_5 [K]	-	3914

4. Results and Discussion

Figure 1 presents the variation of surface heat transfer with respect to time for both smooth and rough surface. In each level of surface roughness, several heat-transfer data are included to verify the reliability of the experimental heat transfer measurement using the thin-film gauges. In each considered case, the averaged heat transfer measurement with its uncertainty is also included.

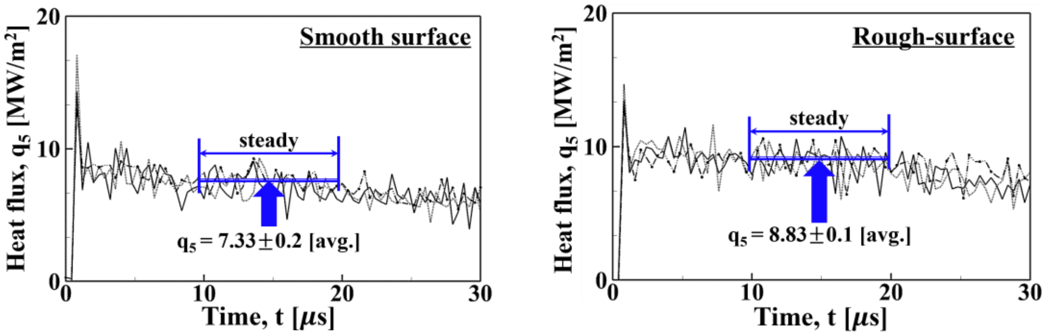

Fig 1. Heat transfer measurement results

Figure 2 shows the surface catalytic recombination values obtained by combining the theoretical formulation with the experimental measurement. The horizontal axis shows the oxygen catalytic recombination values, whereas the vertical axis shows the ratio between the diffusive and conductive heat transfers. The dashed curve depicts the theoretical heat transfer based on the Goulard formulation [3]. At lower surface efficiency values, no significant variation in the diffusive heat transfer is observed. At higher surface catalytic efficiency value, the diffusive heat transfer reaches its maximum value. Using this approach, oxygen surface catalytic recombination efficiency values of the Al2O3 on smooth and rough surfaces were obtained as 1.4e-03 and 7.5e-03, respectively. These recombination efficiency values were used as input parameters for re-entry survivability estimation.

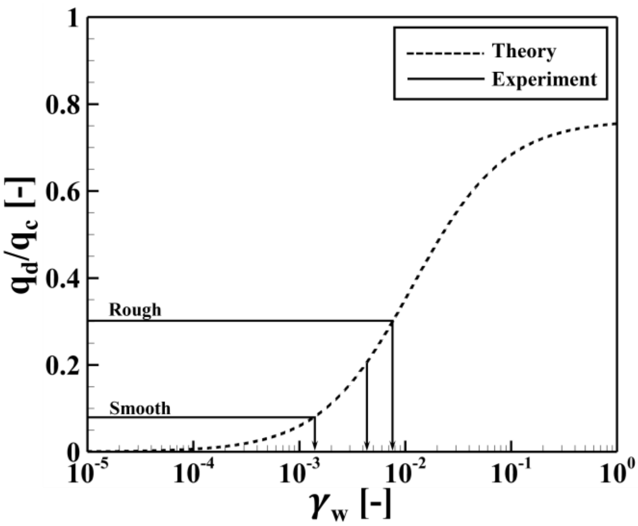

Fig 2. Surface catalytic properties determination

Figure 3 presents the calculated stagnation-point heat flux and integrated heat flux, determined based on measured experimental data. Six components of the trajectory and surface temperature were considered as the re-entry initial conditions: the altitude, flight path angle, inclination angle, relative velocity, latitude, longitude, and initial temperature were 122 km, -0.1°, 28°, 7.4 km/s, 0°, 0°, and 300 K, respectively. The test model was a sphere with a diameter of 0.25 m and the model was made of aluminum. For the calculation, the material properties considered were thermal conductivity (140 W/m-K), heat of fusion (390,000 J/kg), specific heat (1,100 J/kg-K), density (2,700 kg/m^3), melting temperature (850 K), and emissivity (0.3). The initial mass during the trajectory analysis was 17.3 kg**.**

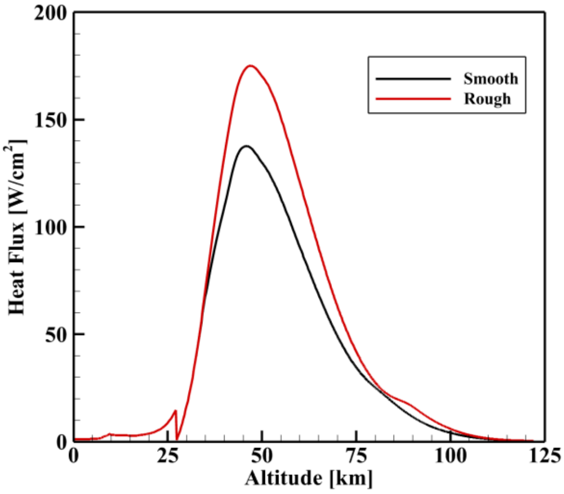

Fig 3. Heat flux at the stagnation point

Table 2 shows the survivability results for the objects with four different levels of surface roughness. The results indicate that, as the surface becomes rougher, the surface heat flux increases, resulting in lower survivability.

Table 2. Re-entry Survivability for Al_2O_3-Coated Surface

Surface Treatment	Catalytic Efficiency	Final Radius	Final Mass [kg]	Survivability [%]
Smooth	1.4×10^{-3}	0.117	13.34	77.1
Rough	7.5×10^{-3}	0.103	7.58	43.8

Conclusions

Re-entry survivability analysis results for aluminum oxide materials with different levels of material surface roughness were presented. The effect of surface roughness was included in the re-entry analysis using the surface catalytic recombination efficiency values, which were obtained from the experimental heat flux measurement in a shock tube using thin-film heat flux sensors. Compared to the smooth surface, the roughened surfaces exhibited increases in surface heat in the order of 21%. The catalytic recombination efficiency values were deduced by comparing heat transfer measurements with values predicted using Goulard's catalytic heat transfer theory. With the obtained surface catalytic recombination efficiency values, the survivability was found to decrease from 77.1% to 43.8%. In this analysis, it was found that the level of surface roughness influenced the re-entry survivability of re-entry objects.

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