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# Experimental investigation of transient heat transfer between Hastelloy C-276/narrow air gap/silicon steel

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ABSTRACT

The heat transfer between rotor can/narrow air gap/silicon steel sheet has an important influence on the shrink fit process of reactor coolant pump rotor can. The accurate thermal conductance data are needed for the optimal design and numerical simulation of the shrink fit process of rotor can. Consequently, in this study, a set of new experimental apparatus and relevant procedure were developed to measure the thermal conductance at the interface between Hastelloy C-276/narrow air gap/silicon steel based on the transient method. The effects of the initial temperature of the Hastelloy C-276 specimen and the dimension of the air gap between the two test specimens on the thermal conductance were evaluated.



## 1. Introduction

Heat transfer across the interface between two solid surfaces is a very important problem in many engineering applications. It is generally known that when two solid surfaces are pressed together, because contact surfaces are never perfectly flat, the interface comprises both point contacts and air gaps and the actual contact area is only a small fraction of the nominal area (Fig. 1). Consequently, there exists an extra resistance to heat transfer across the interface, namely, the thermal contact resistance. The thermal contact conductance is the reciprocal of the thermal contact resistance.

Nowadays, the thermal contact conductance has been an important parameter in such engineering applications as nuclear reactor cooling, spacecraft thermal control, internal combustion engine cooling, metal hot forming, etc. Analytical, experimental and numerical methods have been used to study the contact heat transfer process since the 1930s. There have been several comprehensive reviews which summarize the extensive topics in the field of the contact heat transfer [1,2]. Cooper et al. [3] developed the most classical thermal contact resistance model for a surface contact of elastic deformation, which laid a good foundation for many later studies. Marotta and Fletcher [4] summarized the existing analytical models of direct contact to predict the thermal contact conductance of aluminum/aluminum and aluminum/stainless, and some experiments were conducted in a vacuum environment to verify the predictions. Jeng et al. [5] proposed a thermal contact conductance model considering elastic, plastic and elastic–plastic deformation and compared the predicted results with the experimental data. Xu and Xu [6] measured the thermal contact conductance of a pressed SS304 test pair in a vacuum environment and analyzed the effects of the surface topography and the interfacial temperature on the thermal contact conductance. Rosochowska et al. [7,8] described a method to measure the thermal contact conductance at the interface between the N1019 tool steel specimens. They studied the effects of the contact pressure and the average roughness height of the contact surface on the thermal contact conductance. Xing et al. [9,10] experimentally investigated the effects of the average interfacial temperature and the contact pressure on the contact heat transfer of 5CrMnMo/GH4169 and 5CrMnMo/TC11 test pairs by a new experimental apparatus and method.

Existing investigations focused mainly on the contact heat transfer process and less mention has been made of the heat transfer across the interface between two solid surfaces with a macroscopic air gap. For most contact problems, the thermal conductivity of air is very small and the related thermal conductance can be negligible. However, if there is a macroscopic air gap and no contact spots at the interface between two surfaces, the heat flux can transmit only through the narrow air gap. In this case, the thermal conductance of the air gap is predominant and must be considered.

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**Nomenclature**

| | |
|---|---|
| $x$ | space variable (m) |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $c$ | specific heat (J/kg °C) |
| $k$ | thermal conductivity (W/m °C) |
| $q$ | heat flux density (W/m$^2$) |
| $X$ | sensitivity coefficient (m$^2$ °C/W) |
| $h$ | thermal conductance (W/m$^2$ °C) |
| *Subscripts* | |
| $M$ | at time step, $M$ |
| $a$ | arbitrary |
| $ave$ | average |
| $p$ | peak |
| *Greek symbols* | |
| $\rho$ | density (kg/m$^3$) |
| $\Delta T$ | interfacial temperature drop (°C) |
| $\delta$ | dimension of air gap (mm) |

Rotor can, as one of the key parts of AP1000 reactor coolant pump (RCP), is made of Hastelloy C-276 and can prevent the rotor from being corroded by coolant in RCP [11]. During the shrink fit process of reactor coolant pump rotor can, there is a macroscopic air gap between the heated rotor can and the rotor, and the air gap becomes more and more narrow with time until rotor can and the rotor are in contact with each other. The heat transfer between rotor can/narrow air gap/silicon steel sheet has an important influence on the internal temperature field, the stress–strain field, and even the assembling accuracy and the life of rotor can. The accurate thermal conductance data between rotor can/narrow air gap/silicon steel sheet are needed for the optimal design and numerical simulation of the shrink fit process of rotor can.

The aim of this study is to measure accurately the transient thermal conductance between Hastelloy C-276/narrow air gap/silicon steel utilizing the self-developed transient experimental apparatus and method. In addition, the effects of the initial temperature of the Hastelloy C-276 specimen and the dimension of the narrow air gap between the two test specimens on the thermal conductance were also discussed.

## 2. Experiment

### 2.1. Experimental apparatus

The experiment is based on the inverse transient heat transfer method. Fig. 2 shows the experimental apparatus which is suitable for not only the contact heat transfer case but also the heat transfer between two surfaces with a narrow air gap. It can be seen that the experimental apparatus is mainly composed of loading mechanism, transmission mechanism, heating system and data acquisition system. The test specimens are located on the bars in the resistance furnaces. The load is applied on the test specimens by means of an articulated arm connected to the bar via a ball bearing. The contact load is read directly according to the weights on the loading arm and the maximum interfacial pressure can reach 30 MPa. The left specimen can be impelled to approach toward the other specimen by the transmission screw and the minimum dimension of the air gap between the two specimens is 0.2 mm. The resistance furnaces which can move along the slide rail are used to heat the test specimens to different temperature ranging from ambient temperature to 1000 °C and a thermal insulation is located between the two resistance furnaces. The measurements of the temperature field are performed by six calibrated $K$-type thermocouples which are attached to the test specimens and positioned along the axial direction of the specimens. The data acquisition system, consisting of artificial intelligence (AI) thermometers, PCL-789D amplifier board, A/D converter and industrial computer, is used to monitor, record and analyze the experimental temperature data.

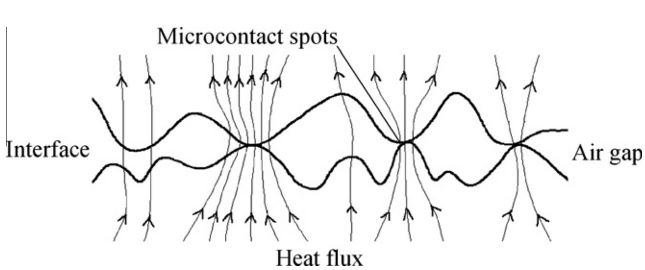


**Fig. 1.** Constriction of the heat flux at the interface.

### 2.2. Experimental specimen and procedure

The test specimens in this study were made of Hastelloy C-276 and silicon steel respectively. All the specimens were cut from a cylindrical metal rod and machined to a diameter of 20 mm and length of 50 mm as shown in Fig. 3. Three holes, 1 mm in diameter and 10 mm in depth, were drilled along the axial direction of the test specimens for locating thermocouples. These holes were 1, 6 and 11 mm away from the test surface of the specimens, respectively. $P_1$, $P_2$ and $P_3$ shown in Fig. 3 are the measuring point near the test surface, the middle measuring point and the innermost measuring point respectively. Of the three points, the measured temperatures of $P_1$ and $P_3$ are incorporated into the calculation of transient thermal conductance. The measured temperature of $P_2$ is used to compare with the numerical results. The used thermo-physical properties of specimens shown in Fig. 4 were measured using an Anter thermal properties analyzer (FL5000) system at the Institute of Metal Research, Chinese Academy of Sciences (IMR, CAS). Furthermore, the density of Hastelloy C-276 and silicon steel are 8850 and 7720 kg/m$^3$ respectively.

Before the experiment, the test surfaces of the specimens were polished using #400 waterproof abrasive papers.

During the experiment, the test specimens were fixed on the bars in the resistances and wrapped around with a thick enough layer of fiberglass insulation material to reduce the thermal radiation and the heat convection of the lateral surfaces of the specimens. Then, the two specimens were heated to the required initial temperatures by the resistance furnace, respectively and held for a period of time. When the temperature distribution of the test specimens achieved a steady-state condition, the right furnace was first pushed rightwards along the slide rail and the thermal insulation was removed manually. Then, the left specimen was impelled to approach toward the right one rapidly by the transmission mechanism until the dimension of the air gap between the two specimens reached the required value. At the same time, the