SCIENCE CHINA
Technological Sciences

July 2010 Vol.53 No.7: 1798–1808
doi: 10.1007/s11431-009-3190-6

Review of prediction for thermal contact resistance

WANG AnLiang[1*] & ZHAO JianFeng[2]

[1] *School of Astronautics, Beihang University, Beijing 100191, China;*
[2] *China Academy of Space Technology, Beijing 100094, China*

Received October 20, 2009; accepted January 19, 2010

Theoretical prediction research on thermal contact resistance is reviewed in this paper. In general, modeling or simulating the thermal contact resistance involves several aspects, including the descriptions of surface topography, the analysis of micro mechanical deformation, and the thermal models. Some key problems are proposed for accurately predicting the thermal resistance of two solid contact surfaces. We provide a perspective on further promising research, which would be beneficial to understanding mechanisms and engineering applications of the thermal contact resistance in heat transport phenomena.

thermal contact resistance, thermal contact conductance, surface topography, deformation assumption, prediction model, numerical simulation

Citation: Wang A L, Zhao J F. Review of prediction for thermal contact resistance. Sci China Tech Sci, 2010, 53: 1798–1808, doi: 10.1007/s11431-009-3190-6

1 Introduction

When two rough surfaces are brought into contact, actual contact only occurs at certain discrete spots or micro-areas, while the non-contacting areas form vacuums or are filled with some medium (such as air, water or oil, etc.). Due to the difference of thermal conductivities of solids and interface materials (or no interface materials), the heat flow through the solid surface may be limited, resulting in a heat transfer resistance at the interface known as thermal contact resistance (TCR). The engineering definition of TCR is the ratio of the temperature drop at the contact interface to the average heat flux across the junction, which is also called thermal boundary resistance or thermal joint resistance in many papers or books. The inverse of the TCR is the thermal contact conductance (TCC). In fact, all are used to describe the heat transfer of the contact interface. The term TCR is used in this paper, and we aim at the solid-to-solid contact problem.

The TCR has been utilized extensively in academics and industry, especially in the cryogenics, aircraft industry, nuclear industry, spacecraft and satellites, microelectronics, nano-technologies, etc. Since 1970s, the power of electronic devices and microelectronics has increased remarkably, while the problem of cooling them to a proper temperature range becomes more serious. Intel Corporation declared that the progress in the field of thermal solutions could not meet the demand for increasing computing and communication needs in 2000 [1]. Now, the problem remains as before. Since the heat generated by chips would conduct first through the contact interface, enhancing the ability of heat transfer via the interface is very important for limiting the size, space and weight of the chips. The TCR problem is important to aerospace research. In a low temperature, vacuum and micro-gravity environment, convection contributes little or nothing to energy transport. Rather, conduction and radiation transfer most of the heat. Many interfaces on the satellites, such as instrument and support frame, apparatus and mounting plate, and the space between the structures, exchange heat only by contact conduction. The electronic elements require a limited temperature range to preserve their reliability and operating lives [2]. Careful prediction of the TCR is therefore critical to thermal analysis and control

*Corresponding author (email: wanganliang@buaa.edu.cn)

of satellites, and equally for the space thruster, the deep explorer and the spacecraft [3–5].

Like many other engineering problems, the TCR research includes two aspects: engineering applications and basic theories. On the one hand, the goal of the research is to decrease (or increase) the TCR to meet the practical needs. For the sake of reliability, the junction temperature of most electronic components must be kept at a relatively low temperature. In order to reach the maximum efficiency of heat removal, the thermal contact component/cooler must be enhanced. Researchers have proposed many methods and means for enhancing contact heat transfer. The most commonly used process for minimizing the thermal contact resistance consists of filling the interfacial gap with some interstitial materials, such as thermal grease, metallic, non-metallic or phase change material coatings and foils. Most TCR problems involving direct application have been studied extensively and have accumulated much data. On the other hand, it is of equal importance that the correlation equations, theoretical models and the numerical methods are explored to help predict the TCR before designing and creating the contact components, choosing the interstitial materials, and deciding on the assembly methods. In order to develop theoretical models and methods for predicting TCR, it is necessary to conduct basic research on several levels: surface geometry, mechanics of contact areas, and thermal mechanism. Theoretical prediction research can not only help to understand the physical mechanism of TCR, but also solve some practical engineering problems.

This paper reviews the theoretical research on TCR and is organized as follows. In Section 2.1, we present several typical TCR models for single contact spots. Section 2.2 summarizes the state of the art research on surface topography, and discusses the key problems to accurately describe the geometrical characteristics of contact interface. In Section 2.3, we present and analyze the deformation assumption of contact summits, though many more experiments are needed to validate actual contact mechanics problems. In Section 2.4, we consider the TCR as a complicated multi-scale thermo-mechanical coupling problem, which could potentially be the reason that there has been limited success in the prediction modeling of contact heat transfer phenomenon. The numerical simulations have thus far proven to be necessary tools. Finally, we provide a perspective on future promising TCR research.

2 Research status and analysis

Since Alcock [6] indicated that the surface contact could be modeled by contact of multi discrete spots, the theoretical and experimental research of TCR on solid-to-solid has carried on over a half century. There are many typical review papers and books on the topic. Some reviews considered the physical mechanism and theoretical models, such as Lambert & Fletcher [7, 8], Yovanovich [9], and Yovanovich & Marotha [10]. Some summarized the industrial applications, the interstitial materials and the experimental data of TCR, such as Fletcher [11, 12], Kraus & Bar-Cohen [13], Yovanovich & Antonetti [14] and Madhusudana [15]. Some focused on the advances in selected areas, such as Madhusudana & Fletcher [16], Fletcher [17], Swartz & Pohl [18] and Gmelin et al. [19]. The understanding of the TCR phenomenon took new dimensions as more and more researchers developed new solutions for enhancing (or isolating) the energy transfer at a solid junction. Since the 1970s, studies of TCR have been conducted in China where some groups have gained positive results, such as Gu et al. [20–22] who carried out the experimental research at ordinary temperatures, and quantitatively analyzed the effects of pressure and temperature. For TCR problems at cryogenic vacuum, Xu et al. [23–29], and Wang et al. [30, 31] have performed a series of theoretical analysis and tests. Han et al. [32], Ying et al. [33, 34], Zhao et al. [35], and Zhu [36] also have conducted experimental and theoretical investigations of TCR problems.

In basic of classical heat transfer, energy can be transferred between two solids contacting interface by three different modes.

1) Conduction, through the solid-to-solid micro contact spots or areas, which plays the primary role (as shown in Figure 1).

2) Conduction or convection, through the interstitial fluid in the gap between the solids, which may be neglected or regarded.

3) Thermal radiation across the gap, which in most typical conditions can be neglected.

In general, the TCR depends on the surface topography of contact interface, the deformation of the contact spot, the thermal and physical characteristics of the material junction, the pressure distribution, the temperature difference between the surface, etc. TCR belongs to a multi-disciplinary problem including geometry, material, mechanics and heat

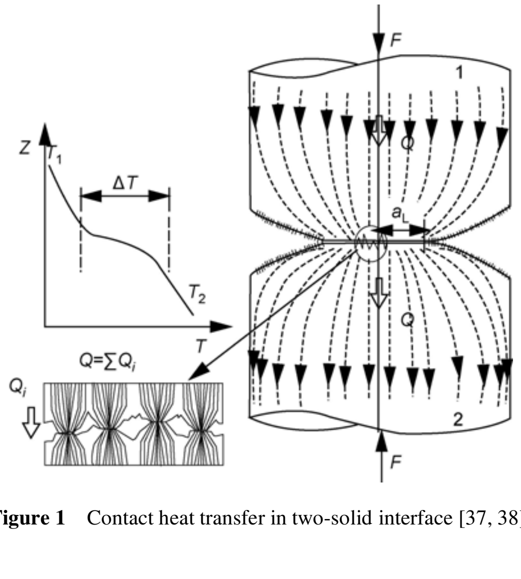

Figure 1 Contact heat transfer in two-solid interface [37, 38].

transfer. Researchers have proposed many prediction models and methods based on their interdisciplinary theories and experience.

2.1 TCR models on a single contact spot

The logical starting point for the discussion of a TCR problem would be a consideration of the thermal conduction model of a single contact spot. The total thermal resistance of two rough contact surfaces is simply the sum of the resistances for all sides of the contact spots. If we consider the heat may enter or leave an isotropic half-space through a single contacted spot (also called an area), the flux lines spread as far apart as the small contact area, then the thermal resistance is called the spreading resistance. The inverse is called the constriction resistance. The actual TCR through a contacted spot has the thermal resistance by the solid conduction, besides the spreading and constriction resistances.

An ideal model is a contact spot located on the boundary of a semi-infinite space. Many mathematical analysis solutions to this problem are available from the researchers, who considered the contact area as the circular, elliptical, rectangular and regular polygon forms, such as Carslaw & Jaeger [39], Gibson [40] and Yovanovich [41]. Yovanovich [9] described in detail the shape factors of TCR for different forms of contact spots.

Another model is the semi-infinite flux tube heat transfer model approximating the real joint. The most simple is the semi-infinite cylinder model, which was analyzed by Mikic & Rohsenow [42], Cooper et al. [43], Gibson [40], Yovanovich [44], and Negus & Yovanovich [45]. They combined the TCR with the characteristic size ratios of flux tubes.

These two TCR models for a single contact spot are based on the Fourier's law, and a TCR model for two real rough contact surfaces could be further established. But near the atomic scale (or molecular scale) and in ultrafast processes, the heat conduction may deviate significantly from the predictions of the Fourier's law, due to the boundary and interface scattering and the finite relaxation time of heat carriers. The energy is carried by thermal particles (i.e., electrons and phonons) scattering at an interface between the two solids. The temperature is correlative with the movement of thermal particles in a cryogenic state, and the thermal conductivity of the contact spot could be affected [18, 19]. If the contact spot is very small (i.e., nanoscale or less), the scale effect of the thermal conductivity is remarkable. There are at least two models dealing with these problems for a single micro contact spot: the acoustic mismatch model (AMM) and diffuse mismatch model (DMM) [18, 19].

In any case, the heat conduction on contact spots between two solids is the most important energy transport mode. For a generally rough contact surface, the key problem is to obtain the dimensions and distributions of all contact spots at the interface, which is used to calculate the actual contact surface area.

2.2 Research on surface topography

The study of surface topography can be valuable for many problems, in addition to TCR, such as tribology, abrasion, contact resistance, and measurement of surface [46–48]. The machined surface topography consists of three types of errors: geometrical form, waviness and roughness [46]. When two rough surfaces are brought into contact, actual contact only occurs at certain discrete spots. If the distribution and size of contact spots can be obtained, the TCR can be predicted using the above mathematical model for a single contact spot. If a filled composite exists in the contact gaps, the capability of heat transfer is modified using the area of the gaps. So the TCR model of a rough surface in a vacuum is widely valuable.

The TCR of a rough surface in a vacuum environment is divided into microscopic TCR and macroscopic TCR by many scholars, such as Clausing & Chao [49], Greenwood & Tripp [50], Holm [51], Yovanovich [52], Burde & Yovanovich [53], Lambert [54], and Lambert & Fletcher [7]. They proposed that the macroscopic TCR could be obtained in order to study the contact between globular spots, when error in geometrical form of surface is simplified via an equivalent globular spot. On the other hand, the microscopic TCR can be calculated using roughness of surface. It's very important to the study of contact heat transfer and attracts many scholars. There is a key problem of how to obtain the distribution and size of microscopic contact spots. Recently, Kumar and Ramamurthi [55] proposed that the waviness of surface is also important to the TCR.

The distribution and size of microscopic contact spots are usually calculated based on the statistics of the roughness profile characteristics. This work began with Greenwood and Williamson [56, 57]. They [56] proposed that the height of the roughness profile should match the Gaussian distribution. They also proposed that the peak height of the roughness profile should match Gaussian distribution even when the height of the roughness profile rarely matched Gaussian distribution. The mathematical model for the distribution and size of microscopic contact spots was established according to the relationship between summits of three-dimensional surfaces and peaks of two-dimensional profiles. Then many TCC models were established based on the above distribution model, such as Cooper et al. [43], Greenwood &Tripp [58], Mikic [59], Bush et al. [60], Sayles & Thomas [61], and McCool [62] and Yovanovich [63, 64]. The assumption that the height of the roughness profile should match Gaussian distribution is also widely used in the fields of tribology, abrasion and surface measurement. On the other hand, Polycarpou & Etsion [65] indicated that the Gaussian distribution of roughness height can be approximated by an exponential distribution under limited pressure, and a simple analytical expression was derived for the real contact area and the number of contacting spots. But Greenwood & Wu [66] recently indicated that the assumption of Gaussian distribution for the roughness profile height was wrong, and perhaps this would be very useful for many models.

Most TCR models were established based on the assumption of a Gaussian distribution for the roughness profile height until the end of 1990s. Sayles & Thomas [67] were the first to propose that the distribution of roughness is a non-stationary random process. During the same period, Mandelbrot [68] founded the fractal theory which can be used to describe the surface topography. There is an ineluctable question as to whether or not the surface topography is fractal. Majumdar et al. [69–71] described the roughness profile of machined surface using the modified W-M function, and Warren et al. [72–74] simulated the surface using Contor fractal set. But there is still the question of how to get the fractal dimension of a surface. Many methods were used, such as the box-counting method, the size method, and the difference methodology. Dubuc et al. [75] compared these methods and considered the difference methodology the best one. However, Motoyoshi et al. [76] and Ge et al. [77] proposed that the covariance method could bring a higher precision. Wang et al. [78–82] proposed a new method to calculate fractal dimension of curve using wavelet transform. The calculation showed that wavelet transform was superior to other existing methods and was consistent in a wide range. Ge & Zhu [83] cited this conclusion in their book. Wavelet transformation is an effective mathematical tool to evaluate the fractal characteristic of the roughness profile and analyze the microscopic surface topography.

Chang & Etsion [84] previously built an elastoplastic contact model based on fractal theory. Majumdar & Bhushan [69–71] evaluated the surface topography using fractal theory in the field of the tribology and heat transfer. Warren et al. [72–74] built an elastoplastic contact model and an elastic contact model by simulating surface topography using fractal set. Zahouani et al. [85] established the relationship between the density of contact spots and the fractal dimension. Blyth & Pozrikidis [86] built a TCR model for the random fractal surface. Recently, Xu et al. [29] performed a TCR experiment using the fractal dimension as a key parameter. Yu et al. [87] and Ciavarella et al. [88] respectively established the TCR models based on fractal theory. These fractal models are based on the fractal surface topography and set the fractal dimension of roughness profile as a key parameter to calculate the density of contact spots and the contact area. It's different from a Gaussian surface in that the distribution of roughness is considered to be a non-stationary random process for fractal surfaces. In fact, Majumdar & Bhushan [71] indicated that more work should be done to find the relationship between distribution index and fractal dimension. Wang et al. [89] found that the size distribution of spots or pits for machined surface is conceptually different from fractal dimension. So it should be especially noted when the density of a spot (or pit) and actual contact area is calculated by fractal theory. To some extent, the fractal surface is an idealized model to describe the surface topography. Further work should be done to apply fractal theory to the field of TCR, contact electric resistance, tribology and abrasion.

Whether for Gaussian models or for fractal models, the roughness height (or peak height) of a profile is assumed to agree with a certain distribution function. Then the number of contact spots or actual contact area can be calculated using the integral of the function. However, this assumption has two problems. Firstly, the assumption is unable to use statistical roughness parameters to describe the anisotropy of machined surfaces. Secondly, it does not consider the size distribution and spatial distribution of spots on machined surfaces. In fact, actual contact only occurs at these discrete spots (or areas) when two rough surfaces are brought into contact. Li et al. [90] and Singhal & Garimella [91] proposed that the deformation and TCR of each peak in the roughness profile (or each equivalent peak in small regions) could be calculated, even if the peak height distribution (or the roughness profile height distribution) did not agree with a function. The TCR of individual spots could be calculated to get the TCR of the whole contact surface. They related the statistical characteristics of roughness profiles to summit deformation. This is a new method to establish the TCR model.

Conclusively, there are three problems with calculating the TCR using the statistical characteristics of roughness profiles.

i) The common view is that the contact only occurs at rough spots. However, the machined surface topography consists of three types of errors. How can these three types of errors be extracted from the original profile? Is the existing method effective to do this? Do the waviness and errors in geometrical form affect the calculation of TCR? These problems have not yet been solved.

ii) Do all measured roughness profiles for a machined surface agree with a function distribution (such as Gaussian or fractal)? Which peaks of the roughness profile actually come into contact? In other words, the criterion for determining contact peaks is ignored for TCR models.

iii) How does the method for transforming contact peaks into summits affect the calculation of actual contact area? Are these contact summits isolated or connected? Which assumption is more reasonable?

In order to solve these problems, we [92–94] proposed a method for transforming contact peaks into summits based on measured original profile to calculate TCR.

Firstly, it was proven that there is a great advantage to using wavelet transform method to extract the roughness profile and the original profile from a profile which is superimposed in the normal function and original function (such as sine function). Secondly, many profiles were calculated to extract the roughness profile and the original profile (consisting of waviness and errors in geometrical form) using wavelet transform. These profiles could respect different positions of the same surface and different surfaces which were machined using different methods. Thirdly, the normality was tested for the roughness profile height. The results showed that for most of the machined surfaces in our study, the roughness profile height did not have a normal distribution. But the histogram indicated that the distribution had some normality, which was in agreement with the opinion of Greenwood & Williamson [56]. Then four different criteria were presented to determine contact peaks, and the normality of contact peaks was tested. Results showed that the distribution of contact peaks was related to the criterion for determining contact peaks. Just like the profile height, the distribution of contact peaks does not have a normal distribution. So we built the relation between contact peak and contact summit based on the contact peak distribution of the roughness profile, and calculated the TCC under different loads.

Then, we analyzed the statistics of TCR results based on the original profile. At present, all the TCR models are based on the statistical distribution of the roughness profile. The density of contact spots and contact area are calculated using the statistical distribution of peaks for roughness profile. Lambert & Fletcher [7] compared the existing TCR models and experiments. The results of all the existing TCR models were dispersive. We proposed that this dispersal was due to the assumption of the statistical distribution of the roughness profile. According to our study, the TCR calculated results based on the statistics of single roughness profile characteristics are very different if using the different profiles coming from different positions of the same surface, as is shown in Figure 2. Therefore, two or three average parameters are insufficient to describe the topography of the whole surface.

There is limited information available on roughness profiles. When the density of contact spots and contact area are calculated in order to get the TCR, it can be assumed that contact peaks can be transformed into spots. This assumption brings uncertainty into the calculation of the TCR. Accordingly, the surface topography should be evaluated from a three-dimensional model. However, it's difficult to measure a three-dimensional topography of rough surface. On the other hand, there is not an effective method to evaluate the radii and density of contact spots.

At present, there are some methods to measure the three-dimensional surface, such as electrical stylus profile meter, optical non-contact three-dimensional scanner, optical interference microscope, laser scanner microscope and tunnel scanner microscope. These methods have different measurement scale ranges and precisions. The electrical stylus profile meter has many advantages such as in the measuring range, operation, cost, data processing and the preparation of the measured object. The electrical stylus profile meter is usually used to measure the original profiles. It's difficult to measure three-dimensional surface using an electrical stylus profile meter because many positions should be measured in order to rebuild a high precision topography of the three-dimensional surface. The optical non-contact three-dimensional scanner is usually used to measure three-dimensional surface. It has a higher precision than the electrical stylus profile meter, and won't destroy the measured object. It also has advantages in the measuring range and data processing, although it is sensitive to the cleanliness of measured object. The optical interference microscope, laser scanner microscope and tunnel scanner microscope are high precision instruments, but the measuring range is limited by the precision. The measured results of these three instruments are in photographic format, which

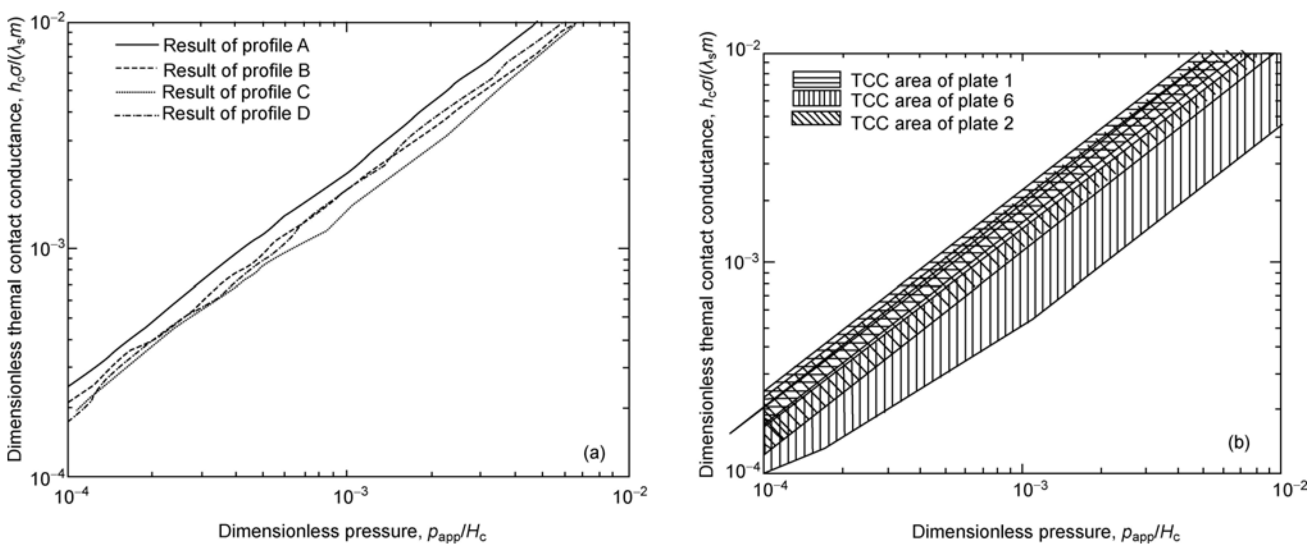

Figure 2 Predicted results of TCR based on the statistics of roughness profile characteristics [94]. (a) For different profiles on the same surface; (b) for different surfaces with the different degrees of roughness.

is difficult to process. Whether these methods are accurate or not, the key problem is the data processing and parameter analysis of the three-dimensional surface topography.

On the other hand, the mathematical simulation of three-dimensional surface topography is carried out. Based on the assumption of Gaussian distribution, three-dimensional surface topography was simulated using linear matrixing, fast Fourier transform, and time series analysis, such as Patir [95], Waton & Spedding [96], Whitehouse [97], Newland [98], Hu & Tonder [99], Chilamankuri & Bhushan [100], Mihailidis & Bakolas [101], and Wu et al. [102]. However, Bakolas [103] introduced a method to simulate a non- Gaussian surface after summarizing the method of describing spatial parameters and frequency parameters. Since the creation of the fractal theory, there has been much interest in surface simulation. Fractal theory is already being used to simulate the topography. There are two fractal methods for surface simulation: random fractal and interpretation fractal [104]. The random fractal consists of the midpoint displacement method, summation method, and Fourier filter method. McGaughey & Atiken [105] simulated a fractal surface using a combination of the fractal method and random process. In the interpretation fractal method, more detailed data are obtained using interpretation of existing data. For all mathematical simulation methods for three-dimensional surface topographies, it's an ineluctable problem to judge which method is closer to an actual surface. In other words, which method is equivalent to the actual surface in statistical calculations?

The purpose of simulating the three-dimensional surface topography is to get the contact area, as well as the density and size of contact spots. In other words, which parameters can be used to calculate the TCR? There are two important aspects of this question.

i) The three-dimensional surface topography also consists of three types of errors: geometrical form, waviness, and roughness. Therefore, an effective mathematical method should be used to extract these three errors.

ii) The mathematical model for calculating the size and density of microscopic contact spots should be established based on three-dimensional roughness surface to obtain the actual contact area.

2.3 Deformation of contact spots

At the contact interface between two solids, the deformation of every contact spot will be assumed for all prediction models. There are three mechanical models: plastic, elastic, and elastic-plastic deformation, according to the studies of macroscopic material mechanics, which could directly affect the TCR. To match with the deformation characteristics, researchers proposed three types of TCR models or correlations related to the load.

Plastic contact models. Cooper et al. [43] developed the primary plastic deformation model based on the assumption that the surface asperities have Gaussian height distributions. A new and more accurate correlation equation was proposed by Yovanovich [106] to modify the Cooper's model. Later, Hegazy [107] introduced the microhardness concept in his thesis, and researched the relations of the Vikers microhardness, as well as Brinell and Rockwell macrohardness. The contact geometric parameters were obtained from the plastic deformation model at different given loads, such as the ratio of real contact area to apparent contact area, as well as contact spots sizes and density. The results predicted by the theoretical models based on plastic deformation were in good agreement with the experimental data at a relatively higher load. But the plastic contact models were not always valid at a lower load [7].

Elastic contact models. Based on the Herz's theory, Mikic [59] assumed all micro contact spots occurred the elastic deformation for a conforming rough surface, and proposed a model for calculating the real contact area and spots density. More complex elastic contact models were given by Geenwood & Williamson [56], Greenwood & Tripp [58], and Sridhar & Yovanovich [64]. Many comparisons showed that the elastic deformation models were better for prediction of TCR for hard materials, such as tool steel, but were not adapted for softer materials.

Elastic-plastic contact models. Sridar & Yovanovich [108] developed an elastic-plastic contact conductance model based on the plastic contact model of Cooper et al. [43] and the elastic contact model of Mikic [59]. They proposed an elastic-plastic parameter to modify the surface geometric parameters. The elastic-plastic microhardness could be determined by means of an iterative procedure. Majumdar & Bhushan [70] thought that the inflexion between the elastic and plastic deformation was related with the surface fractal dimension.

Comprehensively considering the surface topography, deformation characteristic and material physical properties, researchers proposed many semi empirical and semi theoretical correlations. The general form is

$$H_c^* = H_c \frac{S}{K_s} = a\left(\frac{P}{M}\right)^b, \tag{1}$$

where H_c^* and H_c represent respectively the nondimensional and dimensional TCC; S is the statistic parameter related to surface roughness; K_s is related to the coefficient of heat conductivity; P is the contact pressure; M is the hardness or Young's modulus; a and b are the correlation coefficients.

Based on the studies of the surface topography and the deformation mechanism, researchers fitted the different values of a and b coefficients using their experimental data. The differences were categorized into two main reasons: on the one hand, the deformations of all contact spots were assumed by classical material mechanics, whereas the real deformation of every contact spot was very complex in micro-scale. Various aspects of knowledge are required, such as material science, crystallology, micro contact mechanics, and metrology. On the other hand, the surface topography and micro structure were discussed at Section 2.2, and the form, size and position of micro contact spots are random, which affects the real contact area given definite loads. The comparison by Lambert & Fletcher [7] indicated that all empirical and semi-empirical correlations suffered from limited applicability, which was not consistent with all experimental data. Though these correlations have qualitative reference value for some engineering problems and are convenient for applications, it is impossible for a group of *a* and *b* coefficients to fit all test environments and conditions. In addition, some parameters are actually difficult to measure accurately, and the pressure and its distribution on the interface also affect the prediction of TCR.

Most of the deformation models are based on the mechanical theory in macro scale. The key problem is the deformation characteristic of micro contact spot in force. Further experimental and theoretical studies should be conducted on the deformation along with the description of surface microscopic geometry.

2.4 Multi-scale analysis and numerical simulations

TCR is a complex multi scale thermal and mechanical coupling problem. Thermo-mechanical problems of surface contact are usually modeled for engineering applications, but it is known that the physical mechanisms are the interactivity and movement of atoms (or molecules) on the contact surface. The TCR problems cover all ranges, from the atomic to the macroscopic scale. It is the common key problem to investigate the material transport, energy transfer, micro structure evolution, performance variation and active time for material science, solid mechanics and condensed state physics. The electromagnetic field effect should be considered for many complex environments and conditions. To solve the coupling problem is a challenge. Studying the physical mechanisms and solving thermo-mechanical methods are as inevitable as doing the same for electro-magnetic-thermo-mechanical problems, including many micro and macro aspects such as scale effect, material components, interface configuration, interface migration, crystal face direction, material damage, force-field, temperature field and other fields' effects. The research ideas need to be widened. The multi-scale thermo-mechanical problems have recently concentrated on the micro and the nano scales.

Micro/nano-scale heat transfer is currently a hot research subject, and fresh studies emerge frequently [109, 110]. The Fourier's law is inapplicable to micro or nano scale. The heat conduction is affected by the boundary scale. Some interesting discoveries include Matthiessen's law, quantum transport, and Casimir ultimate, which are not involved in classical prediction models of TCR. Scale effect of the TCR is investigated more and more frequently.

To predicate the TCR on a multi scale thermo-mechanical problem, it is necessary to use computer analysis and simulation, in addtion to micro/nano-scale experimental installation with higher performance, more precision and comprehensive parameters.

Along with the development of computer technology, people gradually approach the TCR problem in two opposite simulation models: macroscopic scale and molecular scale, also called "top-down" and "bottom-up" methods.

On the macroscopic scale, in the early 1970s, Yovanovich [9] assumed a single contact spot as a circular, elliptical, rectangular and regular polygon shape, and accomplished many analytical and numerical studies based on the Fourier law. These results are the foundation for many TCR models of surface roughness. Later, Rostami [111] used the Fluent software to analyze the effects of shape, scale and gap geometrical parameters by 3-D numerical simulation based on the heat tube concept. Trujillo & Pappoff [112] proposed a method for constructing three dimensional finite element conduction models, which was validated to be practical to research the effect of meshes on TCR. A finite difference analysis method was developed by Wahid [113] in order to discuss the ratio of gap-to-solid conductance. Black et al. [114] also simulated the effects of the ratio of contact radii, cone angle and gap for TCR. But for general surface roughness, the numerical simulation models should be simplified due to the limitation of describing accuracy of surface topography and uncertainty of contact deformation. There are special techniques on boundary conditions, meshes and solved methods. Laraqi group [115–119] assumed the contact spots to be the square or circular areas with different radii randomly distributed over the surface, and analyzed and simulated the TCR by finite element method. The results portrayed the TCR as a function of contact disorders, number and sizes of disks and relative contact size area, and that the sliding speed also affected the TCR. Tomimura et al. [120] qualitatively simulated the TCR by meshes random distribution. Zhang et al. [121, 122] proposed a grid system with equi-peripheral intervals in the azimuthal direction to express the contact spot distribution, and used an average thermal conductivity of single meshes as the interface condition. With the density of meshes increasing in value, the total TCR simulation result becomes almost constant. For "top-down" simulation, the differences of the models are in surface topography characteristics and deformation assumption, which are important reasons to affect the accuracy and applicability of prediction models.

On the microscopic scale, the solid matter is made up of atoms, ions and molecules. New methods involving the quantum molecular dynamics (QMD), molecular dynamics (MD) and Boltzmann equation (BE) were used to research the non-Fourier effect, scale and boundary effect of thermal conductivity, and thin film conduction [108]. Touzelbaev & Goodson [123] investigated the thermal resistance near diamond-substrate interfaces using phonon transport theory.

They found that the resistance was governed by the number of diamond nucleation sites per unit substrate area, i.e., the nucleate density, the thickness of boundary layer. Prasher & Phelan [124] developed a scattering-mediated acoustic mismatch model (SMAMM) to describe the TCR from high temperature to low temperature. The parameters were defined at a crystal structure, while the prediction results were in good agreement with the experimental data on Rh/MgO interfaces. Chen [125] introduced a ballistic-diffusive equation (BDE) derived from the Boltzmann equation (BE) to deal with the thin films heat conduction problems from nano scale to macro scale, and the contact boundary conditions were simplified. Liang & Yue [126] investigated the interface roughness effect of TCR using a method of non-equilibrium molecular dynamic (NEMD). The roughness was defined by atomic radius and projection area (range of 0.02–0.12 nm). The simulation results showed that with the increase of roughness, the in plane thermal conductivity decreased. Liao & Yang [127] proposed a method coupling atomic and finite element models to simulate the TCR of dissimilar materials. The results indicated that the nonuniform temperature distribution was associated with the characteristic of atoms moving along the interface. There are many other interesting recent studies [128–133]. To analyze and simulate from "bottom-up", researchers have achieved many results and found new physical mechanism on micro scale contact heat transfer. But the scale range of simulation was very limited, no more than 2 orders of magnitude. There are lots of problems to expanding study from micro scale to macro scale.

When dealing with TCR numerical simulations on either the micro or the macro scale, the common key difficulty is characterizing the surface topography and deformation on the contact interfaces. Many assumption conditions are not validated by experimental data. The multi scale models have a very narrow range due to the limitation of the computer's ability. In addition, applicability and validation are needed to explore and carry out the milti-scale thermo-mechanical simulation of TCR.

3 Researches in the future

The prediction of TCR is always a heat transfer research hotspot. Among academic circles in the last tens of years, much theoretical research has been carried out in macro and micro scale ranges which has proposed many analysis models and simulation methods for scientific comprehension and engineering applications of contact energy transport phenomena. For valuable predictions of TCR problems, further investigations should be deeply carried out.

1) Due to the irregularity and the complexity of surface topography, it is important to calculate the real contact area, contact spot size and distribution. More measurements and characteristics of the three dimensional surface topography are needed from micro scale to macro scale, which are important for applications of friction, wear, contact electric resistance and boiling. Manufacturing some special structure and interfacial materials at micro/nano scales, can not only meet the engineering requirements but also be used as the boundary conditions for the TCR models and simulations.

2) Combined with the material properties, contact spot size and shape, the deformation features of real contact spots should be used to carry out the relevant theoretical analysis and modeling. It would be noticed that emphasis should be placed on the experimental test of the micro hardness, elasticity and deformation of material.

3) A multi-scale and multi-field coupling comprehensive analysis is needed. It is an inevitable trend to simulate the TCR problems using a combination of the macroscopic methods and the microscopic methods.

Obviously, the improvement of the prediction ability of the TCR cannot do without the progress of the experimental methods and technologies. The ultimate question is whether or not a general rule or method can be found to describe and predicate accurately the TCR with so many uncertain factors [134]. This is one of the most challenging science and technological issues. We believe that people are working hard to research the various factors affecting the TCR for understanding the scientific intensions and meeting the industrial needs.

The authors want to express their thanks to Professor Yang C X and Professor Yuan X G of School of Aeronautics Science and Engineering, Beihang University for their helpful suggestions and encouragement. The first author wishes to thank the group led by Professor Liu Y, School of Astronautics, Beihang University for their support. We also thank Mr. Christian H M for checking the English manuscript.

1 Viswanath R, Wakharkar V, Watwe A, et al. Thermal performance challenges from silicon to systems. Int Technol J, 2000, 4(3): 1–16
2 Min G R, Guo S. Thermal Control of Spacecraft (in Chinese). Beijing: Science Press, 1998
3 Geng Y B, Wei Y M, Pan H L, et al. The thermal control technologies for electric thrusters (in Chinese). In: The Symposium on Electric Propulsion in China, Beijing, China, 2007. 6–11
4 Ramamurthi K, Kumar S S, Abilash P M. Thermal contact conductance of molybdenum-sulphide-coated joints at low temperature. J Thermophys Heat Transf, 2007, 21(4): 811–813
5 Culham J R, Khan W A, Yovanovich M M, et al. The influence of material properties and spreading resistance in the thermal design of plate fin heat sinks. Trans ASME J Electron Pack, 2007, 129: 76–81
6 Alcock J F. Communications on a review of recent progress in heat transfer. Proc Institution Mech Engineer, 1943, 149: 126–130
7 Lambert M A, Fletcher L S. Review of models for thermal contact conductance of metals. J Thermophys Heat Transf, 1997, 11(2): 129–140
8 Lambert M A, Fletcher L S. Thermal contact conductance of non-flat, rough, metallic coated metals. Trans ASME J Heat Transf, 2002, 124: 405–412
9 Yovanovich M M. Conduction and thermal contact resistances (conductances). In: Rohsenow W M, Hartnett J P, Cho Y I, eds. Handbook of Heat Transfer. Chapter 3. New York: McGraw Hill, 1998
10 Yovanovich M M, Marotha E. Thermal spreading and contact resis-

tance. In: Bejan A, Kraus A D, eds. Heat Transfer Handbook. Chapter 4. New York: Wiley, 2003
11 Fletcher L S. A review of thermal control materials for metallic junctions. J Spacecraft Rocket, 1972, 9: 849–850
12 Fletcher L S. A review of thermal enhancement techniques for electronic systems, IEEE T Component Hybird Manuf Technol, 1990, 13(4): 1012–1021
13 Kraus A D, Bar-Cohen A. Thermal Analysis and Control of Electronic Equipment. New-York: McGraw-Hill, 1983
14 Yovanovich M M, Antonetti V W. Application of thermal contact resistance theory to electronic packages. In: Bar-Cohen A, Kraus A D, eds. Advances in Thermal Modeling of Electronic Components and Systems. New York: Hemisphere Publishing, 1988
15 Madhusudana C V. Thermal Contact Conductance. New York: Springer-Verlag, 1996
16 Madhusudana C V, Fletcher L S. Contact heat transfer——The last decade. AIAA J, 1986, 24(3): 510–523
17 Fletcher L S. Recent developments in contact conductance heat transfer. Transa ASME J heat transf, 1988, 110: 1059–1070
18 Swartz E, Pohl R. Thermal boundary resistance. Rev Mod Phys, 1989, 61: 605–668
19 Gmelin E, Asen-Palmer M, Reuther M, et al. Thermal boundary resistance of mechanical contacts between solids at sub-ambient temperatures. J Phys D-Appl Phys ,1999, 32: R19–R43
20 Gu W L. The experimental research on thermal contact resistance (in Chinese). J Nanjing Univ Aeronautics Astronautics, 1992, 24(1): 46–52
21 Gu W L. The temperature effect on thermal contact resistance (in Chinese). J Nanjing Univ Aeronautics Astronautics, 1994, 26(3): 342–349
22 Gu W L. A calculation method of thermal contact resistance on random surface (in Chinese). J Aerospace Power, 1995, 10(3): 232–236
23 Xu L, Xu J M. Research on the thermal contact resistance of solid surface at low temperature (in Chinese). Cryogenics Supercon, 1996, 24(1): 53–58
24 Xu L, Zhang T, Xiong W, et al. The contact surface effect on thermal contact resistance at low temperature and vacuum (in Chinese). Vacuum Cryogenics, 1998, 4(1): 1–4
25 Zhang T, Xu L, Xiong W, et al. Comparison and analysis of theoretical models in the research of thermal contact conductance (in Chinese). Cryogenics Supercon, 1998, 26(2): 58–64
26 Xu L, Zhang T, Zhao L P, et al. Using double heat-flux meter method to measure the thermal contact resistance of solid material at low temperature and vacuum (in Chinese). Cryogenics, 1999, (4): 185–189
27 Zhao L P, Xu L. Using profile discrimination method to investigate thermal contact conductance between rough interfaces (in Chinese). Cryogenics, 2000, 118(6): 52–57
28 Zhao L P, Xu L, Li Z C, et al. Research on the relationship between thermal contact conductance of solid interfaces and cycling load at low temperatures (in Chinese). Cryogenics Supercon, 2000, 28(1): 51–54
29 Xu R P, Feng H D, Zhao L P, et al. Experimental investigation of thermal contact conductance at low temperature based on fractal description. Int Commun Heat Mass Transfer, 2006, 33: 811–818
30 Chen J. Investigation on the computer simulation of boundary heat transfer process between solids at low temperature (in Chinese). Dissertation of Doctoral Degree. Wuhan: Huazhong University of Science and Technology, 2004
31 Shi L. Investigation of heat transport on the solid-solid contact interface at low temperature (in Chinese). Dissertation of Doctoral Degree. Wuhan: Huazhong University of Science and Technology, 2006
32 Han Y G, Xuan Y M, Tang R F. Heat transfer on the contact surfaces with frictional heating (in Chinese). J Nanjing Univ Sci Technol, 1998, 22(3): 260–263
33 Ying J. The evaluation of thermal contact resistance in heat transfer effect (in Chinese). J Zhejiang Univ, 1996, 30(4): 415–421
34 Ying J. The theoretical and experimental research of thermal contact resistance on roughness surface (in Chinese). J Zhejiang Univ (Sci Ed), 1997, 31(1): 104–109
35 Zhao H L, Huang Y M, Xu J L, et al. Experiment research on thermal contact resistance of normal used joints (in Chinese). J Xi'an Univ Technol, 1999, 15 (3): 26–29
36 Zhu D C. Experiment research on solid interface thermal contact conductance coefficient (in Chinese). Dissertation of Master Degree. Dalian: Dalian University of Technology, 2007
37 Bahrami M, Culham J R, Yovanovich M M, et al. Thermal contact resistance of nonconforming rough surfaces. Part 1: Contact mechanics model. J Thermophys Heat Transf, 2004, 18(2): 209–217
38 Bahrami M, Culham J R, Yovanovich M M, et al. Thermal contact resistance of nonconforming rough surfaces. Part 2: Thermal model. J Thermophys Heat Transf, 2004, 18(2): 218–227
39 Carslaw H S, Jaeger J C. Conduction of Heat in Solids. 2nd ed. Oxford: Clarendon Press, 1959
40 Gibson R D. The contact resistance for a semi-infinite cylinder in a vacuum. Appl Energ, 1976, 2: 57–65
41 Yovanovich M M. Thermal constriction resistance of contacts on a half-space: Intergral formulation. In: Progress in Astronautics and Aeronautics: Radiative Transfer and Thermal Control. New York: AIAA, 1976. 397–418
42 Mikic B B, Rohsenow W M. Thermal Contact Resistance. Mech Eng Rep DSP74542-41, MIT. 1966
43 Cooper M G, Mikic B B, Yovanovich M M. Thermal contact conductance. Int J Heat Mass Transf, 1969, 12: 279–300
44 Yovanovich M M. General thermal constriction resistance parameter for annular contacts on circular flux tubes. AIAA J, 1976, 14(6): 822–824
45 Negus K J, Yovanovich M M. Constriction resistance of circular flux tubes with mixed boundary conditions by linear superposition of Neumann solutions. ASME-84-HT-84, ASME. 1984
46 Mao Q G. The Evaluation and Measurement of Surface Roughness (in Chinese). Beijing: Mechanical Industry Press, 1991
47 Zhou Z R. Advancing of Tribology Development (in Chinese). Beijing: Science Press, 2006
48 Guo F Y, Chen Z H. The Theory and Application of Electric Contact (in Chinese). Beijing: China Electric Power Press, 2008
49 Clausing A M, Chao B T. Thermal contact conductance in a vacuum environment. Trans ASME J Heat Transf, 1965, 87: 243–251
50 Greenwood J A, Tripp J H. The elastic contact of rough spheres. J Appl Mech, 1967, 89(1): 153–159
51 Holm R. Electric Contacts: Theory and Applications. New York: Springer-Verlag , 1967
52 Yovanovich M M. Overall constriction resistance between contacting rough, wavy surfaces. Int J Heat Mass Transf, 1969, 12: 1517–1520
53 Burde S S, Yovanovich M M. Thermal resistance at smooth sphere/rough flat contacts: Theoretical analysis. AIAA 78–871. 1978
54 Lambert M A. Thermal contact conductance of spherical rough surfaces. Dissertation of Doctoral Degree. Houston: Texas A & M University, 1995
55 Kumar S S, Ramamurthi K. Influence of flatness and waviness of rough surfaces on surface contact conductance. Trans ASME J Heat Transf, 2003, 125: 394–402
56 Greenwood J A, Wiliamson J B P. Contact of nominally flat surfaces. Proc Roy Soc A, 1966, 295: 300–319
57 Greenwood J A. The area of contact between rough surfaces and flats. J Lubricant Technol, 1967, 81: 81–91
58 Greenwood J A, Tripp J H. The contact of two nominally flat rough surfaces. Proc Inst Mech Eng, 1970, 185: 625–633
59 Mikic B B. Thermal contact conductance: Theoretical considerations. Int J Heat mass transfer, 1974, 17: 205–214
60 Bush A W, Gibson R D, Thomas T R. The elastic contact of rough surface. Wear, 1975, 35: 87–111
61 Sayles R S, Thomas T R. Thermal conductance of a rough elastic contact. J Appl Energ, 1976, 2: 249–267
62 McCool J I. Comparison of models for the contact of rough surfaces. Wear, 1986, 107: 37–60
63 Yovanovich M M. Thermal contact correlations. In: AIAA 16th Thermophysics Conference, Palo Alto, California, USA, 1981. 83–95
64 Sridhar M R, Yovanovich M M. Review of elastic and plastic contact

conductance models: Comparison with experiment. J Thermophys Heat Transf, 1994, 8(4): 633–640
65 Polycarpou A A, Etsion I. Analytical approximations in modeling contacting rough surfaces. Trans ASME J Tribol, 1999, 121: 234–239
66 Greenwood J A, Wu J J. Surface roughness and contact: An apology. Meccanica, 2001, 36(6): 617–630
67 Sayles R S, Thomas T R. Surface topography as a nonstationary random process. Nature, 1978, 271(2): 431–434
68 Mandelbrot B B. Fractal, Form, Chance and Dimension. Freeman: Sanfacisco, 1977
69 Majumdar A, Bhushan B. Role of fractal geometry in roughness characterization and contact mechanics of surfaces. ASME J Tribol, 1990, 112(1): 205–216
70 Majumdar A, Bhushan B. Fractal model of elastic-plastic contact between rough surfaces. ASME J Tribol, 1991, 113(1): 1–11
71 Majumdar A, Tien C L. Fractal characterization and simulation of rough surface. Wear, 1990, 136: 313–324
72 Warren T L, Krajcinovic D. Fractal models of elastic-perfectly plastic contact of rough surfaces based on the Contor set. Int J Solid Struct, 1995, 32(19): 2907–2922
73 Warren T L, Krajcinovic D. Random cantor set models for the elastic-perfectly plastic contact of rough surfaces. Wear, 1996, 196: 1–15
74 Warren T L, Majumdar A, Krajcinovic D. A fractal model for the rigid-perfectly plastic contact of rough surfaces. Trans ASME J Appl Mech, 1996, 63: 47–54
75 Dubuc B, Tricot C, Zucker S W. Evaluating the fractal dimension of profiles. Phys Rev A, 1989, 39(3): 1500–1512
76 Hasegawa M, Liu J, Okuda K, et al. Calculation of the fractal dimensions of machined surface profiles. Wear, 1996, 192: 40–45
77 Ge S R, Suo S F. The method of calculation the fractal dimension of surface roughness profiles (in Chinese). Tribology, 1997, 17(4): 354–362
78 Wang A L, Yang C X. Wavelet transform method evaluate the fractal characterization of profiles (in Chinese). Chinese J Mech Eng, 2002, 38(5): 80–85
79 Wang A L, Yang C X. The calculation methods for the fractal characterization of surface topography (in Chinese). Chinese Mech Eng, 2002, 13(8): 714–718
80 Wang A L, Yang C X. Wavelet transform method evaluate the fractal characterization of profiles (in Chinese). Chinese J Mech Eng, 2002, 38(5): 80–85
81 Wang A L, Yang C X, Yuan X G. Evaluation of the wavelet transform method for machined surface topography Ⅱ: Fractal characteristic analysis. Tribol Int, 2003, 36(7): 527–535
82 Wang A L, Yang C X, Yuan X G. Evaluation of the wavelet transform method for machined surface topography Ⅰ: Methodology validation. Tribol Int, 2003, 36(7): 517–526
83 Ge S R, Zhu H. Fractal in Tribology (in Chinese). Beijing: China Machine Press, 2005
84 Chang W R, Etsion I, Bogy D B. An elastic-plastic model for the contact of rough surfaces. Trans ASME J Tribol, 1987, 109: 257–263
85 Zahouani H, Vargiolu R, Loubet J L. Fractal models of surface topography and contact mechanics. Math Comp Model, 1998, 28(4-8): 517–534
86 Blyth M G, Pozrikidis C. Heat conduction across irregular and fractal-like surfaces. Int J Heat Mass Transf, 2003, 46: 1329–1339
87 Zou M Q, Yu B M, Cai J C, et al. Fractal model for thermal contact conductance. J Heat Transf, 2008, 130: 101301
88 Ciavarella M, Dibello S, Demelio G. Conductance of rough random profiles. Int J Solid Struct, 2008, 45(3-4): 879–893
89 Wang A L, Wu Y T, Yang C X. The size distribution characteristic of cavities and active nucleation sites in pool boiling surface (in Chinese). J Eng Therm Energ Power, 2003, 18(3): 291–296
90 Li Y Z, Madhusudana C V, Leonardi E. Experimental investigation of thermal contact conductance: Variations of surface microhardness and roughness. Int J Thermophys, 1998, 19(6): 1691–1704
91 Singhal V, Garimella S V. Prediction of thermal contact conductance by surface deformation analysis. In: Proceedings of 2001 ASME International Mechanical Engineering Congress and Exposition, New York, USA, 2001. 43–50
92 Zhao J F, Wang A L, Yang C X. The statistical characteristic of roughness profiles on thermal contact conductance surface (in Chinese). Cryogenics, 2003, 134 (4): 49–56
93 Zhao J F, Wang A L, Yang C X. A model of thermal contact conductance based on the statistic characteristic of roughness profile (in Chinese). J Eng Thermophys, 2004, 25(1): 145–147
94 Zhao J F, Wang A L, Yang C X. Prediction of thermal contact conductance based on the statistics of the roughness profile characteristics. Int J Heat Mass Transf, 2005, 48: 974–985
95 Patir N. A numerical procedure for random generation of rough surfaces. Wear, 1978, 47: 63–277
96 Waton W, Spedding T A. The time series modeling of non-Gaussian engineering processes. Wear, 1982, 83: 215–231
97 Whitehouse D J. The generation of two-dimensional random surfaces having a specified function. Ann CIRP, 1983, 32(1): 495–498
98 Newland D E. An Introduction to Random Vibration and Spectral Analysis. 2nd ed. London: Longman, 1984
99 Hu Y Z, Tonder K. Simulation of 3-D random rough surface by 2-D digital filter and Fourier analysis. Int J Mach Tools Manuf, 1992, 32: 83–99
100 Chilamankuri S K, Bhushan B. Contact analysis of non-Gaussian random surfaces. Proc Inst Mech Eng, 1998, 212: 19–32
101 Mihailidis A, Bakolas V. Numerical simulation of real 3-D rough surface. J Balk Tribol Assoc, 1999, 5: 247–231
102 Wu J J. Simulation of rough surface with FFT. Tribol Int, 2000, 33: 47–58
103 Bakolas V. Numerical generation of arbitrarily oriented non-Gaussian three-dimensional rough surfaces. Wear, 2003, 254: 546–554
104 Zhou X K, Zhou H, Li D L. Fractal Iconography (in Chinese). Beijing: Higher Education Press, 1995
105 McGaughey D, Atiken G J M. Generating two-dimensional Brownian motion using the fraction Gaussian process (FGP) algorithm. Physica A, 2002, 311: 369–380
106 Yovanovich M M. Thermal contact correlations. In: AIAA 16th Thermophysics Conference, Palo Alto, California, USA, 1981. 83–95
107 Hegazy A A. Thermal joint conductance of conforming rough surfaces: Effect of surface microhardness variation. Dissertation of Doctoral Degree. Waterloo: University of Waterloo, 1985
108 Liu J. Micro/Nano-Scale Heat Transfer (in Chinese). Beijing: Science Press, 2001
109 National Nature Science Foundation Council. Engineering Thermophysics and Energy Utilization (2006–2010)(in Chinese). Beijing: Science Press, 2007
110 Sridhar M R, Yovanovich M M. Elastoplastic contact conductance model for isotropic conforming rough surfaces and comparison with experiments. Trans AMSE J Heat Transf, 1996, 118: 3–9
111 Rostami A A, Hassan A Y, Lim P C. Parametric study of thermal constriction resistance. Heat Mass Transf, 2001, 37(1): 5–10
112 Trujillo D M, Pappoff C G. A general thermal contact resistance finite element. Finite Elem Anal Des, 2002, 38: 263–276
113 Wahid S M S. Numerical analysis of heat flow in contact heat transfer. Int J Heat Mass Transf, 2003, 46: 4751–4754
114 Black A F, Singhal V, Garimella S V. Analysis and prediction of constriction resistance for contact between rough engineering surface. J Thermophys Heat Transf, 2004, 18(1): 30–36
115 Salti B, Laraqi N. 3-D numerical modeling of heat transfer between two sliding bodies: Temperature and thermal contact resistance. Int J Heat Mass Transf, 1999, 42: 2363–2374
116 Laraqi N. Thermal constriction resistance of coated solids-static and sliding contacts. Int Commun Heat Mass Transf, 1999, 26(3): 299–309
117 Laraqi N, Bairi A. New models of thermal resistance at the interface of solids connected by random disk contacts. CR Mecanique, 2002, 330: 39–43
118 Laraqi N, Bairi A. Theory of thermal resistance between solids with randomly sized and located contacts. Int J Heat Mass Transf, 2002, 45: 4175–4180

119 Laraqi N. Change of scale effect in the phenomena of thermal multi-constriction. CR Mecanique, 2002, 330:141–145

120 Tomimura T, Matsuda Y, Zhang X, et al. Two-dimensional modeling of heat transfer between contacting metal surfaces with spherical waviness: Estimation of thermal contact conductance based on random numbers surface model. In: 5th International Symposium on Heat Transfer, Beijing, China, 2000. 137–142

121 Zhang X, Cong P, Fujiwara S, et al. A new method for numerical simulation of thermal contact resistance in cylindrical coordinates. Int J Heat Mass Transf, 2004, 47: 1091–1098

122 Zhang X, Cong P, Fujii M. A study on thermal contact resistance at the interface of two solids. Int J Thermophys, 2006, 27(3): 880–895

123 Touzellbaev M, Goodson K. Impact of nucleation density on the thermal resistance near diamond-substrate boundaries. J Thermophys Heat Transf, 1997, 11: 506–512

124 Prasher R S, Phelan P E. A scattering-mediated acoustic mismatch model for the prediction of thermal boundary resistance. J Heat Transf, 2001, 123: 105–112

125 Chen G. Ballistic-diffusive equations for transient heat conduction from nano to macroscales. J Heat Transf, 2002, 124: 320–328

126 Liang X G, Yue B. The interface roughness effect on the in-plane thermal conductivity in nanoscale (in Chinese). J Eng Thermophys, 2006, 27(3): 475–477

127 Liao N, Yang P. Characterizations of interfacial heat transfer for electronic packages by multi-scale modeling. J Thermophys Heat Transf, 2008, 22(4): 581–586

128 Prasher R S, Phelan P E. Microscopic and macroscopic thermal contact resistances of pressed mechanical contacts. J Appl Phys, 2006, 100: 063538

129 Zhong H, Lukes J R. Interfacial thermal resistance between carbon nanotubes: Molecular dynamics simulations and analytical thermal modeling. Phys Rev B, 2006, 74: 125403

130 Hu M, Shenogin S, Keblinski P. Molecular dynamics simulation of interfacial thermal conductance between silicon and amorphous polyethylene. Appl Phys Lett, 2007, 91: 241910

131 Termentzidis K, Chantrenne P, Keblinski P. Nonequilibrium molecular dynamics simulation of the in-plane thermal conductivity of superlattices with rough interfaces. Phys Rev B, 2009, 79: 214307

132 Landry E S, McGaughey A J H. Thermal boundary resistance predictions from molecular dynamics simulations and theoretical calculations. Phys Rev B, 2009, 80: 165304

133 Lyver J W, Blaisten-Barojas E. Effects of the interface between two Lennard-Jones crystals on the lattice vibrations: A molecular dynamics study. J Phys-Condens Mat, 2009, 21: 345402

134 Gu W L. The Semi-Empirical Correlation of Contact Heat Transfer Research and Other Problems (in Chinese). CSAA-99-006. 1999