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Heat flux evaluation in high temperature ring-on-ring contacts

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ABSTRACT

A comprehensive methodology to investigate heat flux in a ring-on-ring tribometer is presented. Thermal fluxes under high contact pressures and temperature differences were evaluated through an experimental campaign and by a numerical procedure of inverse analysis applied to surface temperature measurements. An approximation of a two-dimensional time-dependent analytical solution for the temperature distribution was first developed and subsequently adapted to mimic the specific testing configuration characteristics; the problem was finally simplified to enable further inverse analysis. Experiments were performed using an innovative high temperature ring-on-ring tribometer. The evaluated contact heat-transfer rates were reported as a function of normal load and temperature difference between the discs under steady-state conditions; the results reported here show that, in the present test configuration, the temperature difference has stronger influence than the applied load in terms of heat transfer induced by contact.

1. Introduction

During hot deformation processes, tool surfaces experience severe thermal fluxes which depend on heat conduction. This is, in turn, a function of the surface state, the application of possible lubricants and the presence of surface oxides, as well as of specific contact conditions and temperature differences with the workpiece. In many cases, the transfer of thermal energy is similar in magnitude to the heat transfer generated by frictional forces. Thus, investigations related to this specific topic form a significant research branch within the general realm of tribology [1].

At present, there is a strong industrial need to achieve more accurate, predictive and computer-based models of the underlying physical processes governing high temperature metal-forming processes. However, existing models are somewhat inadequate, mainly due to the inaccurate definition of mechanical and thermal boundary conditions, namely in terms of friction and heat transfer, respectively. For most industrial hot metal-forming operations, the complexity of the interaction between tool and workpiece makes the direct evaluation of the evolution of both friction and heat transfer difficult and impractical. Thus, in the absence of a detailed insight and due to a lack of fundamental understanding of the mechanisms of heat transfer at a moving interface, most models assume oversimplified descriptions, or determine an average value of the so-called heat transfer coefficient (*htc*); often this corresponds to evaluating a coefficient that takes into account all thermal effects [2], without separating the various contributions from conduction through the actual contact spots, conduction through the interstitial medium, and radiation occurring at the apparent contact area [3–6].

In past years, several efforts have been devoted to the understanding of the role played by the heat transfer phenomena during hot deformation processes (see e.g. [2,7]). The availability of complex analytical/numerical models for the process simulation allows the achievement of a more accurate evaluation of the *htc* based on sophisticated experimental data and the advanced use of procedures of inverse analysis. In particular, the adoption of such solutions in the definition of the objective function in dedicated inverse analysis algorithms shall give rise to a more precise and direct characterization of the *htc* for in-service operating conditions. However, many inverse analysis methods are based on filling the gap between measurements and output of the model equations [8–16]; hence, although these methods may provide more refined parameters, they cannot be easily generalized and they are not suitable for the analysis of the influence of the contact parameters governing the problem under investigation. Despite such efforts, the difficulties of performing laboratory measurements, combined with the complexity of the tool–workpiece interface, result in a wide range of the estimated values of *htc* reported in the literature [17].

In the present work, a comprehensive methodology based on combined experimental/analytical analyses is adopted to investigate the global heat flux occurring at the contact region in a ring-

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on-ring tribometer. The testing device and the associated testing protocols, used to characterize the friction between solids under relative motion, are introduced first. These were employed here to assess heat fluxes in high temperature contacts under pure rolling. Then, a newly-developed methodology implemented to model the heat flux and temperature variation within the system under investigation is presented. Quantitative results for realistic in-service conditions are obtained by means of a final dedicated inverse analysis, matching the temperature measurements with the predictions from the analytical model, specifically tailored for representing heat transfer on a ring-on-ring contact at high temperature.

2. Material and methods

Thermal fluxes under high contact pressures and temperature differences were evaluated through a numerical procedure of inverse analysis (discussed in Section 3) applied to surface temperature measurements and developed to produce an accurate estimate of heat transfer at the contact between two components. Experiments were run on a ring-on-ring tribometer, designed to achieve high temperature in the contact between the two rotating discs, in the same range as the temperature experienced during hot deformation processes. The aim was also to control separately the temperature of the two discs. A simplified sketch of the testing configuration and temperature monitoring is illustrated in Fig. 1.

2.1. Materials

Test discs were machined from bars of carbon steel (0.40% C). Two disc dimensions were employed: 120 mm diameter and 25 mm wide (large size); 50 mm diameter and 34 mm wide (small size). All specimens presented surface finishing from the smooth lathe machining (root mean square – r.m.s. – roughness less than 3.2 μm). The testing configuration was obtained by coupling two cylindrical discs of different dimensions. Thermo-physical properties of the material were estimated through the use of a commercial software [18].

2.2. Equipment setup

Specimens were mounted on horizontal electrically motorized spindles of 24 mm diameter and driven independently at controlled speeds. The normal force between the two discs was applied through a pneumatic cylinder. The experimental device was equipped with a main induction heater of 24 kW power for heating up the larger disc and a second induction heater of 12 kW power for the smaller one. Coils were located at an effective radial distance for induction heating. Thus, the temperature rises radially from the external hot spot to the spindle. The disc surface temperature evened out during rotation due to the relative motion of the disc with respect to the heat source. Induction power was regulated in a closed loop in order to attain the target value of surface temperature measured through a devoted pyrometer (Fig. 1).

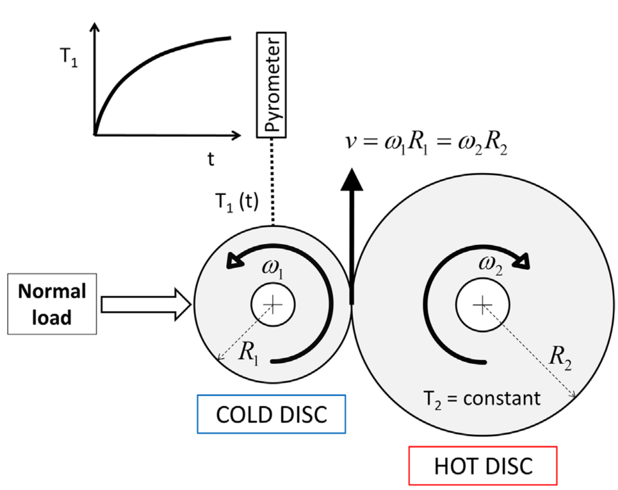

Fig. 1. Schematic of the testing configuration and temperature measurement.

2.3. Experiments

Long-term tests were carried out at a zero slide/roll ratio, corresponding to pure rolling. Initially the rotating discs were heated up separately and in the absence of contact, to target different surface temperatures for the hot disc and the cold disc. The step duration was enough to let both samples to achieve a steady state condition of temperature distribution. Once the steady state temperature was approached, samples were put in contact under the normal load and the test was run for 30 min. At this stage, only the main induction heater was switched on, which guaranteed a constant surface temperature for the hot disc during the whole contact time, whereas the second induction heater was turned off and the surface temperature evolution was recorded for the cold disc. Under these working conditions, the temperature profile of the cold disc evolved due to the following: (i) the heat flux in the contact region, (ii) the radiation from the hot disc, and (iii) the radiation and convection in the surrounding air. The induction heater was excluded to gain more sensitivity towards these variables (uncontrolled fluctuations in power supply could be as relevant as the heat flux).

2.4. Testing conditions

Tests were run at fixed disc rotational speed of 60 rpm for the hot disc, in a range of normal loads and initial temperatures, corresponding to 4 different cases, as shown in Table 1. A single test was carried out for each condition once the experimental reproducibility was proven through preliminary investigations covering a wide range of input parameters.

2.5. Measurements

During the contact step, surface temperature evolution due to the rotating contacts was measured at the surface, in the middle of the specimen width, using a pyrometer located at 90° from the contact region (Fig. 1). The pyrometer provided stable data acquisition from 80 °C to 600 °C. The emissivity was set to a constant value of 0.75, after comparison with the thermocouple measurements.

3. Theory

The inverse analysis procedure used by the authors needed an accurate mathematical description of the physical processes of

Table 1
Test conditions.

Normal load (N)	Initial temperature		Initial temperature difference	*Case* (°C)
	Hot disc (°C)	*Cold disc* (°C)		
500	400	180	220	***1***
	800	340	460	***2***
2000	400	180	220	***3***
	800	340	460	***4***