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Experimental and numerical investigation of contact heat transfer between a rotating heat pipe and a steel strip

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ABSTRACT

A new concept for energy efficient annealing of steel strip comprises of multiple rotating heat pipes. Each heat pipe extracts heat from the cooling strip which is reused to increase the temperature of the heating strip. In this context, the heat transfer between the steel strip and the rotating heat pipe is investigated. When the strip is transported over the heat pipe, gas entrains in the gap. The gas compresses into a uniform gas layer. The contact heat transfer deteriorates due to this phenomenon. A numerical model to quantify the heat transfer between the surfaces is developed. Since there is no direct way to quantify the heat transfer between two moving surfaces, the problem is divided into a gas entrainment and a heat transfer part. The model is validated with experiments executed on a rotating heat pipe test rig. The validation was made varying the strip thickness, specific tension and strip velocity. The results show a uniform gas layer forming within the first 1° of the 180° wrap angle in all cases. The heat transfer is dominated by gas conduction. Results for the uniform gas layer region yield heat transfer coefficients in the range between 4000 and 20,000 W/m^2·K.

1. Introduction

Cold rolling of steel causes an increase in the hardness of the material. In order to restore its ductility, the steel is heated to approximately 700 °C and cooled down to ambient temperature. This energy intensive process is called annealing and is an essential heat treatment process in the steel industry [1]. In a conventional process, none of the applied energy is retained in the product.

Therefore, an alternative technology was developed to reuse the heat extracted during the cooling of the strip in the heating part of the cycle. In this concept, the strip being cooled is thermally linked to the strip being heated with rotating heat pipes [2].

A heat pipe is a highly efficient heat transfer device. It is a closed pipe which contains a fixed amount of working fluid. This working fluid carries the heat from one end to the other by means of evaporation, vapor transport and condensation [3]. In order to work continuously, the condensed liquid needs to be driven back to the evaporation zone. The method used to transport the liquid varies among different types of heat pipes [4, 5]. For rotating heat pipes, this is accomplished by the centrifugal force produced by the rotation of the heat pipe around its symmetric axis [6,7].

Thanks to the high efficiency of the heat pipes, the alternative annealing technology promises a reduction of energy consumption of up to 70% [2]. To implement this technology, the contact heat transfer between the rotating heat pipe and the steel strip needs to be thoroughly investigated.

When a strip is transported over a roll, gas is dragged in between these two surfaces. The gas compresses and forms a stable thin gas layer over the wrap angle. The gas layer forms a thermal resistance between the strip and the roll, thus limiting the heat transfer from one to the other. The thickness of a gas layer between two surfaces moving at relative speed has been extensively studied in the context of foil bearings. However, these studies do not consider heat transfer between the surfaces and do not describe cases where relative motion is zero or near zero.

In the foil bearing studies, it has been observed that, with the exception of inlet and outlet region, a uniform gas layer thickness forms when the foil tension and the wrap angle are sufficiently large [8,9]. Therefore, the work on foil bearings divides the problem into an inlet and outlet region. This approach allows for an asymptotic convergence of the inlet and outlet regions to the

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Nomenclature

C	compressibility parameter
C^*	normalized compressibility parameter
c_p	specific heat, J/kg·K
D	bending stiffness per unit width, N·m
h	gas layer thickness, m
H	dimensionless gas layer thickness
H^*	dimensionless gas layer thickness in uniform region
$\bar{H}$	normalized gas layer thickness
H_e	Vickers hardness, Pa
k_g	thermal conductivity of gas, W/m·K
k_s	harmonic thermal conductivity, W/m·K
K	integration constant
m	slope of roughness peaks
p	gas layer pressure, Pa
p_a	ambient pressure, Pa
p_c	contact pressure, Pa
p_m	pressure required for full contact, Pa
R	arc of curvature, m
r_o	roll radius, m
Ra	surface roughness, m
Ra_e	effective roughness, m
s	coordinate along the wrap angle direction
S	stiffness parameter
$\bar{S}$	normalized stiffness parameter
t	strip thickness, m
T	temperature, K
T_s	strip specific tension, Pa
U	velocity of the strip, m/s
υ	velocity of the node, m/s
z	radial coordinate
$\mathcal{Z}$	radial distance to the node, m
α_{total}	overall heat transfer coefficient, W/m^2·K
α_{solid}	solid contact heat transfer coefficient, W/m^2·K
α_{gas}	gas conduction heat transfer coefficient, W/m^2·K
α_{rad}	radiation heat transfer coefficient, W/m^2·K
β	perturbation parameter
ε	emissivity
θ	angular coordinate
μ	viscosity, Pa·s
ξ	extended coordinate
$\bar{\xi}$	normalized extended coordinate
ρ	density, kg/m^3
σ	Stefan-Boltzmann constant, W/m^2·K^4
Φ	dimensionless pressure

uniform gas layer thickness. A base for infinitely wide and perfectly flexible foil is given in [10]. The foil stiffness is described in [11] and integrated in [12]. The numerical solution for compressing the gas layer is provided in [13]. A review of these studies is provided in [14].

For the specific case where the tension of the foil and the wrap angle is small, the problem can be solved at once, without dividing it into an inlet and an outlet branch. This method also allows for the tension change due to friction between the foil and the roll over the wrap angle. Such a method is described in [15–20]. In these studies, the foil is in physical contact with the roll.

In addition to the determination of the gas layer thickness, the heat transfer between two macroscopically conforming surfaces should be studied for the problem at hand. Heat transfer between two rough surfaces is divided into the heat transfer across the gas gap and the heat transfer through solid contact in [21]. In this extensive study, the complexity of the gap geometry is overcome by simplifying the gap heat transfer as the heat transfer between the projected surfaces. The solid heat transfer is determined using a correlation including contact pressure, surface parameters and thermal conductivities. Results of analytical and experimental studies for the thermal resistance of gases are given in [22]. In [23], the thermal gap conductance is experimentally studied and good agreement is obtained with theory. A comprehensive review of the subject is made in [24].

The experimental investigation of contact heat transfer between a strip and a roll has not been widely addressed so far. In [25] and [26], such a study is performed in a dedicated roll regenerative furnace. In that study, a hollow shell is used as the roll and the strip velocities are relatively low. The contact heat transfer coefficient values reported in [26] are used in the modelling of a multi-roll heat exchanger with two strips moving in opposite direction in [27].

The current study aims to model and experimentally investigate the heat transfer between a steel strip and a rotating roll. In the modelling part of this work, a novel methodology for quantifying the heat transfer is adopted. Since there is no straightforward way to calculate the heat transfer between two moving surfaces, the problem is divided into a gas entrainment and a heat transfer part. The gas layer thickness between the two surfaces is found with an asymptotic approach, incorporating the stiffness of the strip, the contact between the surfaces and the compressibility of the gas. The model therefore is a combination of the approaches found in [12], [13] and [16]. However, the derivation of the governing equations is somewhat different. The solution for gas layer and contact pressure is coupled with the contact heat transfer model described in [21]. With this combination, the contact heat transfer coefficient evolution along the wrap angle is found.

The experimental part of the current work is performed on a test rig comprising of a roll executed as a heat pipe over which a steel strip travels. The temperature evolution of the steel strip as it travels over the wrap angle is measured at various strip velocity, strip tension and strip thickness configurations. During the measurements, the behavior of the heat pipe is also tracked. As opposed to previous work in literature, the use of a heat pipe in the validation process allows for better isolation of the heat transfer between the strip and the roll from outside influence. This is the case because it allows for a Dirichlet boundary condition at the interior of the roll.

The modelling and experimental results are reported for various configurations of strip velocity, tension and thickness. Such a catalogue of contact heat transfer coefficients also sheds light on the parameters affecting the heat transfer for similar applications.

2. Problem modelling

The analysis for the steel strip transported over a rotating heat pipe is simplified to the study of a strip traveling over a roll. The infinitely wide strip travels at velocity U and is tensioned with T_s over the roll radius r_o. The heat pipe is considered to be non-deformable whereas the strip can bend depending on the forces acting on it. As the heat pipe is freely suspending, its velocity is assumed to be equal to the velocity of the strip. The absolute pressure of the gas layer is p and its thickness is h. The wrap angle is divided into three regions; namely the inlet region (A), the uniform region (B) and the outlet region (C). Tension on the strip is applied some distance away from the roll marked as (D) (see Fig. 1).