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Transient thermal stress distribution in a circular pipe heated externally with a periodically moving heat source

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ABSTRACT

This study presents the effects of periodically moving heat source on a circular steel pipe heated partly from its outer surface under stagnant ambient conditions. While the pipe is heated with this heat source applied on a certain section having a thickness of heat flux, the water flows through it to transfer heat. It is assumed that the flow is a fully-developed laminar flow. The heat source moves along from one end of the outer to the other end with a constant speed and then returns to the first end with the same speed. It is assumed that the heat transfer rate has a constant value, and that the thermo-physical properties of the steel do not change with temperature (elastic analysis). The numerical calculations have been performed individually for a wide range of thermal conductivity of steel and for different thicknesses of heat flux. The moving heat source produces the non-uniform temperature gradient and the non-uniform effective thermal stress, and when it arrives at the ends of the pipe, the temperature and effective thermal stress ratio profiles rise more excessively. The tangential component is more dominant in the effective thermal stress than the radial component.

1. Introduction

The estimation of temperature distribution in solids subjected to moving heat source (MHS) has been of great scientific interest since very long time. The MHS, which is a kind of heat source used or generated in machining, is frequently encountered in many manufacturing processes, such as grinding, welding, hardening, cutting, coating, metal forming, etc. Therefore, heat conduction involving a MHS are a crucial problem required solving for numerous engineering processes. The analyses on the problems including the MHS have continued over the last decade. Considerable research studies have been carried out on modeling of the manufacturing processes including these heat problems [1,2]. Furthermore, recently, the MHS problems have been analyzed analytically and/or numerically for several geometries and boundary conditions by many researches. Shuja and Yilbas [3] considered a modeling of the laser gas-assisted heating process. They present that the workpiece movement affects considerably the temperature rise inside the solid substrate. Ali and Zhang [4] established a unified framework for solving heat conduction problems using the relativistic heat conduction model. This paper offers "Fundamental Solutions" in one, two, and three spatial dimensions, for the transient response due to an instantaneous point MHS. Cheng and Lin [5] developed an analytical model to describe the three-dimensional temperature field for a finite plate with a Gaussian heat source moving at a constant velocity and studied the effects of the laser forming parameters on the temperature distributions using this model. Araya and Gutierrez [6] studied on analytical solutions of the transient temperature distribution in a finite solid heated by a MHS. They obtained an analytical solution by solving the transient three-dimensional heat conduction equation in a finite domain by the method of separation of variables. Laraqi et al. [7] solved analytically the three-dimensional temperature distribution and the thermal constriction resistance due to the MHSs on semi-infinite bodies. Alilat et al. [8] derived an appropriate analytical solution for the calculation of three-dimensional temperature distribution inside a rotating disk subjected to an eccentric circular heat source and surface cooling. They have developed a numerical study by using the finite-volume method. Their numerical study using the finite-volume method confirms that the proposed analytical solution provides acceptably accurate results even for high values of heat convection coefficient. The results obtained by the proposed analytical solution are also in good agreement with available models. Yang [9] studied on two moving heat sources in two dimensional inverse heat problem. The results of this study show that the proposed method is an accurate and efficient method to determine the position and the strength of two moving sources in the inverse heat conduction problem. Hou and Komanduri [10] have presented general solutions

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Nomenclature

a, b	axial points
A	area [m^2]
Cp	specific heat [J/kg-K]
E	Energy transfer [J]
E	modulus of elasticity [Pa]
h	heat transfer coefficient [W/m^2-K]
j	j-th revolution
L	length of pipe [m]
MHS	moving heat source
n	total cycle number
q_0	heat flux intensity [W/m^2]
q”	heat flux per unit area [W/m^2]
Q	heat transfer rate [W]
P	pressure [Pa]
P	period [s]
r	radial component [m]
t	time [s]
T	temperature [°C]
u	axial velocity component [m/s]
UDF	user defined function
v	radial velocity component [m/s]
x	axial component [m]

Greek symbols

α	thermal expansion coefficient [1/^{0}C]
δ	axial thickness [m]
λ	thermal conductivity [W/m-K]
ν	Poisson’s ratio
ρ	density [kg/m3]
σ	thermal stress [Pa]
σ^*	thermal stress ratio [°C]
τ	normalized time [s]
ϕ	any arbitrary variable
μ	dynamic viscosity [kg/m-s]

Subscripts

amb	ambient
eff	effective
f	fluid
h	heat flux
i	inner
m	mean
max	maximum
o	outer
θ	tangential
r	radial
s	solid
z	longitudinal

(both transient and steady state) for the temperature rise at any point due to stationary/moving plane heat sources of different shapes and heat intensity distributions. Moulik et al. [11] simulated the grinding of elastic and elastic–plastic workpiece materials and developed an efficient finite element procedure to calculate the temperatures and stresses arising due to a moving source of heat. They obtained that the calculated transient stresses and temperatures in an elastic solid are found to be in good agreement with prior analytical and numerical results. Wang and Wang [12] determined the maximum transient thermal stresses on the boundary of a near-edge elliptical defect in a semi-infinite thin plate subjected a moving heat source were determined by the digital photoelastic technique. The relationships between the maximum transient thermal stresses and the size and inclination of the elliptical defect, the minimum distance from the elliptical defect to the plate edge and the speed of the moving heat source were investigated. The variations of the maximum transient thermal stresses were correlated with the time, the minimum distance between the edge and the elliptical defect, temperature difference, and speed of the moving heat source.

The MHS occurs in welding process which is one of the most important material-joining processes widely used in industry, such as frequently in the repair, modification or extension of gas pipelines. Therefore, heat transfer patterns involving the MHS are a crucial problem required solving. In these heat problems, there are very limited experimental data and thus the researchers have tended to do analytical and numerical analysis. Sunar et al. [13] presented a cantilever assembly subjected to heating at its fixed end, which resembles the welding of a sheet metal. A control volume approach was considered for the numerical analysis while the finite element method was adopted for stress field predictions. They found that the temperature distribution varied significantly in the longitudinal direction, but in the transverse direction did not change considerably. Teng and Chang [14] carried out thermomechanical analysis of circumferentially welded thin walled pipes, which are frequently used in boiling water reactor piping systems, oil pipe transport systems and steam piping systems. They also discussed exactly how the pipe wall thickness influences the welding residual stresses. Murugan et al. [15,16] carried out experimental study to find out the temperature distribution and residual stresses during multipass welding of the above plates and average maximum temperature rise during each pass of welding was calculated. It was concluded that using by these calculations the maximum temperature rise expected in the base plate region during any pass of welding operation could be estimated. The relation between the peak temperatures and the residual stresses in the weld pads were obtained. Sabapathy et al. [17] formed a new mathematical description of a heat source to represent the common in-service welding process. It was shown that it was possible to reliably simulate the process of in-service welding and to predict weld zone geometries and cooling times. Comparisons between experimental and predicted values showed that the thermal fields and weld cooling times calculated with a useful accuracy of 12%. Akbari and Sattari-Far [18] analyzed the thermo-mechanical behavior and residual stresses in dissimilar butt-welded pipes. The results of the numerical analysis were compared with experimentally data and a modeling procedure with reasonable accuracy was developed. Kumar-Krishnasamy and Siegele [19] considered a dissimilar tube welding and used SYSWELD welding software to model the thermal and mechanical analysis. The transient temperature field was incorporated as the input for the mechanical analysis to obtain the residual stresses during welding. The simulations showed that the residual stresses reduced in magnitude but presented even after post weld heat treatment.

On the other hand, the pipe flow problems including conjugate heat transfer find wide application in engineering disciplines. Al-Zaharnah et al. [20,21] analyzed the conjugate heat transfer in fully-developed laminar pipe flow and the thermally induced stresses. These studies show that the low Prandtl number and low thermal conductivity ratios result in almost uniform radial temperatures and low radial effective stresses, and that the wall thickness and pipe diameter are significant parameters affecting the resulting stress distribution. Furthermore, they considered