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Simulation of the temperature rise in Hopkinson bar experiments accounting for heat transfer to the bars

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***Abstract*—The specimen temperature increases in medium and high strain rate experiments because of their short duration. This paper describes a numerical-analytical approach to predict temperature rise in Hopkinson bar experiments. Namely, a two-step one-dimensional model is proposed. The model assumes an elasto-plastic behavior for the tested materials. It is applied to calculate the temperature rise in a Hopkinson bar test on an aluminum alloy at a strain rate about 500/s.**

Keywords—Hopkinson bar; temperature rise, high strain rate, aluminum alloy, Johnson-Cook.

I. INTRODUCTION

Dynamic experiments are very useful to measure the strain rate sensitivity of the mechanical properties of materials. Since the beginning of the 20th century, several machines have been proposed to characterize materials at high strain rate. The most used one is the split Hopkinson bar or Kolsky bars setup [1,2]. Since then, this device has been widely used to assess the dynamic properties of metals [3], polymers [4], composites [5], rubbers [6], etc. Multiple modifications have been proposed on the Hopkinson-Kolsky device since the works of Hopkinson [1] and Kolsky [2]. For example, this technique has been modified to test materials under tensile [7], shear [8], and bi-axial [9] loadings. Besides, the strain rate range was extended to the medium strain rate range by mainly using wave separation techniques [10-12]. Low-impedance bars [13] have been also proposed to test soft materials.

Ductile metallic and polymer materials undergo significant plastic deformation before failure. The plastic deformation energy is then transformed, partially or totally, to heat. Nevertheless, the useful test time of high strain rate experiments, which is of some hundreds of microseconds, is short compared with the heat transferring or dissipation time. Hence, almost no heat is lost, to the atmosphere or to the bars, during the useful duration of the test. Thus, the specimen deformation can be assumed as an adiabatic thermal process [14-17]. The accumulation of heat causes a temperature rise in the specimen.

Chou et al. [14] reported a temperature increase, measured by a thermocouple, of about 16°K for a PMMA which is deformed up to 20% at a strain rate of 1250/s. Mason et al. [15] have measured the temperature rise in steel, aluminum and titanium alloys using a high speed infra-red detector array. Noble and Harding [16] used the same methodology while testing iron. Kapoor and Nemat-Nasser [17] compared the direct technique, using an infra-red technology and an indirect method which is based on a modified Hopkinson bar rig that allows for recovering the isothermal flow stress at high strain rates [18-19]. Liao and Duffy [20] used the infra-red technique in torsion Hopkinson bar experiments. They measured more than 400 °K during formation of adiabatic shear bands. Trojanowski et al. [21] used infra-red methodology with a time resolution as lower as 1μs. They measured a temperature rise of about 50°K after 50% of deformation in a titanium alloy [22] and after 35% of deformation in an aluminum alloy [23]. Lerch et al. [24] and Garg et al. [25] used the infra-red technique with polymers. Guzmán et al. [26] studied the effect of emissivity coefficient on the temperature using infra-red technique.

It is highly interesting to measure the temperature rise during the high strain rate experiments. This can help in the interpretation of the flow stress and linking it to the real material temperature. In this paper, we are interested in proposing a hybrid numerical-analytical approach to measure the temperature rise during Hopkinson bar experiment while accounting for the heat transfer to the bars.

II. METHODOLOGY

A. General approach

The heat transfer problem is a coupled thermo-mechanical problem. Indeed, the heat generation depends on the plastic work. The higher is the plastic work, the higher is the heat generation and the higher is the temperature increase. However, an increase in temperature has a softening effect on the material. Thus, the flow stress and plastic deformation decrease.

For the sake of simplicity, the flow stress is approximated by the flow stress obtained at room temperature. Thus, a mechanical problem can be solved first (see Section B). The solution of which is later used to estimate first the plastic work. This plastic work is then used to calculate the heat generation.

B. Mechanical problem

The objective of the mechanical problem is to calculate the heat generation rate $\dot{q}(t)$ while the specimen deforms plastically in a Hopkinson bar test. First, we assume that the strain rate $\dot{\varepsilon}$ is constant during the Hopkinson bar test. Thus, the strain in specimen $\varepsilon(t)$, assumed homogenous, simply increases linearly in terms of time t:

$$\varepsilon(t) = \dot{\varepsilon}\, t. \quad (1)$$

In the beginning, the behavior is elastic. Upon yielding, the strain is split in an elastic and plastic part, which are denoted ε_e and ε_p , respectively. These elastic and plastic strains read:

$$\varepsilon_e(t) = \frac{\sigma(t)}{E}, \quad (2)$$

and

$$\varepsilon_p(t) = \begin{vmatrix} 0, & \text{if } \varepsilon(t) < \varepsilon_y \\ \varepsilon(t) - \varepsilon_e(t), & \text{if } \varepsilon(t) \geq \varepsilon_y \end{vmatrix}, \quad (3)$$

respectively, where ε_y denotes the yield strain, E holds for the Young's modulus and $\sigma(t)$ is the stress in the specimen. The yield strain writes:

$$\varepsilon_y = \frac{\sigma_y}{E}, \quad (4)$$

where σ_y is the yield stress. The methodology developed here is valid for materials with an elasto-plastic behavior. Therefore, the stress in the elastic range is written as:

$$\sigma(t) = E\, \varepsilon(t); \quad (5)$$

whereas, the stress can be defined by any flow stress law in the plastic range. Without any lose of generality, the flow stress is computed here using the Johnson-Cook constitutive equation [27]:

$$\sigma(t) = \left(A + B\left(\varepsilon_p(t)\right)^n\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right), \quad (6)$$

This constitutive equation depends on the material constants: $A, B, n\ C\ \dot{\varepsilon}_0\ T_0\ T_m$ and m. As the mechanical (this section) and the thermal (Section C) problems are decoupled, we consider that $T = T_0$.

The stress and strain are now calculated, it is possible to derive the plastic work $U_p(t)$:

$$U_p(t) = \int_0^t \sigma(\tau)\, \varepsilon(\tau)\, d\tau - \frac{(\sigma(t))^2}{2E}. \quad (7)$$

The heat conversion ratio or Taylor-Quinney coefficient β is mostly assumed constant and equal to 0.9. Hence, the heat generation in the specimen reads:

$$q(t) = \beta\, U_p(t) = \beta\left(\int_0^t \sigma(\tau)\, \varepsilon(\tau)\, d\tau - \frac{(\sigma(t))^2}{2E}\right). \quad (8)$$

Subsequently, Eq. (8) can be differentiated with respect to time in order to obtain the heat generation rate $\dot{q}(t)$.

TABLE I. PARAMETERS OF THE JOHNSON-COOK MODEL [28]

Material constant	**Aluminum 6061-T6**
A [PA]	3.24E+08
B [PA]	1.14E+08
n	0.42
T_m [°K]	925
T_0 [°K]	293.2
m	1.34
C	0.002
$\dot{\varepsilon}_0$[S^{-1}]	1

TABLE II. THERMAL PARAMETERS [29]

Material constant	**Steel (bars)**	**Aluminum 6061-T6 (Specimen)**
Thermal conductivity [W/m.k]	45	200
SPECIFIC HEAT [J/KG.K]	475	900

As an example, the approach developed here is applied to an aluminum alloy (6061-T6). We consider that the Poisson's ratio, the Young's modulus and the density are then equal to 0.34, 70 GPA and $2800\ \mathrm{kg/m^3}$, respectively. The parameters of the Johnson-Cook model are presented in Table I. The simulation presented here were carried out assuming a maximum strain in the specimen $\varepsilon_{max} = 50\%$ and a strain rate of 500/s.

C. Thermal problem

In this section, we are interested in solving the heat transfer problem. A one-dimensional finite element heat transfer problem is modeled for the split Hopkinson bar setup using the commercial software Abaqus. The incident and transmitted bars are considered 0.5-m long. As the heat transfer problem is localized near the specimen-bar interfaces, there is no need to consider longer bars. The outer ends of the incident and output bars are assumed equal to room temperature. The specimen is chosen to be 5-mm long. The thermal properties of the bars and the specimen are detailed in Table II. A thermal load is applied on the specimen as a heat body flux, which is equal to the rate of heat generation, i.e., $\dot{q}(t)$ where $q(t)$ is determined by Eq. (8).

The bars are meshed using elements of length 1mm and the specimen is meshed using elements of length 0.025 mm.

III. RESULTS

The model presented in section II is now used to predict the temperature rise within the specimen tested with a Hopkinson bar setup at a strain rate of 500/s. Figure 1 depicts the temperature distribution along the specimen length at five levels of strain: 10%, 20%, 30%, 40% and 50%. The temperature rise is maximum in the middle of the specimen and it has the lowest values near the edges, which are in contact with the bars. Indeed, the heat generation is uniform along the specimen as the specimen is uniformly deformed. However, heat is transferred to the neighborhood mainly through the two elastic bars. Thus, the coldest parts of the specimen are those which are the closest nearest to the bars.

Figure 2 shows the temperature evolution for several points of the specimen. This temperature evolution is also compared to the adiabatic temperature rise, which is the temperature rise in the specimen calculated assuming that the specimen is thermally isolated. Except a small region near the edges, the temperature increase rise in the specimen is almost equal to the adiabatic temperature rise. Besides, the average temperature in the specimen is also not far from the adiabatic temperature increase. Thus, the adiabatic assumption is worthwhile at a strain rate of 500/s. However, the temperature field in the specimen is not homogeneous mainly near the specimen-bar interfaces.

IV. Conclusion

In this work, a two-step one-dimensional hybrid numerical-analytical approach has been developed to predict temperature rise in high strain rate experiments. This approach was applied to a split Hopkinson pressure bar test on an aluminum alloy at a strain rate of about 500/s. It was shown that the temperature in the specimen is heterogeneous especially at the edges near the elastic bars. However, the average temperature rise in the specimen is slightly lower that the adiabatic temperature rise.

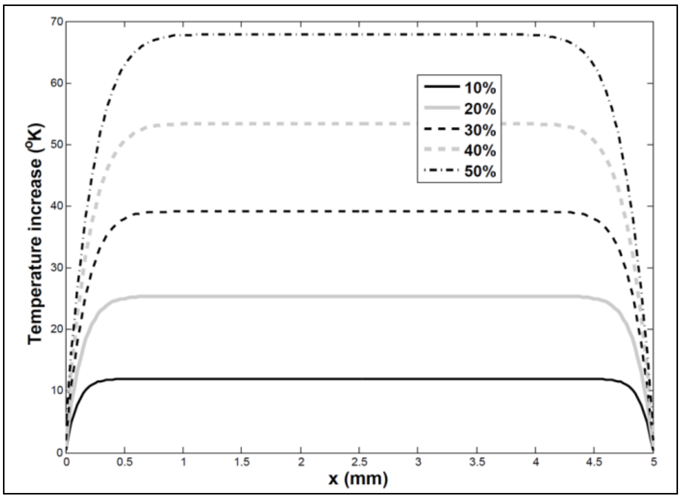

Fig.1. *Temperature distribution in the specimen at different levels of strain (strain rate of 500/s)*

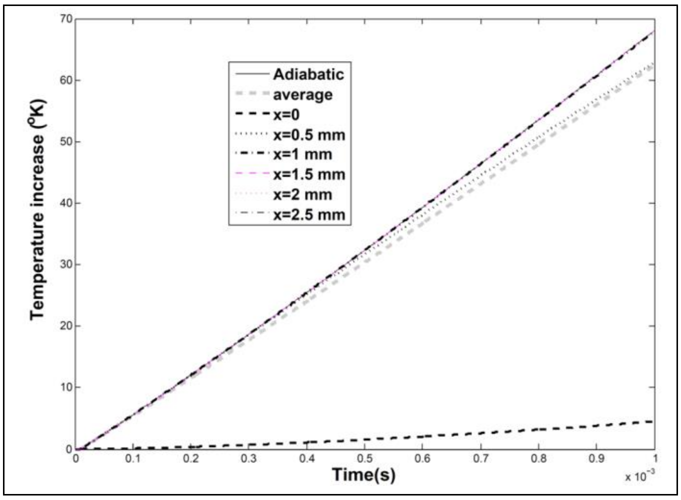

Fig.2. *Temperature evolution with time at several points of the specimen compared to the adiabatic temperature rise (strain rate of 500/s)*

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