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Temperature increment during quasi-static compression tests using Mg metallic alloys

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ABSTRACT

During plastic deformation of metals, part of the plastic work is converted into heat. Therefore, the increases in generated heat may be quantified using an infrared camera to measure the radiation emitted on the surface of the specimen. The goal of this work is to evaluate the way in which the temperature increase is influenced by the initial test temperature, strain rate, and friction condition between specimen and device. Thus, experimental tests were conducted under quasi-static loading conditions using two kinds of materials, a Mg alloy (ZC71) and the same alloy reinforced with ceramic particles (SiC, 12 vol.%). Conclusions are reported on the mechanical behaviour, in term of instabilities, and temperature increase coupled to strain-rate sensitivity. A numerical model defining quasi-static test was used to estimate local quantities such as temperature increase, ΔT, and macroscopic behaviour, $\bar{\sigma}$—$\bar{\varepsilon}^p$.

1. Introduction

During the deformation of a solid, part of the mechanical energy is stored as internal defects, part is dissipated for micro-structural changes as dislocations or phase transformation, and the rest is converted into heat [1–5]. The last part changes the temperature field of the material loaded. This phenomenon depends on the material studied (mechanical properties, conductivity, and other factors), the initial temperature, and the strain rate used during the test. For a material with elastic–plastic behaviour, the energy-balance equation which provides the time course for temperature is defined as

$$\lambda\nabla^2 T - \dot{T} = -\frac{\beta}{\rho C_p}\sigma : \dot{\varepsilon}^p + \frac{\alpha}{\rho C_p}\frac{E}{1-2\nu}T_o Tr(\dot{\varepsilon}^e) \qquad (1)$$

where λ is the material thermal diffusivity, T is the current temperature, σ is the stress tensor, $\dot{\varepsilon}^p$, is the plastic strain-rate tensor, ρ is the material density, C_p is the specific-heat capacity, α is the thermal-expansion coefficient, E is the Young's modulus, ν is the Poisson coefficient, T_0 is the initial temperature, $Tr(\dot{\varepsilon}^e)$ is the trace of elastic strain-rate tensor and, finally, β is the Quinney–Taylor coefficient, which defines the plastic work fraction converted into heat. Generally, β value changes with plastic deformation, as reported in [1,5–8]

Each term of Eq. (1), defines the following quantities:

1. $\lambda\nabla^2 T$ is the temperature variation due to conductivity processes,
2. $\dot{T}$ is the temporal temperature variation by unit of volume,
3. $\frac{\beta}{\rho C_p}\sigma : \dot{\varepsilon}^p$ is the temperature increment associated with plastic deformations (irreversible process),
4. $\frac{\alpha}{\rho C_p}\frac{E}{1-2\nu}T_o Tr(\dot{\varepsilon}^e)$ is the temperature increment associated with elastic deformations (reversible process).

The heat transfer into the air due to convection from the specimen surface is defined by the heat-flux equation:

$$Q = h \cdot A(\theta_b - \theta_s) \qquad (2)$$

where Q is the heat-flux on the surface, h is a reference convective heat-transfer coefficient, θ_b is the temperature on the specimen surface, and θ_s is a reference temperature value.

For measurement of the temperature increase, ΔT, associated with plastic deformation, $\dot{\varepsilon}^p$, infrared thermography (IRT) technique is frequently used [9–12]. The main difficulty using IRT technique is the presence of an additional unknown, which is the coefficient of emissivity, ϵ, on the specimen surface. The application of the IRT technique developed in this paper is based on different assumptions which allow a correct estimation of the emissivity value. The goal of this work is to analyse the influence of the total

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strain rate, $\dot{\varepsilon}$, initial temperature, T_0, and friction coefficient, μ, effects on the temperature increase ΔT during deformation at low strain rates. A numerical model was developed to describe the specimen stress, strain and temperature fields, allowing a better understanding of experiments.

2. Experimental methods

Compression tests in quasi-static loading were performed. During each test the material nominal strain, ε, and stress, σ, as well as the temperature increase on the specimen surface were recorded.

The complete experimental set-up and protocol, developed by Guzmán et al., concerning mainly temperature measurement and calibration, is reported in [13].

The materials tested were a Mg ZC71 alloy and the same alloy reinforced with SiC particles in a volumetric fraction of 12%. The choice of the reinforced alloy was determined by their growing importance in the automobile industry. To compare the influence of reinforcement, the Mg alloy was also studied. The main thermo-mechanical properties of the materials tested are reported in Table 1.

2.1. Experimental set-up

The experimental set-up developed by Guzmán et al. [13], consisted of a test and a dark chamber coupled to an universal testing machine and to an infrared camera (IRC). Fig. 1 shows the experimental set-up used including all elements described previously.

2.1.1. Infrared camera

To measure the temperature increment ΔT on the surface of the tested specimen, a Thermosensorik CMT 384M infrared camera was used. The minimum temperature difference detected by the sensor was in order of 20 mK.

2.1.2. Test chamber

The specimen was isolated and fixed in a chamber, allowing the test temperature to be precisely controlled. This chamber includes electric resistances, controlled by thermocouple, allowing to heat the specimen and to change the initial test temperature in a precise way.

2.1.3. Dark chamber

This chamber was designed to take into account the focal distance of the IRC and to isolate the IRC from spurious external radiation, thereby avoiding errors in the temperature measurements.

2.1.4. Synchronism system

To synchronize the deformation process with temperature measurement, a synchronism system was designed by Guzmán et al. [13]. This system makes it possible to start the temperature-data acquisition for a predetermined time during a mechanical test. The set-up includes two photoelectric sensors (optical fibres), a time counter, and an integrated circuit (I.C.). The sensors, placed in front of the compression device, were used to detect the cross-head movement and to generate an electric signal interpreted by the IRC as a trigger.

This experimental set-up was also used by the authors, as in previous works [13,14], to measure temperature increases under dynamic loading conditions.

2.2. Test procedure

Quasi-static compression tests were performed using different strain rates and test temperatures as initial conditions. Two cross-head velocities, 1.26 mm/min and 10 mm/min, combined with two test temperatures, 300 K and 373 K, were imposed.

During the test, the cylindrical specimens used had a length of 7.0 mm and a diameter of 14 mm. Each specimen was machined from an extruded bar which induces an initial anisotropy. All the

Table 1
Mechanical and thermal properties of the materials tested (source: MELRAM composites, UK).

Materials	α (K^{-1})	K (W/mK)	C_p (J/KgK)	E (MPa)	σ_y (MPa)	ρ (kg/m^3)
ZC71	26×10^{-6}	123	960	44,200	324	1870
ZC71 reinforced	18.5×10^{-6}	112	960	63,000	333	2000

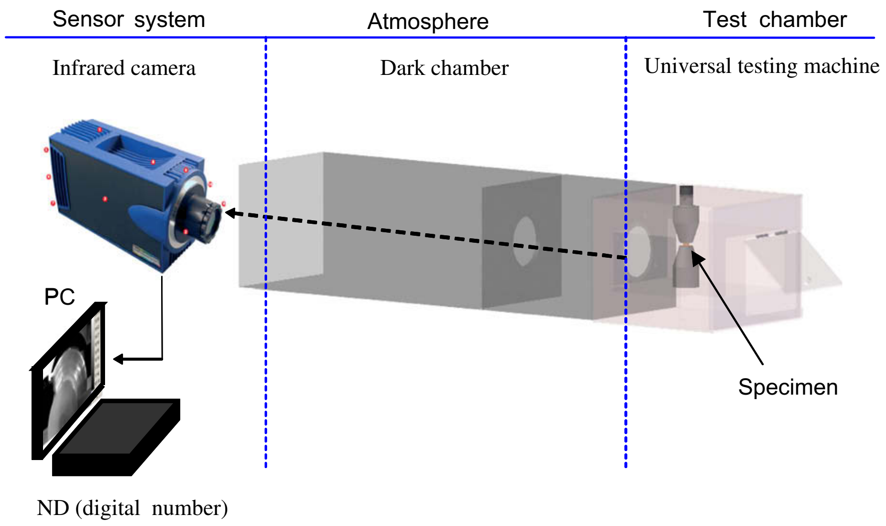

Fig. 1. Experimental set-up used to measure temperature increase during compression tests.