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Thermography in incremental forming processes at elevated temperatures

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ABSTRACT

Temperature measurement is essential for several forming processes at elevated temperatures. It serves to determine and control the workpiece temperature. Thermography as a non-contact-based technology offers the possibility to capture thermograms of complete workpieces without any time-offset. However, the application of thermography requires the knowledge of the fundamentals of radiation thermometry, in particular the emissivity. This paper presents the results of the application of thermography in incremental sheet forming (ISF) with Joule heating and radial–axial ring rolling as a bulk forming process. Using thermography for the determination of the temperature of the forming zone allows for a real-time closed loop control in ISF with Joule heating. Additionally, the results of the temperature measurement of the surface temperature of radial–axial rolled rings are presented, which can be used as a starting point to make a forecast of the rings' dimensions in cold state.

1. Introduction

Temperature is, next to time and force, one of the most important influence factors in forming processes. To realize plastic deformation, forming forces have to be higher than the yield stress of the workpiece material. At room temperature, the appearance of dislocations leads to an increasing yield stress due to strain hardening. To decrease the yield stress and, therefore, the necessary forming forces, an elevated workpiece temperature is beneficial. It eases dislocation jogging and the annealing of lattice imperfections. As for titanium, a temperature increase can enhance formability by the activation of additional slip systems due to a change of crystal lattices. For iron-based alloys (depending on the alloying elements), blue brittleness (usually between 200 °C and 350 °C) can increase yield stress.

Above the material-specific recrystallization temperature, the dislocation density is reduced by material recovery and recrystallization. Thus, no increasing strain hardening at increasing true strain can be observed. With increased forming temperature springback decreases.

At different temperature levels, different mentioned processes take place inside the workpiece. Therefore, the range of the target temperature is dependent on the desired forming and material parameters. To ensure a successful forming of workpieces, the temperature range is usually limited. Although a high workpiece temperature seems to be ideal to reduce the necessary forming forces, the choice of the workpiece temperature is usually a compromise. The temperature levels are chosen with respect to forming forces, energy input, oxidation rate, thermal distortions, complexity of necessary equipment and the mechanical material properties of the product. Hence, the measurement of the temperature is crucial and necessary

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to estimate the material properties and to control or observe the forming and heating process.

Although thermography as a non-contact technology with the possibility to image complete workpieces instead of measuring only one specific temperature value seems to be very appropriate for forming processes, thermography is nowadays used rarely. To show that the application of thermography for the determination of workpiece temperatures in forming processes is beneficial, this paper exemplarily introduces two different applications at two forming processes: measuring the surface temperature after the rolling of radial–axial rolled rings as a hot bulk forming process for process evaluation and measuring the forming temperature during incremental sheet metal forming with Joule heating for closed loop control.

2. State of the art

Optical temperature measurement allows for a fast detection of surface temperatures. There is no time offset due to thermal conduction as in contact thermometry. As only an optical visibility of the object is necessary, moved objects can also be measured. With sensor arrays, as they are used for infrared cameras, a regional resolution of several measuring points can be achieved.

2.1. Fundamentals of thermography

Every surface of an object which has a temperature above absolute zero emits energy by radiation. As this radiation is proportional to the temperature of the emitting surface, it can be used for temperature measurement. In practice, the whole radiation scenario (Fig. 1) has to be taken into account in order to precisely infer the temperature of the measured object. In a general radiation scenario, radiation can be emitted, reflected, absorbed or transmitted. All of these processes influence the amount of radiation, which is detected by the measuring device. The corresponding factors are emissivity ε, reflectance ρ_s, absorbance α and transmittance τ. Depending on its reflectance and transmittance, the object's emitted radiation interferes with reflected radiation from the surrounding scenario and transmitted radiation from the object's background. The sum of this radiation M_Σ passes the atmosphere which is between the measured object and the measuring device. This atmosphere itself has a transmittance which can reduce M_Σ and it has a temperature and thus can emit radiation.

For non-reflective atmospheres and non-transmitting measured objects, the detected radiation M_m can be used to calculate the object's temperature as follows [2]:

$$\vartheta_o = M^{-1}\cdot\{M_\mathrm{m} - (1-\tau_P)\cdot M_\mathrm{Bb}(\vartheta_\mathrm{P})/\tau_\mathrm{P} - (1-\varepsilon)\cdot M_\mathrm{U}(\vartheta_\mathrm{U})\}/\varepsilon.$$

Detectors for radiation thermometry can be categorized in thermal detectors and quantum detectors. Quantum detectors use the inner photoelectric effect to generate an electrical signal due to incoming photons. Such detectors are fast and sensitive and usually expensive. In thermal detectors as thermopiles or bolometers, the change in temperature of the sensor due to the incoming radiation is used to generate an electrical signal. In bolometers, the change of electrical conductivity of the sensor material is used. Most cheap infrared cameras have microbolometer arrays as sensors.

2.2. Thermography of metals

The emissivity ε of a surface depends on the wavelength, temperature, chemical composition of the object, dislocations in crystal lattices, grain sizes, angle of vision and surface properties [4]. In thermography, high emissivity is advantageous. Metallic surfaces, especially of iron-based objects, show decreasing emissivity and radiation intensity with increasing wavelength of the detected radiation. Non-metallic surfaces usually show high emissivity above 4 μm wavelength.

The emissivity in dependence on the angle of vision is different for electrically conducting and non-conducting surfaces. Whereas conducting surfaces have highest emissivity under sharp angles between the object's surface and the angle of vision, it is the opposite for non-conducting surfaces. Especially for the measurement of round objects, such effects have to be taken into account.

In metal forming at elevated temperatures, the surface properties are influenced by different effects. Oxidation, contamination and changing surface roughness can occur during such forming operations. In some cases coatings of e.g. graphite are applied as solid lubrication. All of these effects influence the emissivity.

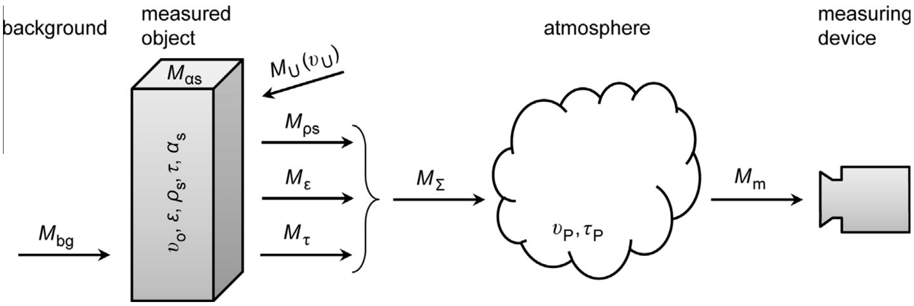

Fig. 1. Radiation scenario (on the basis of [1–3]).