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Theoretical model for temperature prediction in Incremental Sheet Forming – Experimental validation

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ABSTRACT

Temperature prediction is a fundamental aspect of material workability and microstructural evolution. The need to predict temperatures is particularly important for processes where temperature is not a fixed *a priori* as well as in processes where temperature is affected by multiple variables. Incremental Sheet Forming (ISF) is one such process and it is considered particularly relevant in this discussion because the process parameters chosen are the ones that most affect temperature variation in the forming area. The aim of this paper is to define a temperature prediction model based on mathematical formulae. This model can be used to predict the temperature of the material during the forming phase using different process parameters. Two lightweight alloys with different thermal properties were studied. An aluminium and a titanium were chosen because their differences guarantee the generality of the model. Experimental tests were performed to calibrate and validate the quality of the proposed model. An iterative algorithm was implemented to predict the temperature trend of the sheet. Satisfactory results have been found confirming the physical hypothesis made to justify the phenomenon of temperature increase in ISF as well as the reliability of temperature prediction during the process.

1. Introduction

The demand for lightweight alloys has increased in recent years, both in the automotive and the aerospace industries [1], because of their strength to weight ratio. However, Ghamdi and Hussain [2] showed that the formability of these alloys is unsatisfactory at room temperature. According to Wang et al. [3] these forming limits can be overcome by using a suitable temperature range. They analysed the alloy AA2024 through experimental tests to see how temperature affects the microstructure and the failure mechanism. The same relationship was further investigated by examining the sheet formability of magnesium alloy AZ31 through uniaxial tensile and hemispherical punch tests at different temperatures [4]. Temperature variations need to be taken into account and be properly monitored in the new incremental forming technologies. As pointed out by Hmida et al. [5], conventional flow rules as well as forming limit diagrams, which are determined at a constant temperature, are unable to provide an accurate definition of the material behaviour during the process. This is particularly true for the Incremental Sheet Forming (ISF) process [6–7] because problems such as: localized deformation, severe thinning, inhomogeneous temperature distribution and high process lifetime cannot be solved with traditional approaches.

Although the advantages of ISF, such as intrinsic flexibility and reduced lead-time for production, which were fully explained by Jackson and Allwood [8], cannot be denied, the ISF process does not have extensive industrial applicability because of low accuracy and high process lifetime. However, these drawbacks can be considerably reduced through an accurate process design as proven by Ambrogio et al. [9] who used statistical techniques to analyse the effects of different process parameters on three materials. With regard to accuracy, several studies aimed at analysing how process and material parameters affect forming mechanics in relation to the part design have also been carried out. Jeswiet et al. [10] discussed the possible advantages gained through the use of optimized toolpath strategies. Bagudanch et al. [11] showed the high correlation between formability and the heat generated through friction between punch and sheet. To overcome high process lifetime, one of the fundamental limits, the high-speed ISF variant was introduced and validated [12]. Furthermore, lathe technology was proposed instead of conventional milling machines. With this technology the punch velocity can be increased by two orders of magnitude, consequently, the time process is reduced to a few seconds instead of minutes. High velocity affects strain rate and temperature variations of the formed material. In detail, the strain rate is a function of the punch velocity while, the temperature is determined by the generated heat. In fact, plastic deformation and

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Nomenclature

N	set of nodes
L	set of loops
i, i'	index set of nodes
j	index set of loops
$\dot{\varepsilon}_j$	average strain rate during the loop l_j
v	average speed of the process
T_r	room temperature
T_{pj}	temperature of the punch during l_j
T_{ij}	temperature of noden_i during l_j
p	depth step
v	average speed of the process
h_f	final height of the sheet
r_j	radius of the loopl_j
r_p	radius of the punch
s_0	initial thickness of the sheet
s_j	thickness of the sheet during l_j
α	time required to perform l_j
t_j	time required to perform l_j
T_{melt}	melting temperature of the material
$\sigma_{i,j}$	flow stress on node n_i during l_j
$F_{i,j}$	load applied on $n_i$during loop l_j
$A_{i,j}$	sectional area perpendicular to $F_{i,j}$
μ	friction coefficient
$M_{i,j}$	mass of the contact surface $A_{i,j}$
r_p	punch radius
$Q_{i,j}$	heat generated on n_i during the loop l_j
$q^j_{i,i'}$	heat flow generated by conduction between n_i and $n_{i'}$ during l_j
$q^j_{i,p}$	heat flow generated by conduction between n_i and the punch during l_j
c_p	specific heat of the material
λ	% of energy transformed to heat
δ	density of the material
K_m	thermal conductivity of the material
K_p	thermal conductivity of the punch
$d_{i,i'}$	distance between n_i and $n_{i'}$

friction forces can produce the required material heating without using external sources.

The literature discussed so far emphasizes that the heat generated during ISF is a function of different variables such as sheet thickness, depth step, slope angle, thermal properties of the material, punch diameter and tool velocity. However, the temperature variation for different process conditions has not been ascribed to a dissimilar heat generation as proven by Ciancio et al. [13] through a study on AA5754. Instead, the main reason has to be attributed to a reduction of heat dissipation due to a faster process. Finally, the thermal properties of the worked material, such as thermal conductivity and heat capacity, also need to be considered to properly predict the temperature variation during ISF.

In this paper, a model for the prediction of temperature was designed taking into account the considerations highlighted above. An experimental campaign was carried out to properly set

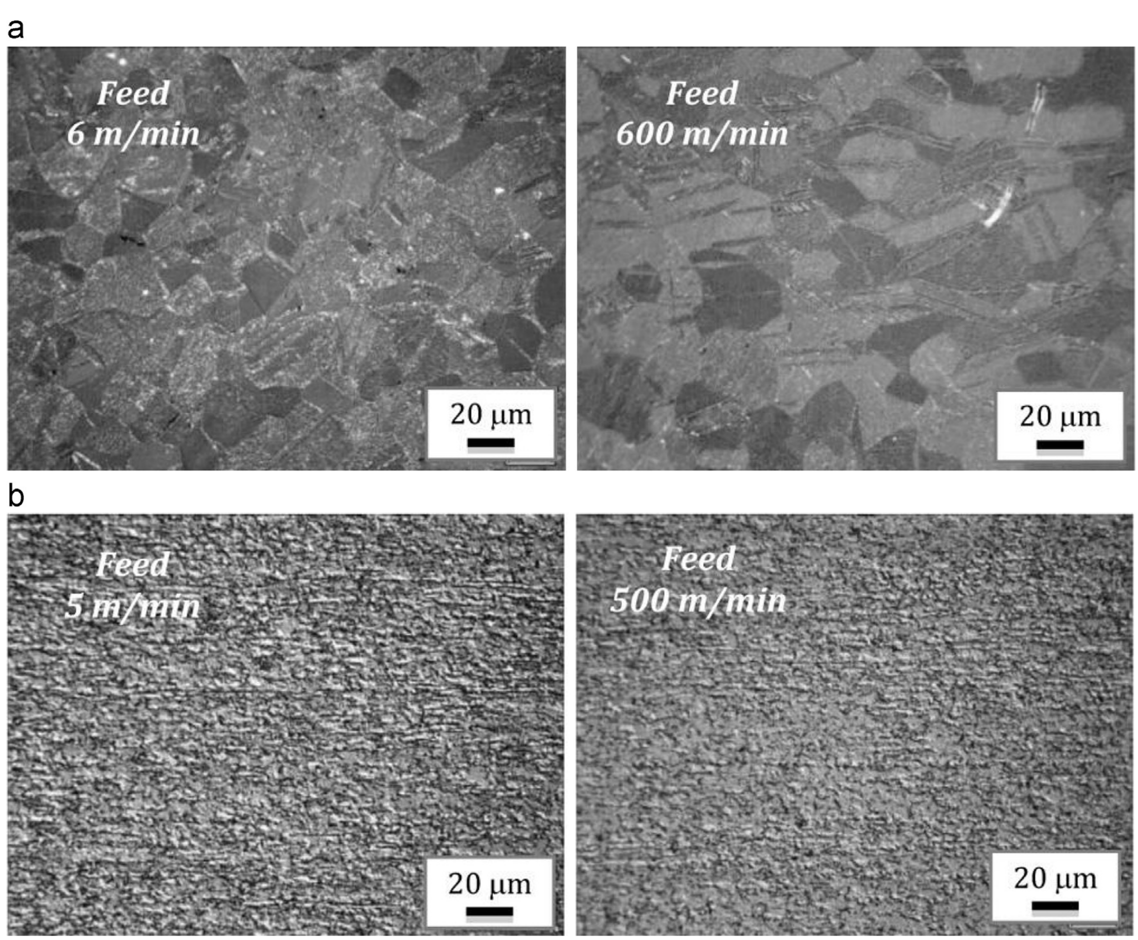

Fig. 1. Influence of the feed rate on the microstructure of (a) pure Titanium and (b) Ti6Al4V formed parts (Ambrogio et al. [12]).