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Probabilistic rupture analysis of a brittle spray deposited Si–Al alloy under thermal gradient: Characterization and thermoelastic sizing guidelines

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ABSTRACT

The spray-deposited Si–Al CE9F alloy is a new material used for space applications involving temperature gradient. Thermal stresses arise and may affect the mechanical integrity of the components. It is therefore necessary to assess the critical temperature gradient to avoid failure. Hence this paper deals with the effect of temperature on the mechanical properties of the Si–Al CE9F alloy from −50 °C to 130 °C: Young's modulus, coefficient of thermal expansion and Weibull's parameters of the material to account for its brittle fracture behaviour through the Weibull's model. The experiments indicate a linear dependence of the Young's modulus with temperature and show that the coefficient of thermal expansion and the Weibull's parameters are almost constant in the temperature range [−50 °C, 130 °C]. From these results, an example of application schematizing a clamped plate under temperature gradient is studied to create abacus of probability of failure. These abacuses provide sizing guidelines and show the impact of the equivalent volume, highlighting the critical temperature gradients.

1. Introduction

The space applications of spray-deposited Si–Al materials are mainly chip boxes to protect the on-board electronic devices from the aggressive outdoor environments. It is essential to ensure the hermetic role of the housing to protect the electronic devices. These latter acts as a heat source inside the box whereas the outer temperature changes depending on the position of the satellite. The temperature variations are generally slow enough to consider them as a sequence of thermal steady states. Once in orbit, the thermomechanical stresses due to temperature gradients are the only loads applied on chip packaging in normal use. That is why studying the impact of the temperature gradients on the rupture is an important design issue. Building abacus of design falls within the scope of the present paper.

At the same time, satellite electronics needs a packaging allowing an efficient heat dissipation to prevent premature failures of semiconductor devices: temperature should not exceed 40 °C. To reduce the stresses at the chip/box interface, the coefficient of thermal expansion (CTE) of protection boxes is required closely matched to GaAs or Si's ones, the main materials of computing chips [1]. Moreover, good mechanical properties and a low density are required as well. The family of spray-deposited hypereutectic Si–Al alloys combines all these requirements [2,3]: it makes them attractive for those applications and they are already applied in optical housing, chips packaging, sensors carriers and lens holders for laser systems.

This family of materials was recently studied [4] and contains several grades with different Si–Al ratios (CE7, CE9, CE11, CE13 and CE17). The present paper only deals with Si–Al CE9F, designed by Sandvik Osprey™, an alloy containing 60 wt.% of silicon and 40 wt.% of aluminium. This material is characterized by a low coefficient of thermal expansion ($\alpha = 9 \cdot 10^{-6}$ K^{-1}), a high thermal conductivity (130 $W \cdot m^{-1} \cdot K^{-1}$) and a low density (2460 $kg \cdot m^{-3}$).

The thermal properties of this material and its family are well-known due to previous studies about the temperature effect on the thermal properties [5,6], especially the linear variations of heat capacity [7], conduction and diffusivity with positive temperatures. The hypereutectic Si–Al alloy can be made by several processes: sintering [8], direct metal deposition [9] or spray-deposited by atomization. Depending on the process, the microstructure [10] and the thermomechanical properties can change significantly. The family of the studied spray-deposited Si–Al are made by atomization by Sandvik Osprey™. The major influencing parameters of the process of atomization [11] (for example: pressure during hot compression step to decrease the porosity [12] and Gas/metal mass flow ratio [13]) were evidenced and analysed to obtain the desired specific microstructure and the corresponding material properties. The specific two-phase microstructure of spray deposited hypereutectic Si–Al alloys was studied as well [14,15]. Nevertheless, the knowledge of its mechanical

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properties and their variation with temperature is limited. Few studies [16,17] already present the values of Young's modulus and flexural strength but do not consider the temperature effect on mechanical properties. Moreover, the main feature of the mechanical behaviour of this material is its brittleness. It is therefore necessary to study the Si–Al CE9F within the framework a brittle fracture theory to introduce the notion of probability of rupture.

The present paper investigates the failure of parts made of such a brittle material under stationary thermal gradients. The calculus of the probability of rupture depends on the applied temperature gradient and on the temperature dependent material properties. A preliminary characterization of the CE9F elastic properties in the temperature range of the intended space application, [−50 °C, 130 °C], is thus mandatory and will be performed in a first part. A second part of this paper is devoted to the assessment of the material strength in the same temperature range, and the results are processed in the framework of the Weibull's theory. In the last part, a case study involving a temperature gradient is analysed through the brittle fracture theory to determine the probability of rupture as a function of applied surface temperatures.

2. Material and methods

2.1. Microstructure

Spray deposited Si–Al CE9F alloy is prepared by atomization process developed by Osprey Metals Ltd. [6].

A Si–Al powder mix is heated up to 1450 °C. The melt is then atomised by a N_2 gas flow. The spray is intercepted by a support to progressively build-up a billet. Once spraying is ended, the still semi-solid billet is subjected to hot isostatic pressing at the temperature of binary Al–Si eutectic (577 °C) to reduce the residual porosity lower than 0.1 vol.% [18,11,15].

This process creates a two-phase microstructure: a globular primary silicon phase with a diamond-like crystallographic structure, in light grey in Fig. 1, and an interpenetrating secondary ductile aluminium phase, the dark grey phase in Fig. 1. The Al-rich phase contains some impurities of iron in small concentrations. The microstructure is fine enough to consider the material as homogenous for volumes higher than 10^{-3} mm^3.

A preliminary study on fracture surfaces shows that the Si–Al alloy has a brittle behaviour. Indeed, SEM pictures of fracture surfaces highlighted cleavage planes, as can be seen in Fig. 2 and represented by striations. These cleavage planes, present in the silicon phase, are a specific feature of brittle fracture. That is why the mechanical samples were designed according to the standard EN-843 – "Mechanical properties of monolithic ceramics". This protocol of mechanical tests also follows the same standard ensuring the repeatability of testing campaigns.

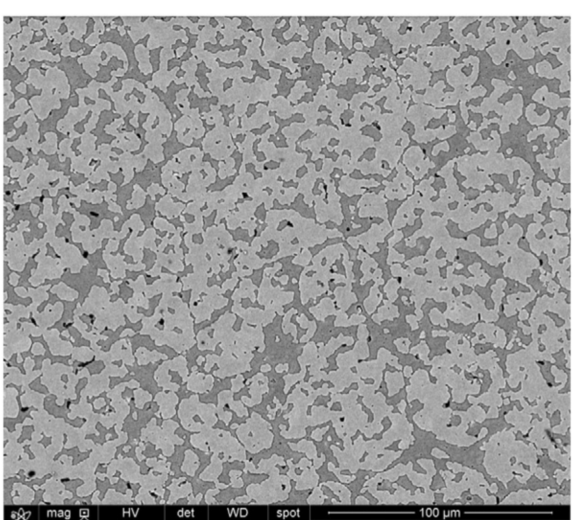

Fig. 1. SEM picture showing the two-phase microstructure of Si–Al CE9F alloy.

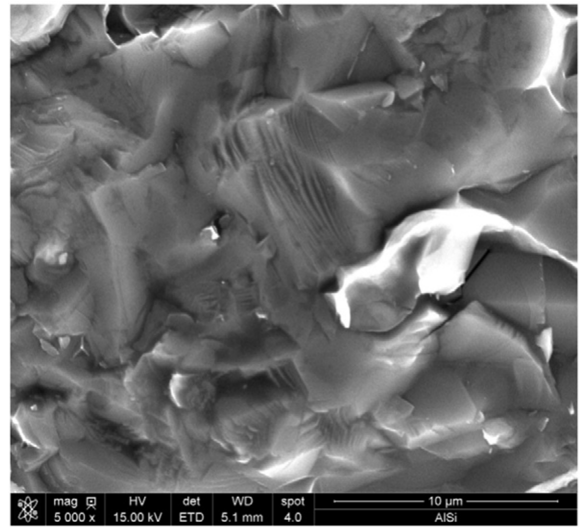

Fig. 2. SEM picture showing the cleavage planes, special feature of brittle fracture.

2.2. Elasticity properties

The study of temperature effect on the mechanical properties is completed by two types of additional measurements. The first one is an acoustic resonance to analyse the variation of the Young's modulus over the temperature following the standard ASTM E1876. This non-destructive method is based on the propagation of a sound wave in a material [19]. The sample is struck by a hammer and the produced sound is recorded, analysed through Fourier's transforms to obtain the Eigen frequencies of the sample. They depend on the material properties, especially the Young's modulus which can then be obtained from Eq. (1), where m is the mass of the sample and f_r is the first eigenfrequency.

$$E = 0.9465\left(\frac{m(f_r)^2}{b}\right)\left(\frac{L^3}{h^3}\right)A. \tag{1}$$

L, b and h are respectively the length, the width and the thickness of the sample. A is a complex constant calculated from the geometry and the Poisson's ratio (υ). The value of this last parameter is determined with the acoustic resonance too, but with a torsional setup at 20 °C. The Poisson's ratio of 0.235, measured at room temperature is supposed to remain constant over the temperature. Nevertheless, the acoustic measurements were only made at positive temperatures because of using an experimental device that is not adapted for negative temperature. The temperature rate is fixed at 1 °C/min.

A dynamic mechanical analysis (DMA) is performed in addition to the acoustic resonance from −50 °C to 60 °C too. The sample is loaded in 3 points bending with an amplitude of 50 µm and a frequency of 1 Hz. The temperature rate is fixed at 14 °C/min.

Results obtained with both methods are shown in Fig. 3. For both cases, a linear decrease of the Young's modulus is observed when varying the temperature. For the acoustic resonance, it decreases of 2.42GPa every 100 °C and for the DMA, of 2.55GPa every 100 °C. The Young's modulus values are different between both methods. Indeed, the measurements of DMA depend on assembly, the frequency and the kind of solicitation whereas the acoustic resonance provides more intrinsic measurements. According to the results of Fig. 3, the Young's modulus