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Torsional and compressive behaviours of a hybrid material: Spiral fibre reinforced metal matrix composite

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ABSTRACT

Armouring metals with strong wires or fibres is a common way of providing them with extra mechanical strength. A metal–metal composite armoured with twisted (spiral-shaped) wires is a particularly attractive option. We propose such a design that can be realised by twisting of a pre-assembled metallic matrix with embedded reinforcing fibres. An analytical model was developed to predict the torsional behaviour and the torque–twist requirements in the twisting stage to fabricate such a metal–metal hybrid material. Also, a semi-analytical multi-shell model was developed based on the upper bound theorem to estimate the plastic deformation behaviour of the hybrid material under axial compression. Samples of commercially pure Cu as the metallic matrix and stainless steel fibres as the reinforcing components were fabricated. A fair agreement of the experimental torque vs. twist data for torsional deformation and compressive load vs. stroke data of the compression test with the model predictions was found. The structural performance of the metal–metal hybrid showed an improvement of properties compared to the solid part without the fibres.

1. Introduction

Fibre-reinforced metals are an important group of metal–metal composites [1] and used widely in a range of applications [2–4]. Armouring a metal with stronger fibres or wires is a traditional way of enhancing its strength [5]. A novel approach to producing metal–metal composites with enhanced ductility was recently suggested by Bouaziz [6]. The concept is based on embedding architectured reinforcements in a metal matrix, which impose a geometrically-induced strain hardening. This postpones the onset of necking, thereby increasing the tensile ductility of the material. A particular realisation of this concept is through embedding helical reinforcement wires that acts as springs and provides the composite with additional strain hardening capability [6]. Fabricating 'architectured' composite metals with nanostructured components is particularly attractive, and traditional methods of severe plastic deformation (SPD) [7] and their recent developments (e.g. [8–10]) appear particularly suitable for that. Indeed, as suggested in [6], SPD techniques make it possible to produce a desired inner architecture of the composite, while at the same time imparting an ultrafine (and sometimes nano scale) grain structure to the constituents of the composite. Not only does SPD processing change the mechanical characteristics of the material, such as tensile strength and fatigue limit, but it can also modify a range of physical properties [7]. However, there are limitations on the industrial applications of most SPD techniques due to the batch character of the processes involved [11]. By contrast, the proposed process is continuous in nature and does not cause such scale-up issues in fabrication of the hybrid materials.

Recently, we proposed to manufacture composite, or hybrid, materials with helical reinforcement structures by employing well established techniques of severe plastic deformation (SPD) [12]. With these techniques, physical bonding of the metallic matrix and the reinforcing fibres is achieved via twisting of a pre-assembled metal composite. In a recent article, the suitability of one of the SPD techniques, known as twist extrusion [13], for producing metal–metal composites with a spiral structure was demonstrated [14]. What is especially attractive in the adaptation of SPD techniques to the fabrication of fibre-reinforced metal–metal composites is the possibility to architecture them in a desired way, while simultaneously imparting to them very substantial grain refinement. It is therefore not surprising that further processing techniques, such as axisymmetric forward spiral composite extrusion (AFSCE) [15, 16], which achieve this dual goal, are emerging. The AFSCE process bears certain similarities with TE, but has the advantage that the formation of dead zones in the corners of the die is avoided owing to its axisymmetric nature. Besides, AFSCE is simpler than TE in terms of tooling and processing. An interesting characteristic of TE and AFSCE is that shear deformation occurs only in the transient regions, including entry-twist zones and twist-exit zones. The deformation in the twist zone itself

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is almost zero and only rigid body motions occur therein. This is conceptually very similar to the archetypal SPD technique of equal-channel angular pressing, in which the shear strain is localised in a very narrow region where the entry and the exit channels meet. A variable pitch version of AFSCE was proposed later [17] to extend the transient zone and increase grain refinement.

In some structures, such as energy absorption systems and crash cushions, a combination of a soft matrix and reinforcing steel wires is required. To design such structures, it is critical to know the combined behaviour of the structure under different loading conditions.

A simple example of the concept presented in [6], viz. that of a metal–metal composite with a spiral structure of embedded armour wires, is proposed here. We consider a metal–metal hybrid which is composed of a cylindrical metallic matrix with a number of reinforcing wires distributed regularly along a pitch circle concentric with the metallic matrix cylinder. We present an analytical model enabling us to study the impact of the design parameters on the plastic torsional and compressive response of the composite.

A metallic sample with embedded armouring wires aligned with its axis is depicted in Fig. 1. This assembly was used in numerical simulations and the actual experiments. In Section 2 we present a model that makes it possible to describe the torsion process transforming the straight wires to spiral ones and then move on to predicting the plastic mechanical response of the hybrid material thus produced to compression loading. Subsequently, in Section 3, the results of experiments on copper armoured with steel wires are presented, which validate the model predictions.

2. Modelling and testing the mechanical response of the composite under torsional deformation

2.1. Concept of the composite

The composite metal sample proposed here is fabricated in two steps. The first step is to produce an assembly composed of a metallic matrix and reinforcing wires, all parallel to the cylinder's centreline. The second step consists in twisting the assembly plastically to produce a physical bonding between the metallic matrix and the wires. Next, the process parameters are defined, followed by an analytical solution describing the torsional behaviour of the composite metal sample.

Fig. 1(a) shows different views of a composite metal sample comprised by a cylindrical metallic matrix rod (gauge section) with two hex shoulders at both ends of the gauge section to allow fixing one end and applying torque M at the other end. Fig. 1(a) also shows six through holes which are drilled parallel to the longitudinal axis of the cylinder with their centres located on an imaginary pitch circle. Six reinforcing fibres, one of which is shown in Fig. 1(a), will be inserted in the holes before twisting the composite sample. In general, N_f fibres are equally spaced over the pitch circle. With increasing the number of the fibres, the sample tends to become an axisymmetric one. Fig. 1(b) shows actual copper samples with a stainless steel reinforcing wire.

Fig. 2 shows a cross-section of a metallic matrix rod with only one reinforcing fibre (for the sake of clarity). The cross-sectional areas of the metallic matrix and the reinforcing fibre, A_1 and A_2, respectively, are also shown. In Fig. 2, the quantities a and r_p denote the sample radius and the radius of the pitch circle of the metallic matrix, respectively, and d is the fibre diameter.

2.2. Mathematical description of the mechanical behaviour of the composite under torsion

As shown in Fig. 1(a), applying a torque, M, at one end of the composite sample with the other end fixed results in a twist angle of θ. The torque can be decomposed into three components; M_1, M_2 and M_3. The first component, M_1, is a torque needed to twist an imaginary solid metallic matrix sample by an angle θ. Assuming a fibre has a relatively small diameter, a correction torque, M_2 (including its sign), is needed to compensate for the lack of metallic matrix in the channels/holes occupied by the fibres. A metallic matrix channel could be imagined as a longitudinal drilled cylindrical hole of diameter d. Finally, M_3 is the torque required to twist the fibres by the same angle θ as the solid metallic matrix to maintain the integrity of the sample. This decomposition can be expressed mathematically as:

$$M = M_1 - M_2 + M_3 = \int_{A_1} r\tau_b dA - \int_{A_2} r\tau_b dA + \int_{A_2} r\tau_f dA \tag{1}$$

where τ_b and τ_f denote the effective yield stresses in shear of the matrix and the fibre, respectively. We assume that the deformation behaviour of both metals can be described in a simplified form of the Ludwik equation, i.e. as a power law:

$$\sigma = K\varepsilon^n \tag{2}$$

where the exponent n is the strain hardening index of the material during plastic deformation and K is a material constant. Both parameters are generally different for the matrix and the fibres. Given the pure shear deformation during torsion, this behaviour can also be expressed in terms of the effective shear stress, τ, and shear strain, γ:

$$\tau = \kappa\gamma^n \tag{3}$$

where the coefficient κ is related to K (see, for example, [18]) through

$$\kappa = \frac{K}{3^{0.5(n+1)}}. \tag{4}$$

Based on the assumed constitutive law, the first torque component M_1 can be expressed [19] as:

$$M_1 = \frac{2\pi\kappa\theta^n}{(3+n)l^n} a^{3+n}. \tag{5}$$

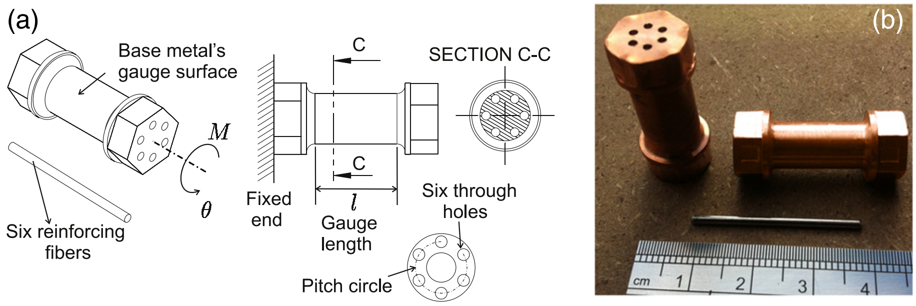

Fig. 1. (a) Schematic of the composite metal sample and (b) copper composite samples and a stainless steel reinforcing wire.