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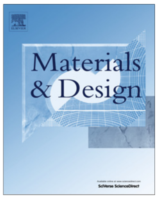

Fatigue strength of a hybrid joint formed between a PA6-GF60 polymer matrix and a S420MC steel insert

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ABSTRACT

A vehicle's brake pedal is considered to be one of its most important safety components. In the past, vehicle weight-reduction initiatives resulted in a highly optimized design of steel brake pedal with an increased strength-to-weight ratio. However, any further reduction in the weight of the brake pedal is only possible by using combined, i.e., hybrid, materials. In this case the joint between the two different materials in the hybrid arrangement must be as strong as possible. Many methods for improving the joint between two highly dissimilar materials are known from the literature, but conventional joining techniques lack either the fatigue resistance, because of a poor notch-effect design (shape-based joints), or are unsuitable for low-cost serial production (material-based joints). This article presents an innovative approach to joining the reinforcing insert with a glass-fiber-reinforced polyamide 6 (PA6-GF) base structure, where the reinforcing insert is molded into the PA6-GF. The improved shape of the reinforcing insert contributes the required strength, while the PA6-GF base structure provides the final form of the specimen/product. The innovative shape of the metal insert not only provides the strength of the component; it also ensures the proper joint between the two dissimilar materials. For different types of reinforcing inserts static durability tests as well as fatigue-life tests of the insert-PA6-GF-matrix joints were performed. Our experimental research shows that the most promising shape-based hybrid joints reported in the literature are not the best solution when the hybrid joint's fatigue life is the decisive criterion for a product's durability.

1. Introduction

The automotive industry is facing increasingly stringent environmental requirements that define the sophisticated technical solutions that manufacturers of vehicles are transferring to suppliers that have sufficient development capacity [1,2]. Drive train components and fuel consumption are the focus of these initiatives, which as a result include reduced vehicle weights. However, this reduced weight affects the load-carrying capacity of the structure, and so sufficient strength, durability and reliability must be ensured in the early phases of the product's development. The results of such vehicle weight-reduction initiatives are highly optimized designs of vital components with better strength-to-weight ratios. Practically every part or component of a motor vehicle is subjected to a weight-reduction demand. An example of such a part is the vehicle's brake pedal, which is a part of the main car-safety system, i.e., the braking system. The brake pedal must be strong enough to perform its function, even in the case of a car crash, while keeping its weight as low as possible [3]. In the past, vehicle weight-reduction initiatives resulted in a highly optimized design of the steel brake pedal with an increased strength-to-weight ratio. Further weight reduction is only possible by using combined, i.e., hybrid, materials.

Recently, structural components with a hybrid (metal–polymer) composition have been developed. Their production technology can be described as a derivative of an injection over-moulding technology, a process that has been patented [4]. The first successful implementation of this innovation was in 1996, when Audi manufactured a front bumper from a metal-sheet–polymer hybrid composition [5]. However, the hybrid technology was first used for a brake pedal in 2006 for the Fiat Ducato. The core element of this pedal was a thin-walled, U-shaped steel beam, reinforced with PA6-GF 30 polymer ribs. The polymer and metal parts of the pedal's structural component were joined mechanically, with polymer ribs and plugs, moulded into openings in the U-shaped steel beam [6]. Some other practical implementations of the metal–polymer hybrid structural parts were developed by ZF Friedrichshafen [7] and Trelleborg [8], but these components are still in the validation phase.

After the bonding of two different materials, the resulting hybrid structure assumes the properties of the weakest component.

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Nomenclature

N	number of cycles to failure	Y	dependent variable
S	amplitude stress	X	independent variable
k	exponent of the S–N curve	DV	dummy variable
b_0	constant term in a S–N curve equation	b_2, b_3	regression coefficients
b_1	scale coefficient in a S–N curve equation		
β	shape parameter of the Weibull distribution		
η	scale parameter of the Weibull distribution		

If the hybrid structure should take over only the desired characteristics of the two joined materials (i.e., the high strength of the insert and the low weight of the base matrix), one has to ensure a proper bonding between the materials. Only in this case, the hybrid structural part demonstrates better properties than the weakest component. There are three basic principles when joining components: a material joint, a geometric joint and a frictional joint. In the case of the material joint, the load is shared and distributed between the bonded components by means of an additive material, which may be different (for example, an adhesive) or the same as the base material (in the case of welding). In the case of the geometric joint, the load is shared and distributed between the bonded components by means of properly shaped components. In the case of a frictional joint, the friction effect is used to share and distribute the load between the bonded parts.

The most widely researched hybrid joints between metals and non-metals were different versions of material joints. In almost all cases, the subjects of such research were adhesively bonded joints [9]; however, these are too expensive for the serial production of high-volume, low-cost, structural parts, since a sophisticated surface treatment or cleaning is required before bonding together the two components. Some other limitations are the production technologies and the price of the adhesives. To overcome these drawbacks the optimum solution for a hybrid joint would be to keep both parts tightly coupled, while leaving them intact from a chemical point of view. This means that a geometric or frictional joint would be the perfect solution for hybrid structural parts. Some potential solutions have been proposed by a ‘ clinch-lock’ type bond [10] and different shapes of perforations in the overmolded inserts [11]. These will be used as a reference and for comparison in the article. The static, tensile, load-carrying capacity of a hybrid joint between a sheet-metal (S420MC steel) and a polymer (PA6-GF60) was studied numerically and experimentally in detail. Our findings regarding this study were presented in a previous article [12]. From the results of numerical simulations and static tensile tests we were able to conclude that the geometric joint has better and more repeatable strength properties than the frictional joint.

A satisfactory fatigue life is a very important issue when designing brake pedals. Unfortunately, there is a blind spot in the available literature about the fatigue life of geometrically joined polymer–metal hybrid joints or structural components. That is why we decided to experimentally investigate the fatigue-life characteristics of the selected polymer–metal hybrid joints that are known from the available literature and were developed by ourselves, which could be applied for the design of hybrid brake pedals. For this purpose a certain shape of the hybrid specimen was defined, which was then shared by all the investigated hybrid joints. Next, the fatigue durability curves were experimentally determined for different polymer–metal hybrid joint types. The significance of their differences was also statistically evaluated.

The article is structured as follows. After the introductory section, a theoretical background is given for estimating the durability curves together with their scatter and for the multiple regression analysis, which was used to test the statistical differences between the durability curves of the different hybrid joint types. The article continues with a section dedicated to a description of the applied specimen shape and the experiment. In Section 4 the experimental results are presented, evaluated and discussed. The main findings of the article are summarized in the concluding section, which is followed by the acknowledgements.

2. Theoretical background

2.1. Estimating durability curves and their scatter

To estimate the reliability of structures during their use the durability curves of the applied materials, as well as their scatter, should be accounted for [13–15]. When estimating the durability curves and their scatter, it is very often considered that the durability curves of different materials can be described in the high-cycle fatigue domain with the following equation:

$$\frac{N_1}{N_2} = \left(\frac{S_1}{S_2}\right)^{-k} \tag{1}$$

S_1 and S_2 are two arbitrary amplitude-load (stress) levels in the high-cycle fatigue domain, N_1 and N_2 are the corresponding numbers of load cycles to failure and k is the exponent of the durability curve. Eq. (1) can be transformed into a linear form by generalizing $N_1 = N$ and $S_1 = S$:

$$\log(N) = \log(N_2) + k\cdot\log(S_2) - k\cdot\log(S) \tag{2}$$

which becomes the Basquin model if:

$$b_0 = \log(N_2) + k\cdot\log(S_2) \tag{3}$$

$$b_1 = -k$$

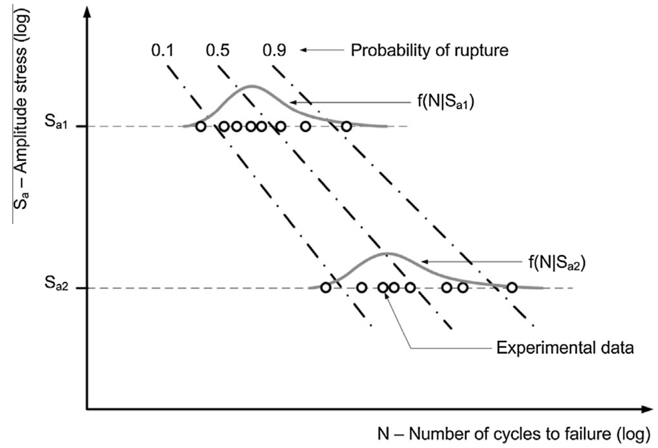

Fig. 1. *S–N* curve and its scatter modeled with a probability density function.