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A methodology for the determination of foamed polymer contraction rates as a result of cryogenic CNC machining

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ABSTRACT

The ability to produce products, suited to a particular individual is becoming more prevalent in today's society. This requires more efficient and rapid methods for manufacturing of bespoke products. One such method being currently developed is the cryogenic CNC machining of soft materials for producing personalised shoe insoles and outsoles. A major element of cryogenic CNC machining is the freezing of the soft polymers, which subsequently contract. This paper describes a method for predicting and compensating for the effect of cryogenic material contraction for the commonly used shoe midsole foamed polymer, ethylene vinyl acetate (EVA). Using the linear coefficient of thermal expansion a scaling factor for EVA has been developed to enable it to be accurately cryogenically CNC machined. This factor is then applied to the *X*, *Y* and *Z* scaling within the Delcam CAM software to shrink the model. The process is tested for a series of EVA cube test pieces and the results provide a scaling factor, which shows that the linear scaled dimension are within 1% of the measured contracted *X*, *Y* and *Z* dimensions. The scaling factor is subsequently used on an example low density EVA orthotic insole, which is cryogenically machined and then compared dimensionally with the original CAD model. It was found that using the cryogenic contraction factor the cryogenically machined insole had a dimensional *X*, *Y*, *Z* error of less than 1% when compared and analysed with the original CAD model.

1. Introduction

Ethylene vinyl acetate (EVA) is an extensively used material for a number of applications, particularly for shoe soles, midsoles and insoles [1–3]. The material is durable and offers substantial cushioning and comfort to the user. EVA products including shoe soles are formed using traditional injection moulding technology [4], which is extensively used in the mass produced market.

However the ability to produce personalised shoe soles and insoles using the current state of the art injection moulding technology is not possible due to the complexities and high cost of producing individual moulds for individual designs. A concept currently being developed at the University of Bath is the cryogenic CNC machining of soft materials, in particular EVA [5,6]. However one of the major problems of the cryogenic CNC machining of such soft materials is the contraction of the material after it has been subject to a cryogen, such as liquid nitrogen (LN_2). This contraction can distort the final product shape, thus it needs to be compensated before the cryogenic CNC machining process can take place.

This paper reports on the development of a method for establishing suitable contraction factors for EVA at cryogenic temperatures based on linear scaling factors. Experiments are also developed and conducted to provide analysis of the developed linear scaling factor method. Finally a framework for using the developed knowledge is proposed and an example EVA grade 1 insole is produced using the developed cryogenic contraction process and is further analysed using a reverse engineering 3D scanning method to determine the part *X*, *Y* and *Z* dimensional accuracy.

2. EVA characteristics

To understand the behaviour of a material it is important to understand its structure. Copolymerising ethylene with vinyl acetate molecules produces EVA polymers; the ethylene provides a chain backbone, which incorporates a percentage of the monomer vinyl acetate (VA). The properties of EVA co-polymers are strongly dependent on the ratio of vinyl acetate to ethylene in weight [7], the amount of VA added to the ethylene can vary from 2% to 50% [4]. This percentage content controls the material's crystallinity and thus its flexibility. There are a number of different grades of EVA that are used in the sports shoe sole industry, particularly for the midsole as it provides cushioning

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impact between the running surface and the foot [3]. EVA can be catogorised into three different grades, low, medium and hard density, each with differing durometer values. Two different grades of EVA were used for testing and analysis. EVA grade 1 is low density with a durometer value of 25 A, and EVA grade 2 is medium density with a durometer value of 50 A. The durometer value is a measure of firmness and is used specifically for polymers. A high durometer value material is firm and will not dissipate pressure, whereas a low durometer material is soft [8].

During the cryogenic CNC machining process the foamed polymers are subjected to temperatures at or below their glass transition temperatures. Below this temperature, the amorphous component of the polymer is glassy and when loaded, will distort elastically before yielding or fracturing. A polymer foam in this state is classed 'rigid' [9].

Fig. 1a and b illustrates a scanning electron microscope (SEM) image of open celled EVA foam, typical of that used in the midsoles of running shoes. The structure is suitable for sport shoe soles and midsoles as the material will deform on loading and return to its original shape after loading, absorbing energy and limiting the peak force in the heel strike [3].

2.1. Determining the glass transition temperature

The glass transition temperature (T_g) for a given material can be determined using two different methods, namely, dynamic scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA). For this particular study the DMTA process was selected and the following figure illustrates a typical DMTA material plot, which shows the T_g for EVA grade 1 and the elasticity value at the materials specific T_g value. The principle behind the DMTA method is that an oscillating force is applied to the sample causing sinusoidal stress to be applied, which in turn generates a sinusoidal strain [10]. By measuring the magnitude of deformation at the peak of the sine wave and the lag between the stress and strain waves, various properties of the material can be calculated, one being the T_g [10]. Fig. 2

3. Cryogenic CNC machining

The traditional method for manufacturing polymer products including EVA is through injection moulding and forming methods [4]. However as stated previously this method is not economical nor is it rapid when considering the production of personalised products, for which there is an ever growing consumer market. The following Fig. 3 illustrates the traditional mass consumer model for mass-producing the same polymer product. This model is extensively used as it has significant cost benefits over a long period of large batch quantity manufacture for a repetitive mass produced product, such as a generic shoe sole.

Fig. 4 provides the author's vision for the future of producing high-end personalised shoe soles. The major novel concept is to cryogenically freeze the soft material, in this case EVA at or below its measured T_g value, and directly machine it using conventional CNC machines to produce personalised shoe soles and insoles. The process chain is significantly reduced when compared with the traditional mass produced method as shown in Fig. 3. However at present the cryogenic method is not intended for the mass consumer market, but for the personalised medical market and professional sports domain, for which there are numerous potential applications.

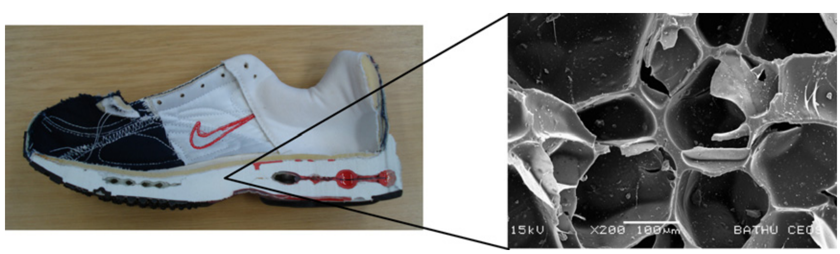

Fig. 1. (a) Sports shoe example. (b) SEM image shoe sole EVA.

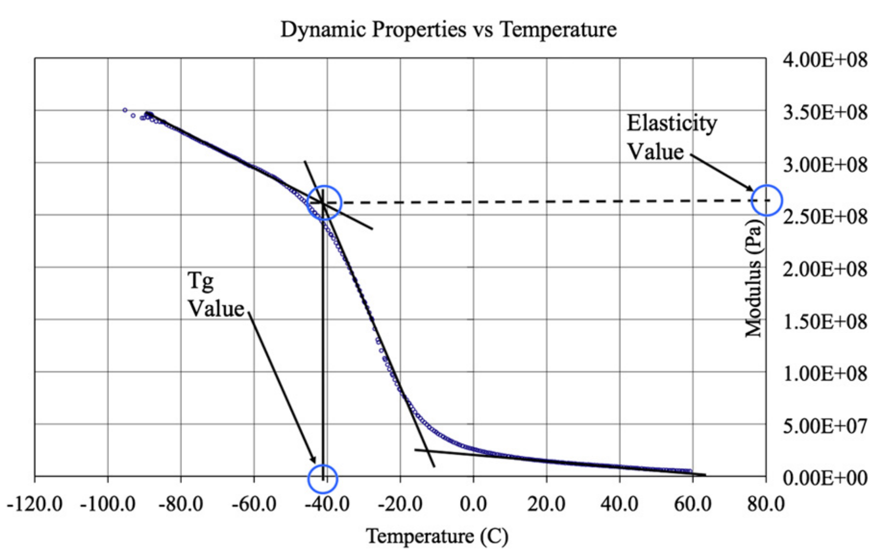

Fig. 2. DMTA example plot for EVA grade 1.