Cryogenic micromachining of soft and stretchable polymer for wearable sensing devices

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ABSTRACT

A growing number of microchannel applications, particularly high-actuating wearable sensing devices, need novel fabrication techniques for acrylic-based soft polymer. Fabricating microchannel patterns on such soft polymers is highly challenging with the conventional lithography process due to their unpredictable mechanical response to deformation. Mechanical micro-milling process is a feasible method to fabricate various microchannel patterns. However, mechanical micro-milling has not yet been applied to soft polymers like VHB (Very high bond) acrylic elastomer. Due to low elasticity and high adhesion, machining of VHB is nearly impossible at room temperature. In order to machine a microchannel, mechanical micro-milling is proposed in combination with the cryogenic cooling process to cut the VHB around glass transition temperature because of its remarkable change of property from rubbery to glassy state. In this study, cryogenic micro-milling experimental setup is fabricated based on glass transition characteristics of VHB. Fixed machining parameters are then used to evaluate the effectiveness of micro-milling of VHB at room and cryogenic temperature. The result of the cutting test shows that the microchannel can be fabricated in VHB by the proposed cryogenic machining technique. In this context, cutting force and channel microstructure were also analysed at different machining conditions.

1. Introduction

In recent years, highly stretchable soft polymers have attracted significant interest in both industry and academia sector because of their promising applications in wearable sensor (Souri & Bhattacharyya, 2018), artificial skins (Peng et al., 2020), body motion detection and so forth. Low cost, facile, reliable and scalable microfabrication strategies are highly desirable for the large scale manufacturing wearable strain sensors (Souri et al., 2020). Generally, such sensors are prepared in silicon based soft polymer by fabricating microchannel over the surface through traditional microfabrication process like soft lithography, injection molding and hot embossing process (Mallick et al., 2022). Currently, acrylic polymers are used for such application due to high stretch ability and outstanding durability over large number of cycles (Sahu & Patra, 2016). Conformal attachment of strain sensors on the human body is major important consideration for the efficient body strain measurement. High adhesions of acrylic soft polymers avoid sliding of sensors from skin, inducing zero noise in the response of strain sensor and achieve actual strain. However, aforementioned microfabrication process are only applicable to only silicon based material, forming microchannel over acrylic soft polymers by such process are quite impossible. To encounter such issue, attempts were made to fabricate channel over highly demanding stretchable acrylic based polymer, VHB 4910, by conventional micro-milling process. As the soft polymer is too soft and adhesive at room temperature, tearing of the material occurs during machining. For addressing such problem, Kakinuma et al. (Kakinuma et al., 2008) applied cryogenic micro-milling process to cut PDMS material in which cutting was performed when transition of the polymer from rubbery to glassy state occurs. They reported that polymers which are soft at room temperature could be transformed to glassy state by cooling below its glass transition temperature

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Table 1
Material properties and composition of VHB 4910.

Material	Composition	Glass transition temperature or DBTT (T_g)	Density (Kg/m^3)	Elastic Modulus at 25^0C (MPa)	Poisson's Ratio	Thermal expansion coefficient	Thermal conductivity	Adhesive strength at 25^0C (MPa)
VHB 4910	Acrylic structure	-40^0C	960	0.1	0.49	180	0.16	3.792

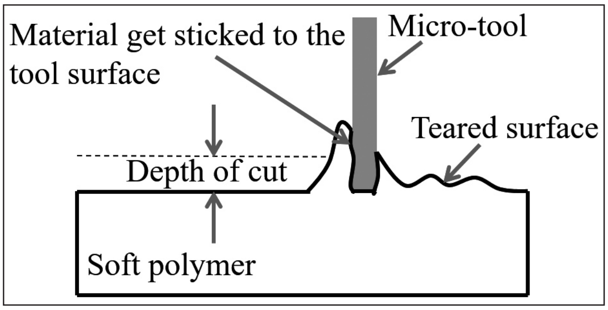

Fig. 1. Micromachining of VHB at room temperature.

(T_g). They further mentioned that only at particular temperature range of T_g, ductile mode of cutting is possible.

Generally, attempts were made by various researchers (Kakinuma et al., 2012) to immerse the workpiece completely at low temperature by direct supply of cryogen inside the cooling chamber. But as the control of cryogenic cooling at glass transition zone is highly difficult, especially at particular T_g, such cooling method leads to risk of material breakage during machining. In cryogenic micro-machining process, no such study was made on cooling of workpiece uniformly throughout the surface. The present study is to investigate the effect of uniform cooling below T_g of VHB by a novel chamber design, on quality of the machined surface produced under cryogenic condition. Although extreme attention has been put to distribute the temperature uniformly inside the chamber, there still is a difficulty of maintaining small temperature fluctuation during the whole machining time. Hence, channel microstructure formed at different temperature of cryogenic condition is not considered in the present work, where emphasis is laid on research frame. The research background concerning microchannel formation on VHB is non-existent for the specific technique of cryogenic machining. Therefore, the following proof-of-concept experiment like cutting force and micrograph of the channel under room and cryogenic condition are provided for validation and further development of the technology. Also as the polymer will be used as a sensor at room temperature, the effect on stretch ability after cryogenic treatment is compared with untreated sample.

2. Cryogenic Micromachining of Viscoelastic Acrylic Based Soft Polymer

2.1. Concept

It is difficult to cut viscoelastic acrylic soft polymer like VHB precisely at room temperature because of their extreme adhesion, softness, and elasticity. At room temperature, instead of cutting, material springs back and adheres to the tool after advancement of the cutting tooth, as shown in fig 1. Soft polymers display visco elastic response to an applied force that ensures dependency of deformation rate upon temperature of the workpiece and the time over which the load is applied. When soft polymers are cooled below their glass transition temperature (T_g), transition of material property from rubbery state to glassy state occurs. This phenomenon causes dramatic increase of stiffness in several orders of magnitudes. Table 1. shows the ductile-brittle transition temperature (DBTT) of VHB 4910 along with its property and composition.

Fig.2 shows the concept of cryogenic micromachining of VHB. The cooling system enables a uniform cooling of polymer surface, wherein a continuous supply of cryogen from the LN_2 cylinder occurs. This is achieved by innovative solution for equal temperature distribution inside the cryogenic chamber by expanding LN_2 at varying cross section and pass through perforated wall before comes in contact with the work piece. Due to such cooling phenomenon, time for molecular arrangement of the VHB against thermal disturbance increases and the structure at which motion of the molecular chains get arrested is more patterned and regular (Xiao & Zhang, 2002).

Table 2
Cutting conditions.

Parameters	Feed (mm/min)	Feed (µm/tooth)	Spindle speed (rpm)	Depth of cut (µm)
Values	100	2.5	20000	10
Tool material	Tungsten carbide micro square end mill			
Dia. of tool	500µm			
Workpiece	VHB 4910			
Cryogen	Liquid nitrogen (LN_2)			

Table 3
Micro end mill specifications.

Tool diameter (µm)	Edge radius (µm)	Helix angle (Degree)	Rake angle (Degree)	Clearance angle (Degree)
500	5	30	5	7

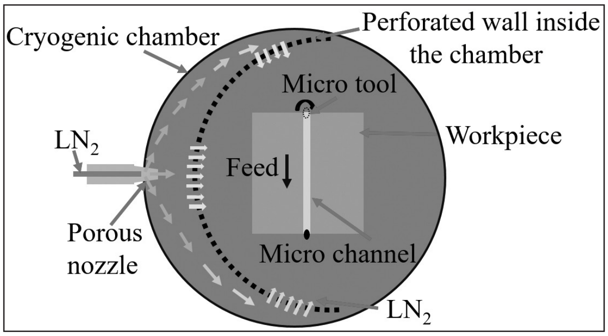

Fig. 2. Micromachining of VHB at cryogenic condition (Top view).

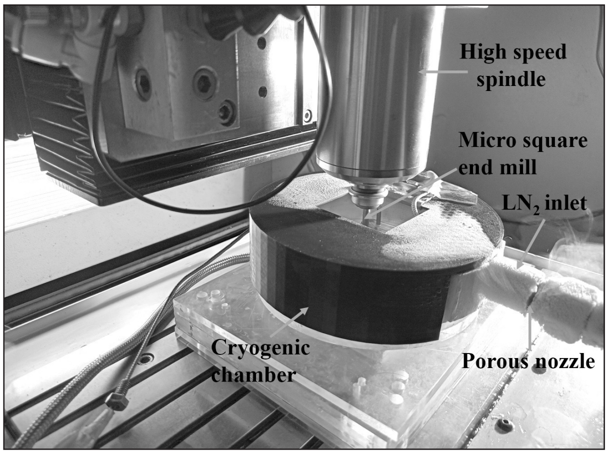

Fig. 3. Experimental set up of cryogenic micromachining.

Due to decrease in interatomic distance and directional alignment of the molecular chain while cooling, on deforming below Tg, propagation of the load on machined surface occur uniformly. In addition, after the material retards back to room temperature, the decrease in entanglement of the molecular chain also increase the stretch ability of VHB in comparison to initial condition.

2.2. Experimental set up and procedure

In order to machine VHB below its glass transition temperature (T_g), a special chamber wall for uniform passing of liquid nitrogen over the workpiece is constructed. The cutting conditions are summarized in Table 2. The experimental cryogenic cooling system comprised of an air compressor (GA550), two 12volt DC one way solenoid valve, LN_2 cylinder (CRYOCAN, IS:11552, Indian oil, India), K-type thermocouple, stainless steel tube for cryogen supply and machining chamber. From cryogen cylinder, liquid nitrogen (LN_2) was passed over the VHB 4910 substrate in gaseous form at a pressure of 0.1 MPa and a flow rate of 0.1L/min. The nozzle of 10 mm diameter was used for discharging the LN_2 at chamber inlet. Machining has been done by two fluted TiAlN coated WC/Co micro flat end mill cutter. For current investigation, the specifications of the micro end mill are illustrated in Table 3. The cutting force is measured with dynamometer attached under the work fixture. Workpiece material is VHB acrylic soft polymer of dimension 50 mm x 50 mm x 1 mm. The experimental set up is shown in fig 3. Temperature inside the chamber was measured at multiple location using a K-type thermocouple.

Channel microstructure was investigated using Scanning Electron Microscope (SEM) (Zeiss, Gemini 500). In order check the effect of cryogenic cooling on stretch ability of soft polymer, tensile test (Zwick/Roell Z010) of untreated and cryo treated sample is performed. Sample with microchannel is not considered for testing as it may acts as a stress concentrator and cause early failure of material. The test was conducted at room temperature with strain rate of 0.01/s and for repeatability three sample were tested under each condition.

3. Experimental Proof of Concept

The purpose of experimental work was to validate the proof-of-concept, where cutting force and microstructure of the channel on VHB 4910 at room and cryogenic condition with present designed chamber and experimental set up is demonstrated. Fig 4. shows the behavior of cutting forces in the direction of feed at room and ultralow temperature. At room temperature, non-periodic cutting force is observed and low cutting force value depicts that no chip formation has occurred. Under cryogenic condition, large magnitude and periodic changes of cutting force with rotation of the cutting tool confirms that machining of VHB is possible with the present cooling technique.

Fig 5. shows the shape of micro channel observed by SEM at room and cryogenic cutting condition. It is evident from the micrograph that VHB cannot be machined at room temperature while by machining at cryogenic condition, microchannel can be precisely formed. The desired shape of the channel is 500 µm wide and 10 µm deep. Due to uniform cooling, small difference in shrinkage of VHB show less dimensional error.

Fig 6. illustrates that untreated VHB samples have less strain values than those of cryo treated VHB samples with high fracture strength. Three samples were taken for each condition to check the repeatability of the test. The slow cooling rate and uniform cooling mechanism tune mechanical response of VHB by directional alignment and orientation of the molecular chain (Sheng et al., 2012). The stretch ability of the VHB polymer remarkably improved from 800% to 1600% after cryogenic treatment. Chopra et al. (2021)

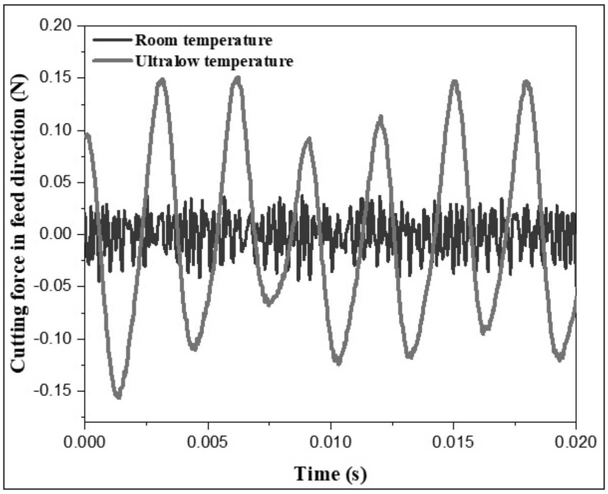

Fig. 4. Cutting force pattern at room and ultralow temperature.

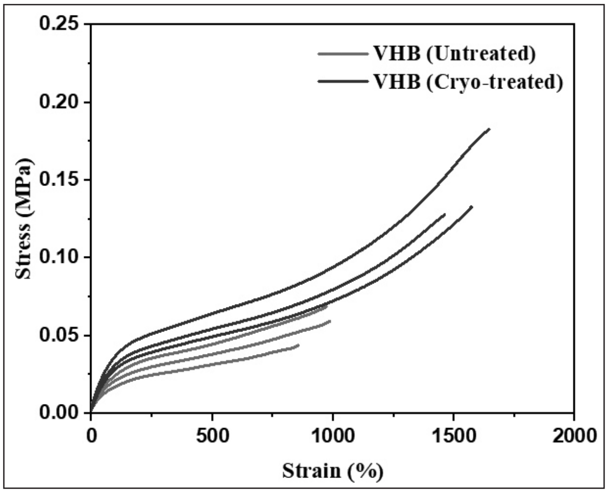

Fig. 6. Stress-strain curve of VHB for untreated and cryo treated samples.

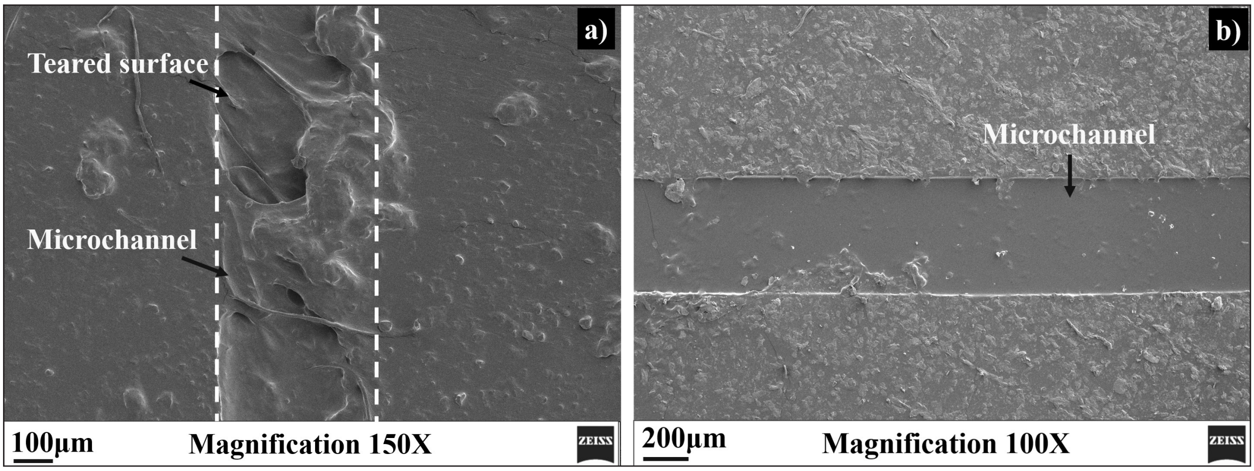

Fig. 5. SEM micrograph of the channel formed under a) room temperature b) cryogenic condition.

reported that after cryogenic treatment of acrylic based polymer, all the weaker carbon hydrogen bond disappears, and new bonds are formed with increase in length of molecular chain. The formation of new strong bonds of VHB followed by cryogenic treatment is possibly attributed to the flexible motion imparted to the polymeric chains. Wang et al. (2017) further added that due to molecular disentanglement, and formation of new molecular configuration after cryogenic treatment, the non-covalent bonds of VHB get enough time to slip and break with improved mechanical strength. Therefore, material undergoes larger deformation after cryogenic treatment. This makes it clear that when transitions of VHB from a rubbery to a glassy phase occur under cryogenic conditions, it improves machinability, and due to orderly arrangement of molecular structure during cooling, material's stretch ability improves after it heated back to ambient temperature.

4. Conclusions

Cryogenic cooling during machining with current fabricated set up found to be effective for the micro removal of VHB. Generally, it is difficult to machine such polymer with existence cryogenic micromachining technique because of breakage of material by overcooling. However, the proposed chamber can be used for the precise machining of too soft materials. Therefore, in this study, possibility of cryogenic micromachining of VHB and its effect on stretch ability after cryogenic cooling inside the chamber for approximate machining time were studied. The following results were obtained through this study.

- In cryogenic micromachining process, the VHB surface in the cutting region loses its elasticity and adhesive behavior that leads to being machined well, instead of tear type failure.
- With a uniform cooling technique, VHB shows suitable cutting mode of transition and avoids crack formation on the surface. From the viewpoint of cutting force and microstructure of the channel, cryogenic micromachining is a preferable technique to form microchannel over soft polymer.
- Since high stretch ability of the polymer is a key factor in determination of stability of the wearable sensor, the improvement in strain property of VHB by cryogenic microfabrication process validate the importance of current micromachining technique compared to other fabrication process

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