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Mechanism of Cutting Elastomers with Cryogenic Cooling

Matthias Putz (2)[a,b], Martin Dix [b,*], Mike Neubert [b], Torsten Schmidt [a]

[a] Fraunhofer Institute for Machine Tools and Forming Technology (IWU), Reichenhainer Str. 88, 09126 Chemnitz, Germany
[b] Institute for Machine Tools and Production Processes (IWP), Technische Universität Chemnitz, Reichenhainer Str. 70, 09126, Chemnitz, Germany

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ABSTRACT

Machining of elastomers offers more flexibility of product shape in comparison to the common compression moulding, especially for small batch series. In this context the entropy-elastic behaviour of the material with low Young's modulus is the main barrier for high-quality manufacturing. This material behaviour could be temporarily adapted by cryogenic cooling for precise cutting. In this article, the different mechanisms, e.g. forces, friction and separation procedures, are analysed for elastomers with different material behaviours. Different chip formation mechanisms are shown in comparison to metal machining. As a result, the friction ($\mu \approx 1$) between work piece, chip and tool dominates. An analytic chip formation model has been applied.

1. Elastomers–manufacturing and properties

1.1. Introduction

Elastomer components play an important role as sealing, bearings or as electric insulators in engineering. Primary shaping such as injection moulding or compression moulding are the most common technologies for manufacturing elastomer parts. However, as it requires expensive custom-made pressing moulds, the fabrication of single parts and small batch sizes is uneconomic. Shape cutting as an alternative production technology for small quantities enables a reduction of cost and increases the flexibility of handling. However, the high elastic material behaviour with low Young's modulus is the main barrier to economical machining with high accuracy and high quality surfaces.

1.2. Material behaviour of elastomers

Elastomers are usually thermoset plastics with widely meshed cross-links between the twisted molecular chains. Under loads the twisted molecular chains are oriented in the direction of the force. The cross-links ensure that the chains get back in the twisted initial state when the part is unloaded. When this process is 100% reversible and all the mechanical work for deformation can be regained, the material characteristic is ideal elastic. Yet, in case of conventional elastomers such as the often-used nitrile butadiene rubber NBR the material characteristic is viscoelastic. This means that the material is elastic under short-time loads, but viscous under long-time loads. Also mechanical energy dissipation occurs at every load cycle which is based on internal friction. During long-time loads mechanisms such as creep and relaxation were detected. The dynamic material behaviour can be described by the complex dynamic modulus G, which is based on the storage modulus and the loss modulus G″. G′ defines the elastic behaviour and the G″ defines the viscous behaviour [1].

$$G-\sqrt{G'^2+G''^2} \qquad (1)$$

Both moduli are influenced by deformation rate and temperature. So G' and G″ increase with increasing deformation rate. This means that the elastomer becomes harder at higher deformation rates and also dissipates more energy. Especially the reduction of the operation temperature results in an increase of the moduli (Fig. 1). Thus the material characteristic can be modelled.

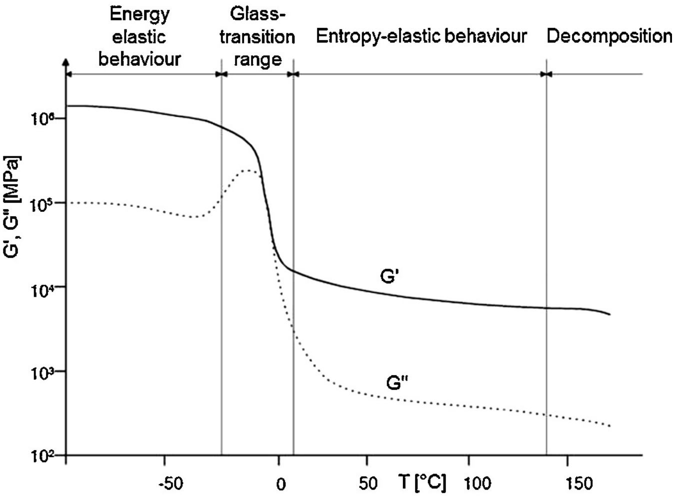

Fig. 1. Dynamic material parameters [3].

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[*] Corresponding author. Tel.: +49 371 531 36678.
E-mail address: martin.dix@mb.tu-chemnitz.de (M. Dix).

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Therefore, the viscoelastic behaviour will be changed to an energy elastic behaviour by cooling to low temperatures [2].

This transition from entropy-elastic/viscoelastic to energy-elastic is defined as glass-transition-range. High strain-rates move this range towards higher temperatures. This correlation between temperature and strain-rate was described by an analytical equation derived by Williams, Landel and Ferry [4].

The main problem in machining elastomers consists in high elasticity combined with the low Young's modulus. Thus high elastic deformation occurs in the entire workpiece during machining, which results in poor manufacturing qualities. Based on the shown general material behaviours, two strategies are possible to increase the machinability of elastomers. One is the increase of the cutting speed to obtain a stiffer material, i.e. higher G' and G″, by increasing the deformation rate. This strategy was tested by Bargel [5]. He analysed the influence of different cutting parameters on the machinability of an acrylonitrile-butadiene-elastomer under dry conditions. Thus the cutting speed has the highest influence. The second strategy, which is discussed in this article, is the cooling of the workpiece under the glass-transition-range to achieve the energy elastic material behaviour with a higher Young's modulus.

2. Measured mechanical properties of NBR

2.1. Tensile stress

A thermomechanical analysis was necessary to determine the required temperature range for machining nitrile-butadiene-rubber NBR. Therefore tensile tests were conducted at different temperatures on a Zwick material testing machine (testing speed: 0.05 mm/s; preload force: 10 N) in a temperature chamber used for low temperatures. The measured results are shown in Fig. 2, demonstrating that decreasing temperatures lead to an increase in elastic modulus and in tensile stress. The maximum elongation first increases by reducing the temperature and achieving a local maximum at $\sim -20\,^{\circ}$C. At this temperature the maximum elongation falls significantly. A brittle and quasi-elastic material property is achieved at $\sim -70\,^{\circ}$C.

Based on these findings cryogenic cooling with liquid nitrogen LN ($T_{\text{boiling}} = -196\,^{\circ}$C) was chosen for pre-cooling the rotating workpiece. It was cooled down by a LN2 jet shortly before the turning operation started. Bulk temperature was assumed to be below glass transition temperature.

2.2. Friction on elastomer surfaces

The friction behaviour of elastomers against hard counter-bodies differs greatly from metallic materials. Therefore there should be a distinction between the mechanisms of internal and outer friction. Outer friction is defined by the surface contact between the two friction partners which are characterized by adhesion processes [6]. The resulting adhesion friction portion is important only for sufficiently clean and smooth surfaces [7]. Internal friction is a hysteresis process which is caused by the deformation of the elastomer during sliding over an uneven counter-surface. The generated oscillating forces lead to repetitive deformations of the elastomer. As a consequence, the loss module G″ leads to energy dissipation. The appropriate friction portion hysteresis composed with adhesion results in the friction force F_R. Khan [7] described in his work that the friction force has the same temperature dependence as that of the elastic modulus [7].

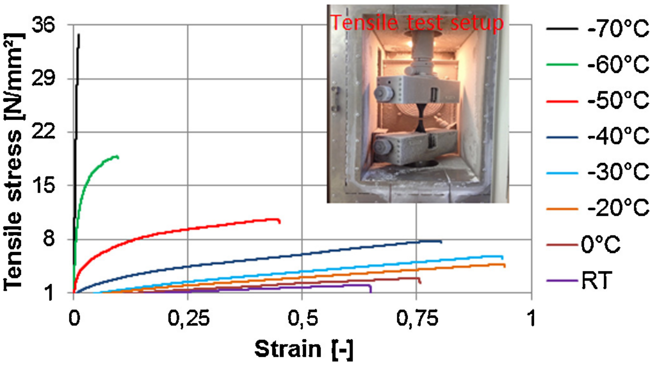

Fig. 2. Measured stress-strain curve of NBR at different temperatures.

The friction on elastomer surfaces strongly depends on the sliding velocity. The reason for this is the frequency dependence of the complex model of the elastomers. Each roughness peak of the hard counter body leads to a deformation of the elastomer and stimulates certain frequencies. Therefore, the frequency is raised with increasing sliding speed.

Friction experiments were performed on a rotational tribometer (TRM5000 WAZAU GmbH, Ring on disc, radius 35 mm) to evaluate the temperature dependence like the one of the complex elastic modulus. The experiments were conducted under dry and cryogenic conditions. The normal force was varied by a constant increase from $F_N = 100$ N up to $F_N = 250$ N over a time period of $\Delta t = 200$ s. Characteristic results are presented in Figs. 3 and 4.

It is shown that under cryogenic conditions the friction force and the friction coefficient have higher values than under dry conditions at 20 °C and at the same velocity and loads. So a value of $\mu_{\text{cryo}} \approx 1$ was determined. The observation of friction behaviour in dry conditions is consistent with the investigation results of Grosch [6]. He observed a nonlinear increase of the friction with increasing velocity. At each sliding velocity, friction decreases with increasing temperature [6].

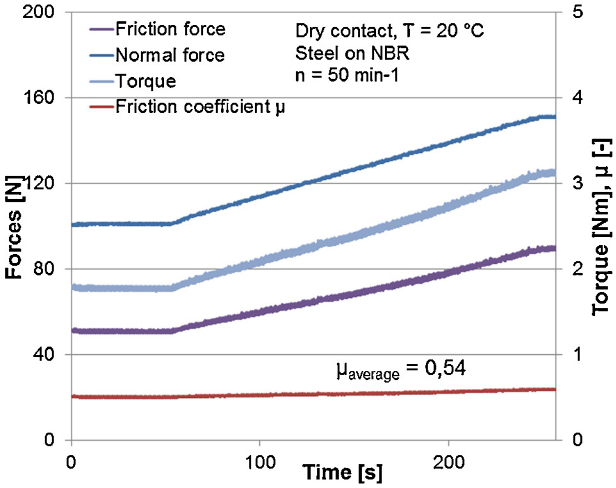

Fig. 3. Friction analysis under dry conditions - NBR ring on ground steel ring.

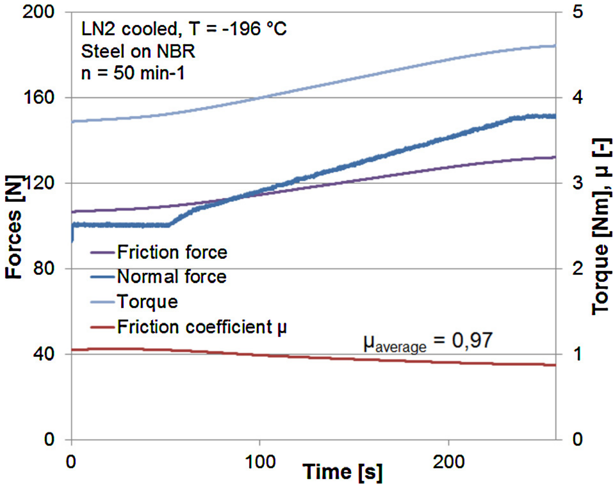

Fig. 4. Friction analysis under cryogenic conditions–NBR ring on ground steel ring.

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