Wear 268 (2010) 803–810

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

The influence of injection molding on tribological characteristics of ultra-high molecular weight polyethylene under dry sliding

Hsien-Chang Kuo, Ming-Chang Jeng*

Department of Mechanical Engineering, National Central University, Chung-Li 32054, Taiwan

ARTICLE INFO

Article history:
Received 8 July 2009
Received in revised form
26 November 2009
Accepted 7 December 2009
Available online 4 January 2010

Keywords:
Tribology
Ultra-high molecular weight polyethylene
Friction
Wear
Injection molding

ABSTRACT

The objective of this study is to investigate the effects of various injection molding process parameters on the tribological properties of ultra-high molecular weight polyethylene (UHMWPE). The tribological properties, such as the friction coefficient and wear volume loss, were obtained using the Schwingum Reibung Verschleiss (SRV, oscillation friction wear) ball-on-plane wear tester. In addition, the mechanical properties of UHMWPE were investigated as well. The variable parameters of the injection molding process were melt temperature, mold temperature and injection velocity. Experimental results show that different wear contact loads and varied injection molding conditions influence the friction coefficient and wear volume loss of the UHMWPE specimens. As the sliding contact loads increased, the friction coefficient also increased. Moreover, the lowest wear volume loss mostly occurred in highest injection molding conditions. The morphologies of the worn surfaces and the specimen cross sections were examined with an optical microscope and a scanning electron microscope, respectively. Plastic deformations, grooves and wavelike formations are the main wear mechanism on the surface in the UHMWPE wear tests. Experimental results also showed that the tensile strength and surface hardness are affected by injection molding conditions and sliding contact loads.

1. Introduction

Ultra-high molecular weight polyethylene (UHMWPE) is a polymer with extremely high molecular weight. It possesses excellent wear resistance, high impact strength, good sliding quality, and low friction loss, and its self-lubrication performance can be widely used in engineering applications [1–3]. Unal and Mimaroglu [4] studied the wear behavior of contact loads and sliding speeds. The authors found that the friction coefficient of UHMWPE slightly increases as the load increases, but the wear rate was not affected. Moreover, the worn surface of UHMWPE was wrinkled. Atkinson et al. [5] indicated that adhesive and fatigue on the surface of UHMWPE were the two main wear mechanisms. The adhesive process occurred quickly after sliding, and fatigue only appeared after long periods of sliding. Song et al. [6] studied the effects of machining on the tribological behavior of UHMWPE under dry wear; they found that severe plastic deformation and ploughing are the main wear mechanisms. Bartenev and Lavrentev [7] observed wear mechanisms; when the UHMWPE is against rigid bodies, the main wear mechanisms are fatigue and abrasion. Da Silva and Sinatora [8] developed severity conditions for UHMWPE wear; they observed the worn surface analysis and found that the three wear mechanisms include abrasion, fatigue and adhesion. Some reports have studied the relationship between wear behavior in contact loads and/or UHMWPE sliding speeds and its composites. However, these samples of UHMWPE are mostly made by compression molding [2,4,6,9,10,15,16,19]. In order to more understand the difference in mechanical properties for common UHMWPE and some relevant polymers with this study, such as the wear test conditions, friction coefficient, hardness and molecular weight are listed in Table 1. Furthermore, some papers reported that the thermal effect on wear mechanisms of UHMWPE, frictional heating, might be related to the wear of UHMWPE through softening or some other effects [11–15].The review of the above mentioned publications shows that most UHMWPE specimens are processed by compression molding or extrusion molding because the viscosity of UHMWPE is very high, which means it does not flow well. Therefore, it is difficult to mold by injection molding [16]. Recently, an UHMWPE material has been improved such that it is suitable for injection molding technology. Furthermore, injection molding is one of the most important processes. An important advantage of injection molding is that the material can be easily shaped into complex geometries in a short production cycle or in a single production step with an automated process. Therefore, the main purposes of this study are the following: (1) to investigate the relationships between molecular orientation and different injection molding conditions; (2) to understand the effects of tribological characteristics of UHMWPE wear parameters; (3) to observe the

* Corresponding author. Tel.: +886 3 4267331.
E-mail address: jeng@ncu.edu.tw (M.-C. Jeng).

0043-1648/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2009.12.012

Table 1
Referenced polymers and their mechanical and physical properties.

Materials	Against material	Molecular weight	Wear load	Wear speed	Friction coefficient	Hardness	Reference
Common UHMWPE	316 L stainless steel	1.5×10^6 g/mol	1, 2.5 MPa	0.5 m/s	0.10, 0.16	$Hk_{25\,g}$ 21.2	[2][a]
Common UHMWPE	X5CrNi18-10	5.0×10^6 g/mol	21.2 N	28.2 mm/s	0.12	n/a	[3]
Common UHMWPE	Stainless steel	n/a	20, 30, 40 N	0.88 m/s	0.15, 0.18, 0.20	n/a	[4][a]
Common UHMWPE	45 # steel	3.5×10^6 g/mol	15, 30, 50 kg	200 rev/min	0.09-0.10	Shore D 65	[11]
Common UHMWPE	AISI D2 steel	n/a	0.35, 0.70, 1.05 MPa	1 m/s	0.41, 0.34, 0.27	n/a	[12]
Common UHMWPE	316 L stainless steel	3.0×10^6 g/mol	196 N	0.42 m/s	0.21	HB 49	[15][a]
Common UHMWPE	ZrO_2 ball	3.0×10^6 g/mol	5 N	0.19 m/s	0.09	HB 30	[23]
POM	Stainless steel	n/a	20, 30, 40 N	0.88 m/s	0.12, 0.17, 0.15	n/a	[4]
POM	AISI D2 steel	n/a	0.35, 0.70, 1.05 MPa	1 m/s	0.37, 0.35, 0.29	n/a	[12]
PA 6	316 L stainless steel	3.5×10^4 g/mol	1, 2.5 MPa	0.5 m/s	0.20, 0.26	$Hk_{25\,g}$ 29.8	[2]
PA 6	Stainless steel	n/a	20, 30, 40 N	0.88 m/s	0.09, 0.11, 0.12	n/a	[4]
PA 66	AISI D2 steel	n/a	0.35, 0.70, 1.05 MPa	1 m/s	0.52, 0.42, 0.37	n/a	[12]

[a] The UHMWPE samples are made by compression molding.

wear mechanism on worn surfaces by optical microscope (OM) and scanning electron microscope (SEM).

2. Experimental

2.1. Materials

The material used in this study is an injection molding grade of ultra-high molecular weight polyethylene (UHMWPE, GUR5113, from Ticona, USA). It is a linear polyolefin resin. The bulk density is 0.93 g/cm^3, and the molecular weight is 3.9×10^6 g/mol. Other physical and mechanical properties of UHMWPE are listed in Table 2. The recommended nozzle temperature is between 250 and 260 °C, and the recommended mold temperature is between 30 and 90 °C. The material was preheated at 80 °C for 3 h using a dehumidifying drier before use in the injection molding machine.

2.2. Specimen preparations

The mold design is used to generate a tensile specimen, and the dimensions are based on the ASTM procedure D638 (Type IV). The mold is made of tool steel. One semicircular rotary plug is designed to allow the part to be molded with or without a weld line. A wear specimen is cut from the central position of the injection molding specimens. The specimen design and cut are shown in Fig. 1.

All wear specimens are prepared on a FANUC electric injection molding machine (ROBOSHOT S-2000i 50A). The machine can offer a maximum clamping force of 50 tons and a maximum injection velocity of 330 mm/s. The screw diameter is 22 mm, and the maximum injection volume is 29 cm^3. A mold temperature controller is used to prepare the specimens at various mold temperatures. The molded parts are cooled for 6 s in the injection molding period. Under each set of injection molding conditions, 10 shots are made to ensure that the process is stable before specimens are collected. If no significant variation is observed during these first 10 runs, the specimens from the next five runs are collected as the samples for tribological characterization.

Table 2
The physical and mechanical properties of UHMWPE.

Property	Unit	GUR 5113
Density	g/cm^3	0.93
Viscosity	mg/l	2000
Volume density	g/cm^3	0.5
Tensile modulus	MPa	750
Tensile stress at yield	MPa	17
Tensile strain at yield	%	20
Vicat softening temperature	°C	80
Molecular weight	g/mol	3,900,000

2.3. Injection molding conditions

In this study, three basic conditions of the injection molding, the melt temperature (250, 265 and 280 °C), mold temperature (50, 70 and 90 °C) and injection velocity (150, 180 and 210 mm/s), are varied. The levels of the molding factors are selected through our initial tests and recommended by the manufacturer. The specimens and the injection molding conditions are listed in Table 3.

2.4. Sliding wear tests

The wear tests were done on a Schwingum Reibung Verschleiss (SRV oscillation friction wear) tester, as shown in Fig. 2. The wear test specimens with dimensions 5.0 mm × 5.0 mm × 2.0 mm were cut from the central part of the tensile specimen. Before wear test, the UHMWPE surface was not ground and polished. Surface roughness of the UHMWPE specimens was measured by using a HANDYSURF E-35A profilometer. Three specimens were measured for each injection molding condition to obtain an average roughness value R_a. The measured surface roughness data are listed in Table 4. Furthermore, surface roughness of a weld line was always

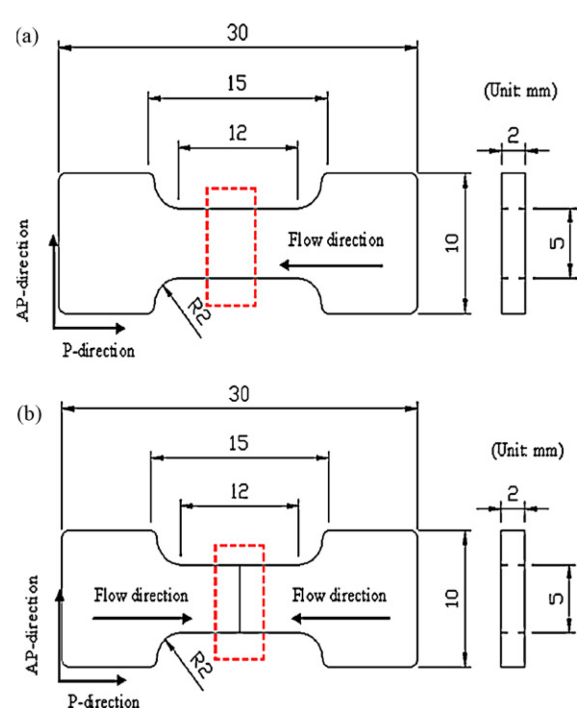

Fig. 1. Dimensions of the molded specimens (a) without a weld line and (b) with a weld line.