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Araştırma Makalesi / Research Article

The Investigation of Production Parameters and Their Effect on the Tribomechanical Properties of the Compression Molded Polymeric Bearing Materials

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ABSTRACT: UHMWPE (Ultra High Molecular Weight Polyethylene) is a widely used polymer due to its superior mechanical properties. The microstructural, mechanical, and tribological properties of this polymer material produced by the compression molding technique significantly depend on the production parameters. The different molding pressures and temperatures dramatically impact the properties of the material. In this study, UHMWPE polymer samples were produced at three different molding pressures (150 Bar, 250 Bar, and 350 Bar) and molding temperatures (120°C, 150°C, and 180°C) using the compression molding technique. The microstructural, mechanical, and tribological properties of the samples were examined. It is observed that low-temperature molding production parameters cause an increase in strength. On the other hand, this situation enables decreased ductility. It has been determined that as the molding temperatures increase, ductility increase in all the same molding pressure groups. Similarly, it was observed that increasing the molding pressure in the same temperature group increased the strength of the material. It has been determined that there is an optimum molding pressure and temperature for wear resistance. It has been observed that the coefficient of friction (COF) behavior is not much affected by the molding parameters. Agglomeration of polymer particles is envisaged as the main reason for forming optimum pressure and temperature conditions in wear resistance. Agglomerated particles in the microstructure reduce bonding strength and deteriorate wear resistance. The study determined the optimum molding pressure (250 Bar) and temperature (150°C) for the production of UHMWPE material by a compression molding technique.

Keywords: UHMWPE, Compression molding, Tribology.

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1. INTRODUCTION

A significant number of mechanical components are made of polymer materials in engineering applications (Ginzburg et al., 2006; Sarı and Salman, 2016). Polymers cover a primary technological sector due to their simple forming capabilities and economical production methods (Feyzullahoglu and Saffak, 2008; Kumar et al., 2017). Engineering polymers, in particular, are utilized due to their superior mechanical and tribological qualities in the automotive and aviation industries (Dearn et al., 2013; Ginzburg et al., 2006; Rymuza, 2013). These advanced polymers are frequently used in friction applications (Panin et al., 2015). They are a perfect substitute for many materials because of their superior wear resistance, low lubrication requirement, lightweight, and affordable price (Koç, 2011; Sarı and Salman, 2016). Bearings and bearing mechanisms are among the areas that utilize the most frequent candidate for metallic materials (Ginzburg et al., 2006). Due to their low density and superior wear resistance, and low friction characteristics, polymeric bearings can function without lubrication (Dearn et al., 2013). The main reason for the superior tribological performance of polymer materials is the monomolecular films that form at the contact surfaces (Bahadur, 2000; Hüseyin and Yetgin, 2010). These films, which develop between contacting bodies, have cohesive bonds that are more powerful than adhesive bonds (Bahadur, 2000; Jintang, 2000). Ultra-high molecular weight polyethylene (UHMWPE) is one of the most widely used polymer materials for bearing parts. UHMWPE is a type of polymer formed due to the bonding of 4 to 6 million molecules (Gürgen, 2019; Uzuner and Gediktaş, 2010). Compared to other polymers, UHMWPE has a high impact on toughness (Hüseyin and Yetgin, 2010). They produce a transfer film more rapidly than other polymers due to their high molecular density (Rymuza, 2013). UHMWPE is widely used in engineering applications due to its low friction behavior and superior wear resistance (Tong et al., 2003).

UHMWPE has been examined in several research articles since it is utilized to produce rolling bearing parts (Hüseyin and Yetgin, 2010; Panin et al., 2015; Uzuner and Gediktaş, 2010). The wear rate and COF behavior of the polymers under various speeds and loads were examined in the researches. UHMWPE material can be employed in applications requiring a superior wear resistance and COF, based on the literature research (Hüseyin and Yetgin, 2010; Sarı and Salman, 2016; Uzuner and Gediktaş, 2010). Studies on the tribological performance of polymers are very complex compared to metallic materials. The main reason is that the formed transfer film layer depends on the shear rate, pressure, surface roughness, and temperature (Wu et al., 2002). When the literature is examined, it is seen that the tribological performance of UHMWPE has been investigated superficially. The wear and friction behavior of cast UHMWPE material under dry conditions were investigated. As a result of the researches, it was determined that the COF decreases with increasing load and increases with increasing sliding speed (Hüseyin and Yetgin, 2010; Sarı and Salman, 2016). The tribological performance of twelve different polymeric materials was investigated concerning sliding distance and surface pressure (Uzuner and Gediktaş, 2010). The COF increased with increasing sliding speeds and decreased at high surface pressures. It was also observed that UHMWPE exhibits superior wear resistance in all groups. Another study investigated the effect of the contact of UHMWPE and polished steel on the tribological and microstructural properties. It was found that while the COF decreases with the shear rate at low pressures, it decreases much more at high pressures. This situation was explained by the fact that the lamellar structure of the UHMWPE material in the crystalline region remained parallel throughout the movement at low pressures (Klapperich et al., 1999).

When the studies are examined, the tribological performance of the UHMWPE material varies significantly due to the sliding speed, contact pressure, surface roughness, temperature, and environmental conditions. This observed fluctuation is thought to be due to uncertainty in the production conditions. In this study, UHMWPE samples were produced at three different molding pressures and temperatures. The microstructural, mechanical, and tribological properties of UHMWPE specimens were analysed by tests. The production parameters have been optimized.

2. MATERIALS AND METHODS

In the study, UHMWPE (43951, Alfa Aesar) was used as the rolling bearing material. The thermophysical properties of the material used in the experimental studies are shown in Table 1. 2 grams of UHMWPE powder was used in the compression molding technique. The molding process was performed for 5 minutes (3 minutes of heating and 2 minutes of cooling cycles).

Table 1. Thermophysical properties of UHMWPE powder material used in the experimental studies

Material Name	UHMWPE
Formula	$(CH_2CH_2)n$
Melting Point	150°C
Autoignition Temperature	343°C
Molecular Weight	3-6 million
Average Particle Size	150 µm
Density	0.945 g/cm^3

The samples were produced at three different pressures, 150 Bar, 250 Bar, and 350 Bar, and three different temperatures, 120°C, 150°C, and 180°C, respectively. The production algorithm used in the experimental studies is shown in Table 2. Struers CitoPress-1 hot mounting press device was used to produce the samples.

Table 2. Sample production plan used in the experimental studies

Sample Code	Molding Pressure (Bar)	Molding Temperature (°C)
1		120
2	150	150
3		180
4		120
5	250	150
6		180
7		120
8	350	150
9		180

The microstructural analysis of the produced samples was performed under Nikon Clemex optical microscope. The microhardness of the samples was measured using a Future Tech FM-800 device at a load of 100gf and a dwelling time of 20 seconds. The mean hardness for each control group was calculated using the average of three hardness tests. The standard deviation was used as an error function to minimize uncertainty. Having completed optical microscopy and hardness analysis, wear tests were applied to the samples using the CSM tribometer. The tests were carried out in ball-on-disc type according to ASTM G-99 norm. A Ø3 mm diameter ball (containing 90% WC and 10%Co) was used as an abrasive counter body. The counter body ball has a hardness of 91.6

HRA. The wear test was performed in a rotating projectile with a 4 mm radius, a load of 10N, and 470 RPM (20 cm/s linear speed), 500 meters wear distance. The instantaneous data collection rate of the wear test was chosen as 10 Hz. The surface depth and width of the wear tracks formed after the tests and the average surface profile of the samples immediately after production were carried out using the Mitutoyo SJ-400 surface profilometer. Average surface profiles were obtained as R_a, R_z, and R_q for 2,4 mm. Both average and worn surface profile scanning was performed in accordance with the ISO R97 norm. Raw data were processed using Gaussian Filtering Technique. Two profile measurements were performed for each worn surface, and the average cross-sectional area was used in the specific wear rate calculations. The measured maximum cross-sections are also exhibited as a Figure in the study. In addition, the mean COF values of the samples were recorded and reported during the experiments.

3. RESULTS AND DISCUSSION

3.1 Microstructural Analysis

Figure 1 shows macro structure photographs of the produced samples, UHMWPE powder and hot molding device used in the experiments. When the photograph is examined, it shows that the powder polymer material is lighter in color than the molded samples. Similarly, it is seen that the samples produced at low temperatures are lighter in color than the samples produced at high temperatures. It is known that this situation is due to higher crystallinity in polymer powder and samples pressed at low temperatures (Wu et al., 2002). When the samples are examined in general, it can be said that the light-colored samples contain more non-melting particles and voids. In addition, as the molding temperature increases, the edges of the specimens turns from light colour to darker colour. This incident shows that increasing the molding temperature improves the microstructure crystallinity (Gürgen, 2019).

Figure 1. Macrostructure photographs of the produced samples, UHMWPE powder, and hot molding device used in experiments

Figure 2 shows a comparative optical microstructure photo of the produced samples. As seen from the optical microstructure analyses, solidification was detected in the samples without complete dissolution at all temperatures at 150 Bar molding pressure (Samples 1, 2, and 3). This situation is related to the fact that the applied pressure cannot sufficiently bond the molten UHMWPE powder even though the temperature increases. These molten regions prevent the complete homogenization of the microstructure. In the productions carried out with 250 Bar molding pressure, it is observed that the partially molten regions have decreased but still exist in the microstructures (Samples 4, 5, and 6). In the production at 350 Bar molding pressure, it is seen that these formations completely melt together with the increasing pressure and provide complete unity (Samples 7, 8, and 9). When the microstructure of samples 7, 8, and 9 are examined, which has the highest production pressure, it was seen that the microstructure was homogeneous, and the molten parts were eliminated.

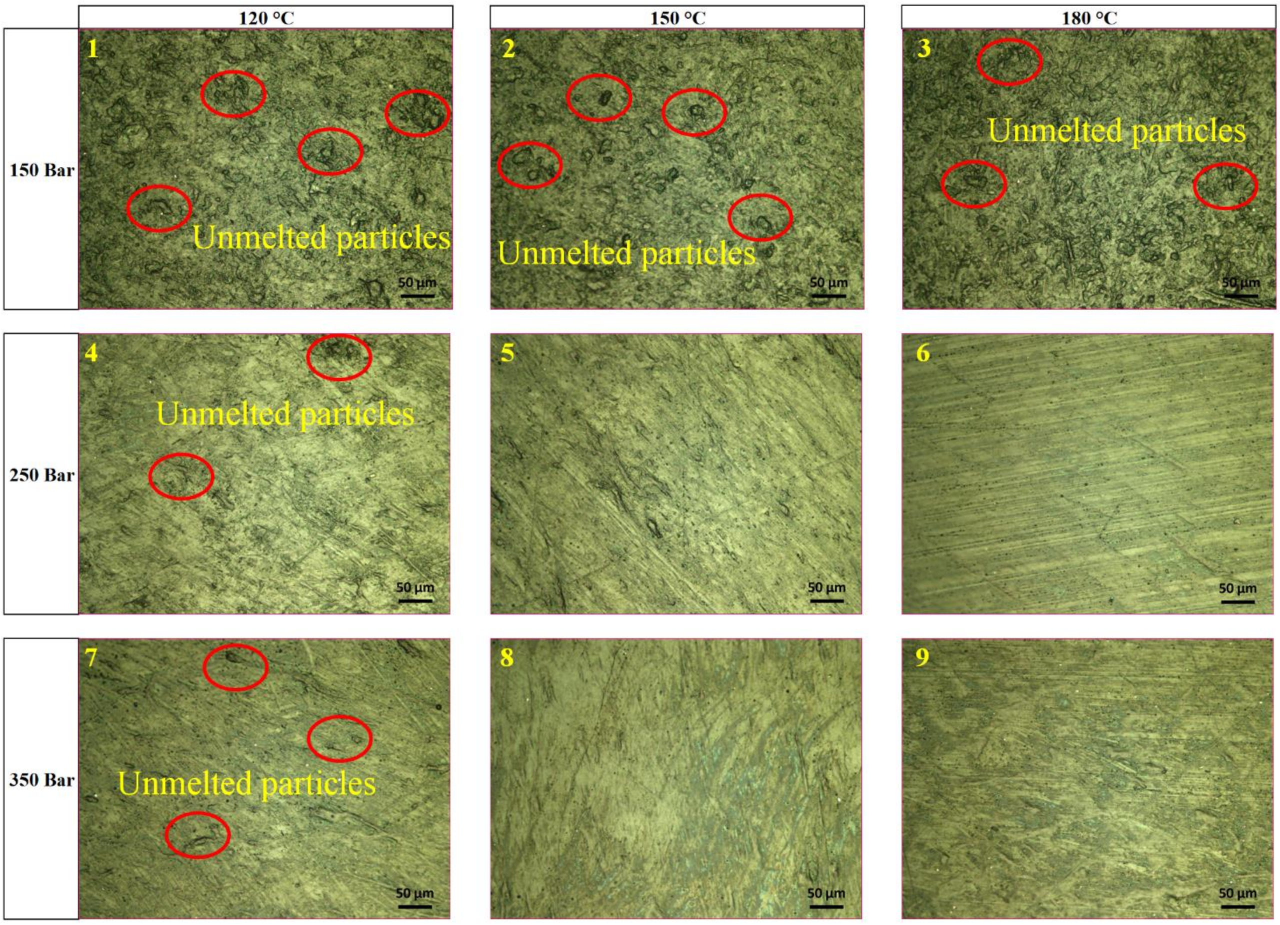

Figure 2. Optical microstructure image of the produced samples

3.2 Surface Roughness Analysis

Table 1 and Figure 3 show the average surface roughness values and morphology of the surfaces of the produced samples, respectively. When the results are examined, it is observed that the sample with the highest average surface roughness value is sample 1, which belongs to the low molding pressure and temperature. When these sample surfaces are examined, which have the highest average surface roughness, discontinuities formed by semi-molten forms are observed. This production defect is also observable in the optical microstructure photograph of the samples. Generally, the highest differences between peak and depths (R_z) are measured in the samples produced with the 120°C molding temperature. Since the heat given in the samples in this group is lower than the melting temperature of the UHMWPE material, it is not sufficient to melt it completely (Ge et al., 2003; Gürgen, 2019; Xiong and Ge, 2001).

Table 3. Average surface roughness values of the produced samples

Sample Code	R_a (µm)	R_z (µm)	R_q (µm)
1	0.28	2.0	0.38
2	0.28	1.9	0.38
3	0.34	2.1	0.44
4	0.28	1.8	0.35
5	0.15	1.1	0.20
6	0.22	1.3	0.27
7	0.28	1.5	0.34
8	0.22	1.6	0.29
9	0.24	1.6	0.31

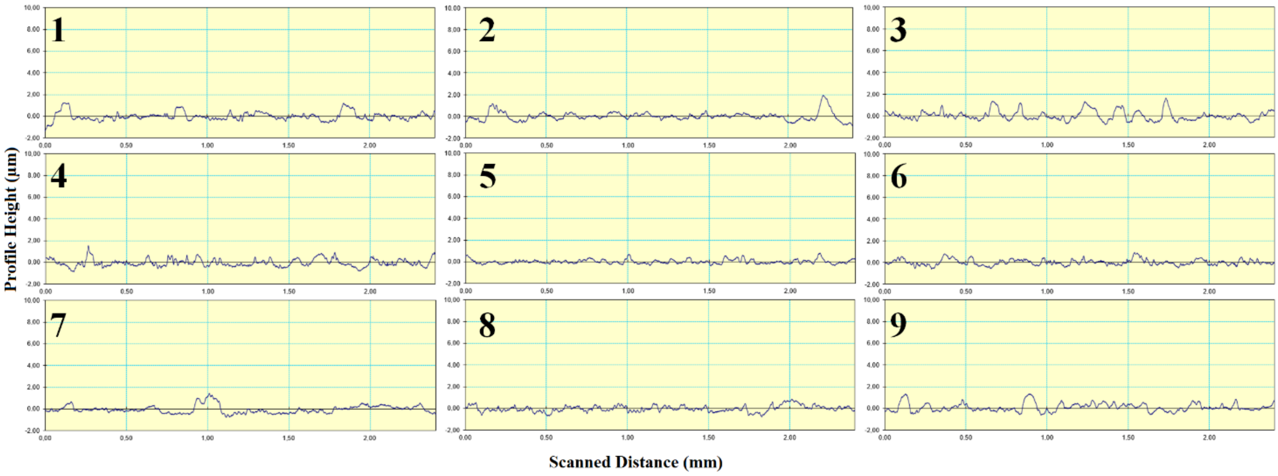

Figure 3. Average surface profiles of the produced samples

3.3 Hardness Analysis

Table 2 and Figure 4 show the average microhardness values of the produced samples. The analyzes are shown on the Vickers microhardness scale. As can be seen from the analyzes made, the molding pressure has a direct effect on the hardness of the UHMWPE material. It is seen that the hardness of the material increases with the increase of the molding pressure at the same molding temperature. This incident is thought to be the reason for the high temperature and high-pressure related bonding between the particles. As can be seen, the hardness alteration is not significant between 150-350 Bar. This situation proves that the 150-350 Bar molding pressure shows a regular alteration. Different studies also found similar results (Gürgen, 2019; Wang and Ge, 2007).

In contrast to the molding pressure, there appears to be a systematic alteration in the molding temperature. When the results are examined, it is seen that the hardness decreases with increasing molding temperature. It is known that as the molding temperature increases, the polymer material's crystallinity decreases. With the recrystallization process after melting under high temperatures, the degree of crystallinity decreases compared to the polymerized powder UHMWPE material. A high degree of crystallinity can dramatically improve mechanical properties. Therefore, changes in molding temperature directly affect the polymer material’s mechanical properties (Kanaga et al., 2008; Oral et al., 2010). Therefore, one can infer that the polymers produced at high molding temperatures exhibit more ductile plastic deformation.

Table 4. The average microhardness data of the produced samples

Sample Code	Groups		Measurements (HV) 1	2	3	Mean Hardness (HV)
1	**150 Bar**	**120°C**	9.60	8.10	6.70	8.13
2		**150°C**	7.30	7.10	6.80	7.07
3		**180°C**	6.60	6.10	5.90	6.20
4	**250 Bar**	**120°C**	8.50	8.00	8.60	8.37
5		**150°C**	7.20	7.10	7.60	7.30
6		**180°C**	6.20	6.20	7.10	6.50
7	**350 Bar**	**120°C**	9.40	8.70	8.00	8.70
8		**150°C**	7.50	7.30	7.70	7.50
9		**180°C**	6.80	6.30	6.90	6.67

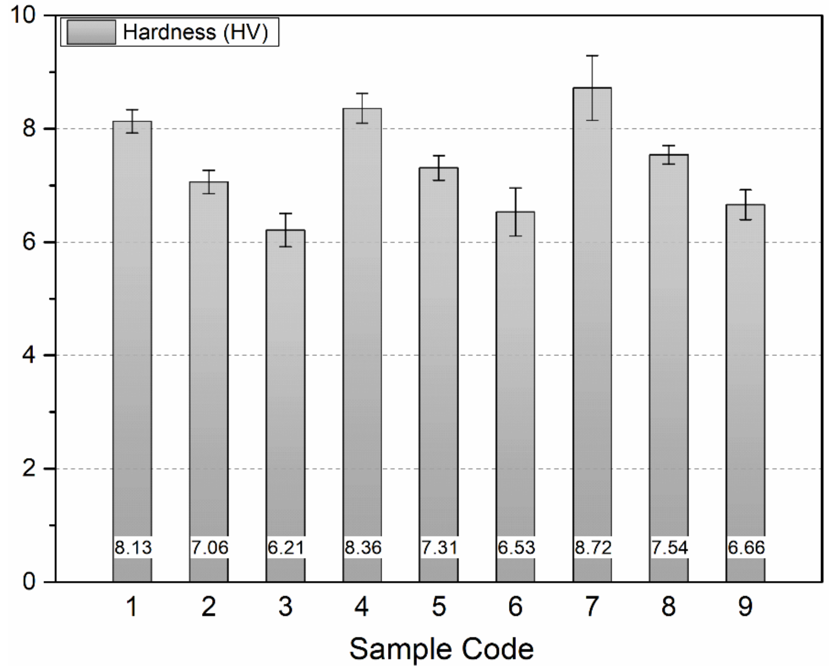

Figure 4. Average microhardness values of the produced samples

3.4 Wear Test

Table 3 and Figure 5 show the mean COF and wear rate values of the samples. The highest wear rate was observed in the 150 Bar molding pressure group. This group also has the lowest molding pressure. When the wear rates of the samples produced at different molding temperatures at a constant molding pressure are examined, it is seen that the wear resistance is lower at 120°C molding temperature, which is also the lowest molding temperature. It is seen that wear resistance increases in productions carried out at 150°C and 180°C. When the mean COF values are examined, the highest mean COF values are seen in samples 1, 2, and 3. These samples produced at the lowest molding pressure (150 Bar) exhibited the highest friction behavior.

Table 5. The mean COF and wear rates of the produced samples

Sample Code	Area Measurements		Mean area (mm^2)	Wear Rate ($10^{-4}mm^3/Nm$)	Mean COF
	1st	2nd			
1	0.11049	0.11677	0.1136300	5.711498320	0.107
2	0.07440	0.07868	0.0765400	3.847206560	0.106
3	0.10703	0.03867	0.0728500	3.661732400	0.088
4	0.03610	0.03266	0.0343800	1.728076320	0.077
5	0.02504	0.01405	0.0195450	0.982409880	0.047
6	0.02275	0.01779	0.0202700	1.018851280	0.071
7	0.02161	0.02251	0.0220600	1.108823840	0.074
8	0.02395	0.02201	0.0229800	1.155066720	0.058
9	0.02316	0.02264	0.0229000	1.151045600	0.067

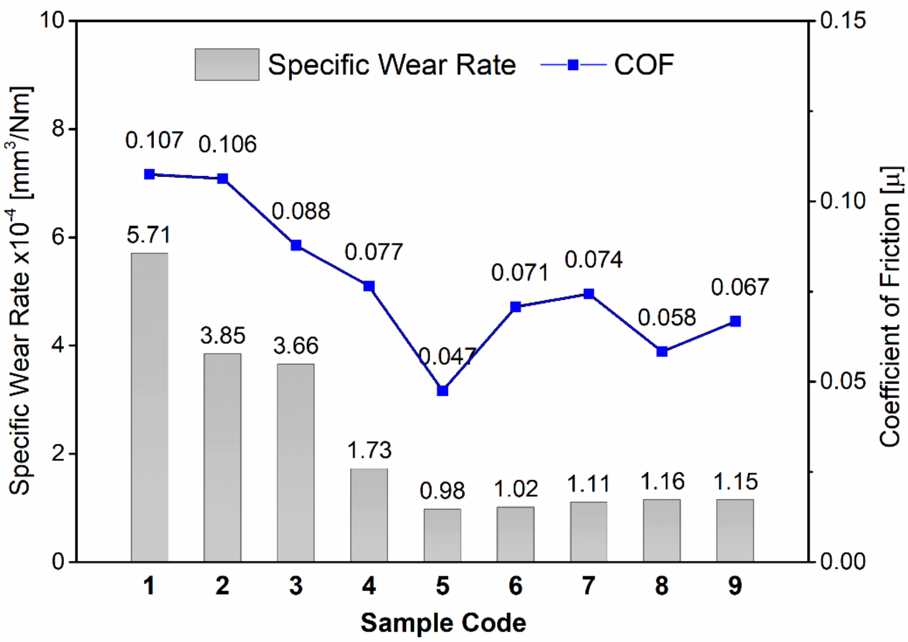

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Figure 5. The mean COF and wear rates of the produced samples

Figure 6 shows the variation of the COF with the distance during the wear test. When the graphs are examined, it is seen that the mean COF values of the samples at 150 Bar molding pressures are higher than the other groups. This situation indicates that the bonding in these groups does not have adequate load-carrying capacity due to the semi-molten form. It is thought that the fluctuations formed during the test are semi-molten grains that break off from the surface and stuck in the contact area during the test. This situation is also seen in the test results of other samples produced at low molding temperatures. It is seen that the load-carrying ability of polymeric materials depends on a drastically complete molten polymer particle by the use of increased molding pressure and temperature (Sample 4-7). When the COF diagram of sample-5 is examined, no fluctuation is also observed, with this sample performing the highest wear resistance. This phenomenon occurs since the amount of fragmentation from the surface is not sufficient due to the high surface strength. A similar situation can be seen in sample 8, molded at a temperature of 150°C and a pressure of 350 Bar. This sample behavior shows a critical threshold at the molding temperature, which is 150°C. It is seen that increasing molding temperature causes an increase in the mean COF value. As the molding temperature rises, crystallinity gets lower, and as a result, crystallinity decreases in the material. Therefore, polymeric materials molded at high temperatures are more ductile. Therefore, the load-carrying capacity is reduced (Gürgen, 2019; Kanaga et al., 2008; Mourad et al., 2009; Oral et al., 2010; Wu et al., 2002).

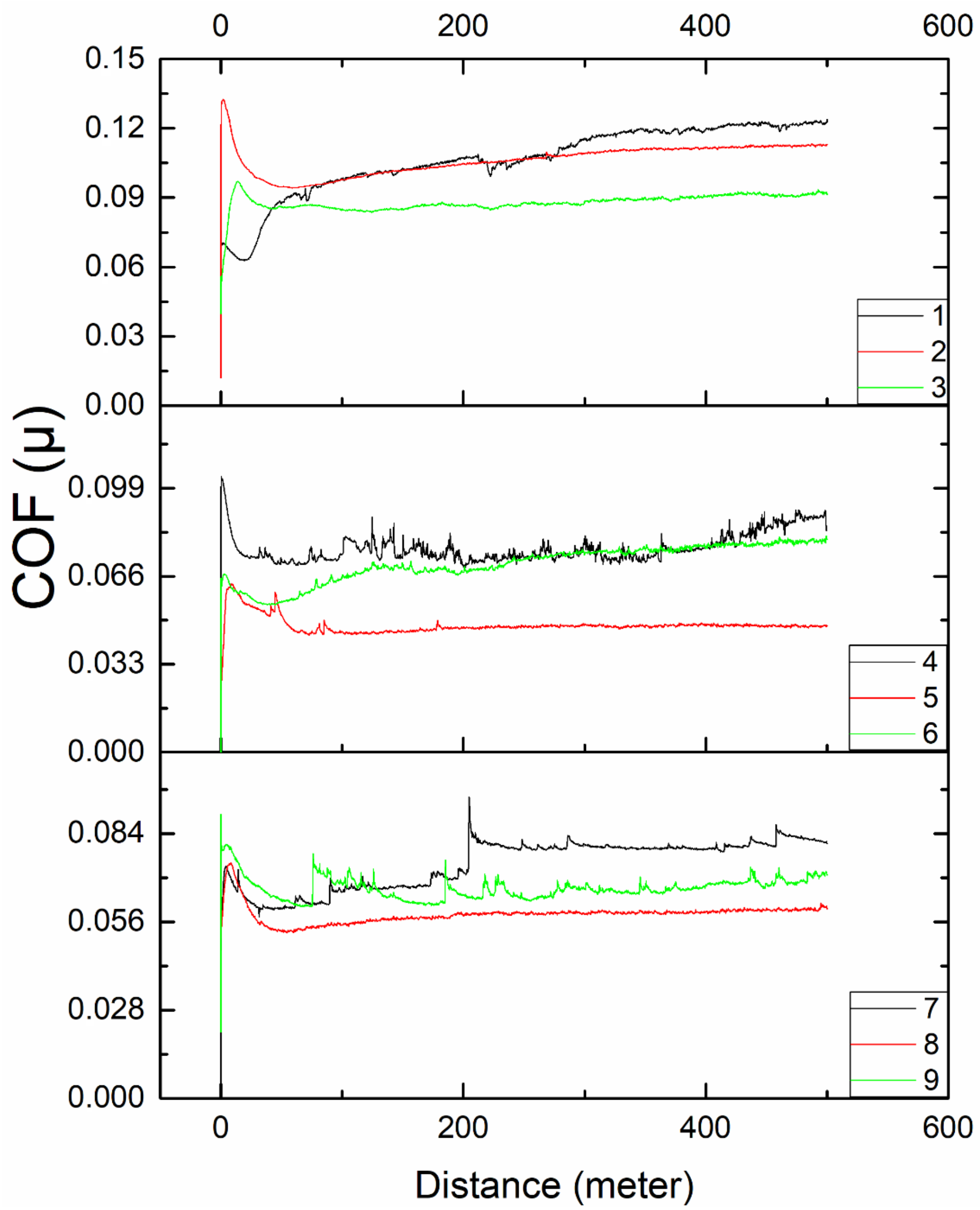

Figure 6. Mean COF variation based on the distance for the produced samples

Figure 7 shows the optical microstructure of the worn surfaces. It is seen that abrasive and adhesive wear are effective on the surfaces. Abrasive wear effects on the samples are seen as deep traces and voids. The signs of adhesive wear could be seen as fragments from the surfaces due to the increased temperature based on friction. When the surface of sample 1 with the highest wear rate is examined, it is seen that both abrasive and adhesive wear signs are evident on the surface. Semi-molten particles appear on the surface. These particles are on the surface and have low bonding strength due to the low molding pressure and temperature. Fragmented particles could also be seen in all 150 Bar molding pressure samples (1, 2, and 3). The particles ruptured from the contact zone repetitively over time and fluctuated the friction behavior. A similar situation was observed at all low-temperature and pressure molded samples (Samples 4 and 7). It is observed that the abrasive effects are reduced in molding performed at 150°C temperature. Semi-molten particles are eliminated due to the high fusion in the microstructure. The wear effects are reduced. Therefore, the highest wear resistance was observed in samples 5 and 8, respectively. Although the increase in the molding temperature provided good bonding of the structure, it caused softening due to crystallinity and weakened the microstructure against abrasive wear (Samples 6 and 9).

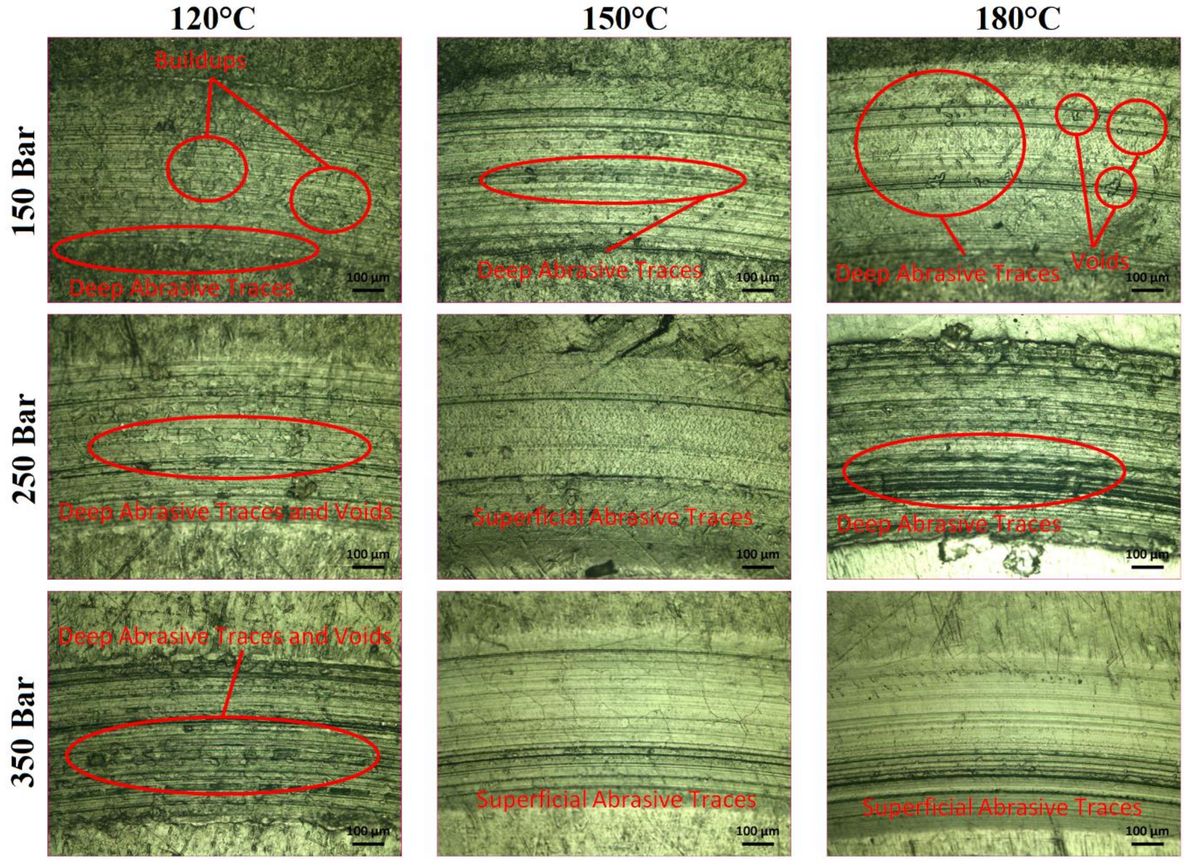

Figure 7. Optical microstructure images of the worn surfaces of the samples

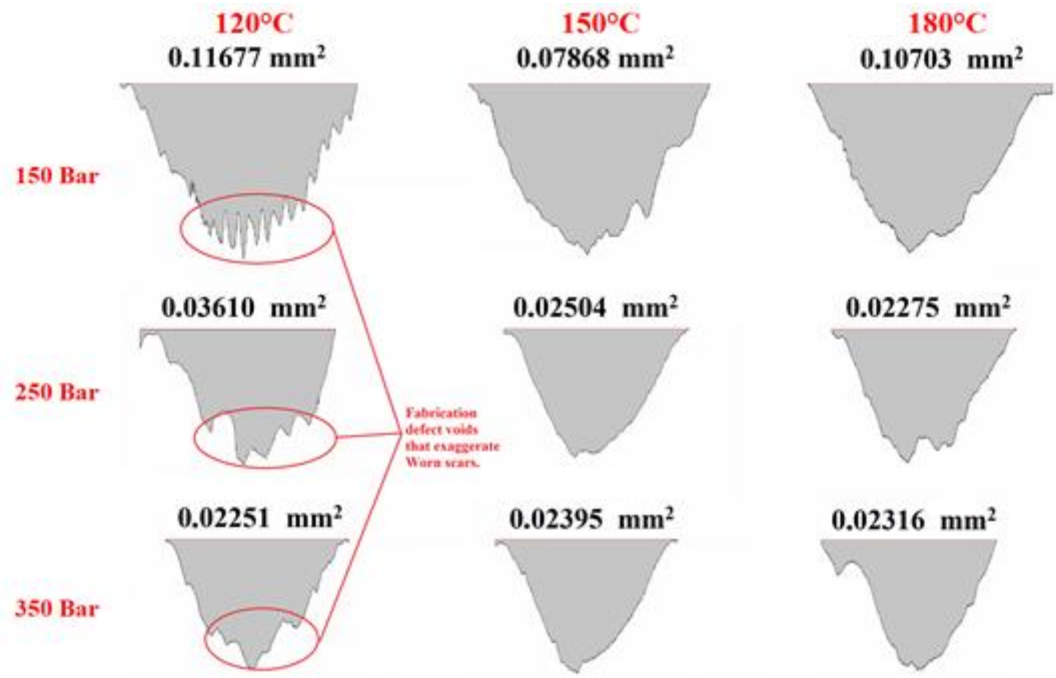

Figure 8. Highest measured cross-sectional surface profile of the worn surfaces of the samples

Figure 8 shows the cross-sections of the worn surfaces. There are deep pits in the bottom of the worn channels of samples 1, 4, and 7. These pits are the cavities formed in the microstructure due to low molding pressure and temperature. Together with the formed worn channel, these voids merged and affected the wear resistance adversely. With increasing molding pressure and temperature, the voids decreased as the internal microstructure of the material was completely joined (Samples 5, 6, and 8, 9). Samples 5 and 8 have the lowest worn area. One can infer that these samples have optimum molding pressure and temperature combinations and exhibit the highest wear resistance.

4. CONCLUSION

In this study, UHMWPE polymeric bearing material was produced by compression molding technique at different molding pressures and temperatures. Factors affecting molding technique were examined based on microstructure, mechanical and tribological properties. The obtained findings in the experimental studies are summarized below.

- It was determined that microstructural bonds were not sufficient at low molding temperatures.
- The samples produced at molding temperatures of 150°C and above exhibit better microstructural properties such as good bonding and elimination of voids.
- It has been determined that the molding temperature is more effective than the molding pressure in material properties. More ductile structures were obtained due to the increase in crystallinity in the molding process at 180°C.
- Increasing molding pressure and temperature improves the powder consolidation, so the hardness and wear resistance increase.
- Considering the results found, 250 Bar and 150°C were considered as the optimum molding pressure and temperature that can be used for polymeric bearing production. The machine parts produced from the samples with this combination would provide superior wear resistance.

5. CONFLICT OF INTEREST

Author approves that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

6. AUTHOR CONTRIBUTION

Esad Kaya determined the concept and design process of the research and research management, data collection and analysis, data analysis and interpretation of results.

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