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INVESTIGATION OF THE MACHINABILITY OF PEEK, PP AND PTFE HIGH PERFORMANCE ENGINEERING THERMOPLASTICS FOLLOWING HEAT TREATMENT

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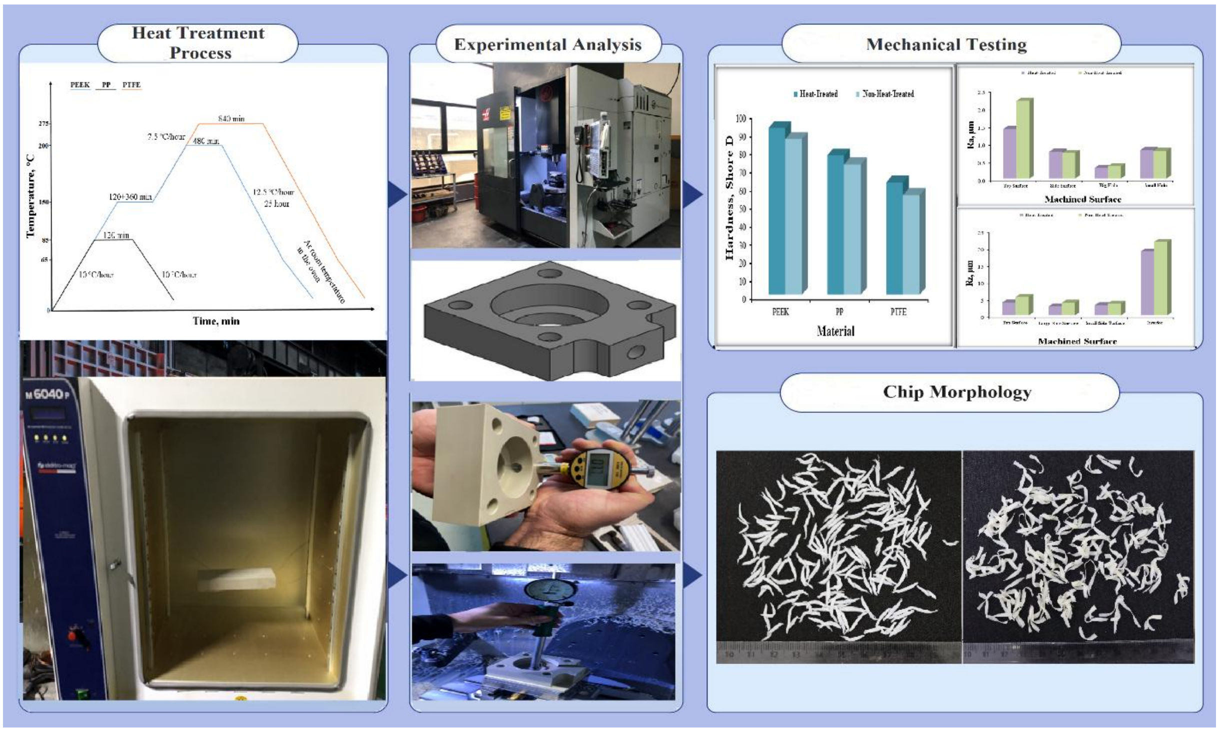
Highlights

- Dimensional accuracy is achieved after heat treatment on PEEK, PP and PTFE plastic materials.
- The surface roughness values of the surfaces processed by machining after heat treatment decreased.
- Heat treatment caused notable changes in chip morphology improving machinability.

Graphical Abstract



Schematic view of experimental studies

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ABSTRACT: This study investigates the machinability of heat-treated engineering thermoplastics, focusing on Polyetheretherketone (PEEK), Polypropylene (PP), and PolyTetraFluoroEthylene (PTFE), widely used in industry. The materials were annealed at various temperatures, holding times, and cooling rates in an industrial furnace. Heat-treated and non-heat-treated specimens were compared for dimensional accuracy and hardness. Machining, including both milling and drilling operations, was performed on a 5-axis HAAS UMC 750 CNC machine using different cutting tools and machining parameters. Results showed that heat treatment improved dimensional accuracy, especially in PEEK and PTFE, and increased hardness by 7%, 6%, and 11% for PEEK, PP, and PTFE, respectively. Surface roughness decreased, enhancing the surface quality of machined parts. Significant changes in chip morphology, including thickness, color, and length, were observed in heat-treated specimens. These findings demonstrate the beneficial effects of heat treatment on the machinability and mechanical properties of thermoplastics, offering valuable insights for industrial applications.

Keywords: *Polyethereterketone, Polypropylene, Polytetrafluoroethylene, Heat Treatment, Machinability*

1. INTRODUCTION

Engineering thermoplastics, which play a critical role in advanced technology fields, are frequently preferred in industrial and academic areas due to their numerous properties that distinguish them from other engineering materials. These properties include high flexural strength, energy absorption, corrosion resistance, thermal insulation, vibration damping, ease of machining, and more [1], [2]. In recent years, the rapid advancement of technology necessitates that engineering materials have the potential to withstand increasingly challenging working conditions. Plastics, due to their significant combination of properties, have a much broader range of considerations in designs compared to all other design materials. Understanding plastic materials and processing methods in engineering science, and comprehending performance differences, will aid in improving product designs. The performance characteristics of plastic materials can be defined in many different ways. Some of these performance attributes include lightness, high strength, resistance to degradation in various environments, compatibility with mass production methods, a wide range of colors and appearances, heat and ablative resistance, machinability, and cost. Consequently, they are widely used in applications such as gears, cams, bearings, bushings, valve seats, and more [3] - [5]. In recent years, growing environmental awareness has significantly increased interest in products and production methods that minimize pollution and long-term ecological impact. Among the various applications of engineering plastics that contribute to the reduction of carbon emissions, electric vehicles stand out prominently. Environmentally friendly engineering plastics have garnered considerable attention due to their alignment with sustainability goals. For effective utilization, it is imperative to assess machining characteristics such as surface treatment, channel creation, and hole milling [6].

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Plastic materials are produced with different polymeric compositions and physical structures, offering various properties at the macro, micro, nano, and molecular levels. Consequently, materials manufactured through different production techniques exhibit distinct behaviors under external loads during usage conditions, leading to phenomena such as fracture, elongation, bending, tearing, breaking, or disintegration depending on the magnitude of the load. The mechanical property of a material is known as the response it shows against applied loads [6], [7]. Improving the mechanical properties of a material, enhancing its hardness and impact resistance, improving machinability, developing electrical and magnetic properties, and positively altering grain structure are the fundamental objectives of heat treatment applications [8]. These processes result in alterations to the atomic arrangement within the material's internal structure or modifications to its existing configuration. Consequently, the material acquires enhanced strength and hardness properties, rendering it suitable for its intended applications.
The heat treatment applied to restore the material's previous structure is called "annealing" [9]. Yan et al. [10] examined the machinability of thermoplastic polymers (PMMA, PEEK, and PI) in high-speed micromilling. The study revealed that machining temperature affects material removal, with brittle removal providing better surface quality than viscoelastic removal. Additionally, they reported that lower feed rates increase burr formation and that cutting chips vary with temperature and machining parameters. Butt and Bhaskar have studied the hardness values of different polymer materials after heat treatment. It was observed that the hardness of all materials increased with heat treatment, but each material was affected differently. The hardness increase was attributed to the reduction of internal stresses, and it was noted that harder materials are generally more brittle, with surface roughness having a significant impact on hardness [11]. Gnatowski et al. [12] investigated the effects of heat treatment on the machining of polymer materials for gear wheels. They found that the annealing process improved the hardness and brittleness properties of PVDA Tecaflon, enabling higher feed rates without surface degradation. Due to their recyclability and superior performance characteristics, thermoplastics are considered potential candidates to replace traditional materials. For instance, Polyetheretherketone (PEEK), a significant thermoplastic, is used as a matrix system in carbon fiber composites for aerospace applications. Significant studies are being conducted to enhance the mechanical properties of thermoplastics used in such critical applications. Thermoplastics typically possess a semi-crystalline material structure. This characteristic indicates that the morphology of thermoplastics can be altered by annealing near their melting temperatures. If thermoplastics are to have widespread application among engineering components, it is crucial to improve their mechanical properties, eliminate low material performance through stress-relieving processes, enhance the overall quality of the product, and increase the material's lifespan to ensure environmental sustainability [13]. Heat treatment induces changes in the physical and chemical properties of polymers, significantly affecting their machinability. Processes such as cross-linking and hardening enhance the hardness of polymers, yet simultaneously increase machining challenges due to elevated wear and cutting forces. Additionally, crystallization processes contribute to increased hardness, further complicating the machining of polymers. Thermoplastic polymers become softened and more manageable for processing under heat treatment conditions, whereas thermoset polymers undergo hardening, thereby reducing their machinability. Furthermore, heat treatment can lower polymer viscosity, rendering the material more fluid, which facilitates efficient material removal [14], [15]. Annealing heat treatment, which facilitates machinability and alters material properties, achieves this by increasing the sustainability of plastic deformation under tensile stress before fracture. With the rapid development of industry in recent years, plastic materials have become widely used across all sectors. Their usage has increased in fields such as medical, optical, electronics, and precision machinery due to the advantages provided by their superior properties. Plastic parts used in such precision-demanding areas should be manufactured using machining methods instead of molding processes [16]. Wang et al. [17] demonstrated in their research that heat treatment enhances the crystallization, surface roughness, and hardness of polymer composites. Similarly, Coban et al. [18] investigated the impact of heat treatment on PEEK materials, concluding that the process significantly increases the scratch hardness of PEEK nanocomposites. Today, due to the diverse applications of

engineering plastics, secondary processes such as turning, milling, and drilling are also required [14]. In applications where plastic materials are designed to withstand mechanical loads, the mechanical properties of polymers are crucial. The Polyetheretherketone (PEEK) polymer is used in many industrial areas today due to its strength properties, thermal properties, resistance to chemicals, wear resistance, electrical properties, resistance to radiation, and other attributes [16]. In many literature studies, it is seen that the usage areas of PEEK material are increasing and its use is becoming widespread, especially in dental areas as well [19], [20]. Polypropylene (PP) is a semi-crystalline thermoplastic that is resistant to chemicals and heat, has low density, is easily weldable, has low moisture absorption, high tensile strength, and electrical insulation properties. PP also possesses significant dimensional stability and is an easily processable material. However, its flammability, difficulty in painting, degradation under UV light, and high thermal expansion coefficient are considered disadvantages of PP material. Due to its low density and ease of processing, PP material is used in many applications [21]. Polytetrafluoroethylene (PTFE), although a polymeric material, has a high melting point, high viscosity, and high thermal stability. It exhibits high insulation properties as it is resistant to electric current. It is a material highly resistant to chemicals. Despite PTFE’s significant properties, special techniques must be applied to enhance its machinability to achieve high performance from the final product [22].

A wide variety of solid materials can be shaped by machining. Engineering plastics can also be processed by machining. Regular geometries such as flat and circular surfaces can be created by machining. Almost all complex geometries can be obtained by applying several machining operations in sequence. With machining, workpiece dimensions can be obtained with very close tolerances and very good surface quality can be achieved. The reshapeability of thermoplastics makes them ideal for machining, which requires multiple passes and adjustments. Within the framework of the general principles and purposes of engineering plastics, improving the properties of plastics by heat treatment and machining processes in order to improve their useful properties is one of the goals of today's material technology. The chemical composition and crystal structure of engineers' plastics greatly affect the properties of the material. However, many properties such as dimensional stability can be changed by heat treatment. The properties of plastics are improved by heat treatment by eliminating the internal stresses resulting from the production process. If these stresses are not relieved, the stress can intensify and cause the plastic to crack; plastic may bend or deform under load or over time, or stressed plastic may have lower mechanical strength, chemical resistance, or dimensional stability. Heat treatment aims to reduce the stresses that occur in the early stages of machining. It can also increase machinability, as heat treatment can make it easier to cut, drill, or tap plastic without cracking or breaking. Heat treatment can offset additional stresses resulting from machining; for example, improper speeds and feed rates that generate excessive heat [12], [23] - [26]. For the reasons mentioned above, this study addresses the machinability of engineering plastics with heat treatment processes. The heat treatment process of engineering plastics can facilitate the machining of certain plastics by reducing internal stresses that may cause them to crack or break during cutting operations. Although there are studies on machinability in the literature, the number of studies that include the heat treatment process is insufficient, and this study attempts to fill the existing gap in the literature. Engineering plastics represent one of the fastest-growing product categories globally, with continuous advancements enhancing their performance, expanding their applications, and providing innovative solutions to various challenges. Understanding the machinability of these materials, commonly employed as machine components in industrial settings, is essential. During the machining of engineering plastics, it is critical to select cutting speeds and feed rates appropriate for the material type. Measures must also be taken to mitigate stresses and distortions resulting from the high heat generated during cutting processes. Where feasible, stress relief should be applied, as failure to do so may lead to cracking or breakage of the parts over time. Furthermore, the disadvantages associated with machining plastics must be carefully considered to ensure the preservation of material quality and its inherent properties during production [27]. Although heat treatment applications, which particularly enhance mechanical properties, increase costs, they have become a necessity before machining.

Although several studies in the literature have examined the machinability of engineering plastics, this study offers a more comprehensive evaluation by specifically focusing on the effects of heat treatment on the machinability of PEEK, PP, and PTFE. This study is novel in that it systematically investigates the effects of heat treatment on the machinability of PEEK, PP, and PTFE by comparing dimensional accuracy, hardness, surface roughness, and chip morphology after both milling and drilling operations an approach not comprehensively addressed in previous literature. Unlike earlier works, it applies material-specific heat treatment operation and evaluates the results using precise CNC machining and characterization methods, offering new insights into optimizing thermoplastic machining performance. The findings were subsequently evaluated through comparison with results reported in the existing literature.

2. MATERIALS AND METHODS

2.1. Engineering Plastic Materials Used in the Study

This study utilized engineering plastics identified as Polyetheretherketone (PEEK), Polypropylene (PP), and Polytetrafluoroethylene (PTFE). The dimensions of the X (length), Y (width), and Z (thickness) axes for these materials are detailed in Table 1. Additionally, Table 2 outlines the mechanical properties of the engineering plastics used in the experiments.

Table 1. Dimensions of engineering plastics used in experiments (mm)

Plastic Type	X	Y	Z
PEEK	230	70	30
PP	135	115	50
PTFE	190	27	20

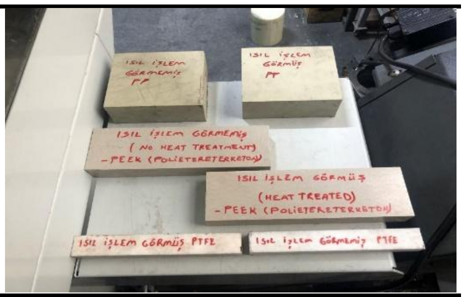

Table 2. Mechanical and thermal properties of engineering plastics used in experiments [28] - [30]

Properties	PEEK	PP	PTFE
Hardness, (Shore D)	86	72	55
Tensile Strength, (MPa)	65.0	29.41	17.16
Specific Weight, (gr/cm^3)	1.32	0.92	2.10
Elongation, (%)	11	50	220
Modulus of Elasticity, (GPa)	7.58	1.25	3.60
Melting point, (°C)	341	160	325
Glass Transition Temperature Tg, (°C)	150	-20	120-130
Specific Heat, J/(g·K)	0.24	1.92	1

2.2. Heat Treatments Applied to Plastic Materials

In this study, the PEEK, PP, and PTFE test specimens were subjected to heat treatment in an Elektro-MAG brand dry air sterilizer oven with a digitally controlled electric thermometer, ranging from 5 °C to 300 °C. The PEEK, PP, and PTFE materials were placed inside the air-circulating oven in a manner that allowed air to circulate around them.

In the experiments with PEEK material, the oven was heated up to 150 °C at a maximum heating rate of 7.5 °C per hour. The oven temperature was maintained at 150 °C for 120 minutes, with an additional 30 minutes for every 3 mm of thickness [28]. Since the thickness of the PEEK material used in the experiments was 30 mm, it was kept in the oven at 150 °C for an additional 360 minutes, totally 480 minutes. The oven was then heated to 200 °C at the same maximum heating rate of 7.5 °C per hour. Similarly, the oven temperature was maintained at 200 °C for 120 minutes, with an additional 30 minutes for every 3 mm of thickness, totally 480 minutes at 200 °C. The oven was then cooled to 65 °C at a maximum cooling rate of 12.5 °C per hour over more than 25 hours. Before removing the test specimen, the oven was turned off at 65 °C and left to cool to room temperature.

In the experiments with PP material, the oven temperature was increased at a rate of 10 °C per hour until reaching 85 °C. The test specimen was then held at 85 °C for 2 hours for each 25 mm of thickness. After this cycle was completed, the oven was brought down to room temperature at a rate of 10 °C per hour. Once the oven reached room temperature, the material was removed from the oven.

In the experiments with PEEK material, the oven was heated to 150 °C at a maximum heating rate of 7.5 °C per hour. The oven temperature was maintained at 150 °C for 120 minutes, with an additional 60 minutes for every 3 mm of thickness. Since the thickness of the PTFE material used in the experiments was 20 mm, it was kept in the oven at 150 °C for an additional 360 minutes, totally 480 minutes. The oven was then heated to 275 °C at the same maximum heating rate of 7.5 °C per hour. The oven temperature was maintained at 275 °C for 240 minutes, with an additional 60 minutes for every 3 mm of thickness, totally 840 minutes at 275 °C. The oven was then cooled to 65 °C at a maximum cooling rate of 12.5 °C per hour over more than 25 hours. Before removing the test specimen, the oven was turned off at 65 °C and left to cool to room temperature. The heat treatment parameters (temperature, hold times, and the rates of temperature increase and decrease) have been selected according to the Plastics International guidelines. Figure 1 graphically shows the heat treatment processes of PEEK, PP, and PTFE engineering plastic materials in terms of temperature and time.

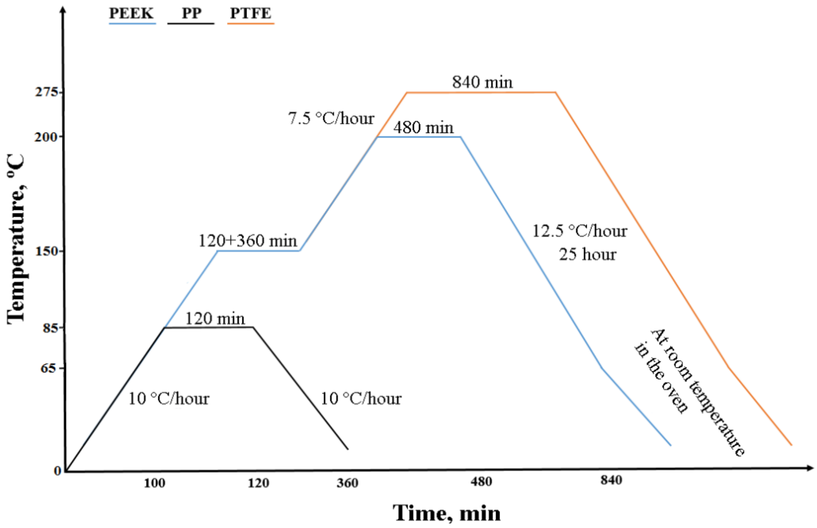

Figure 1. Heat treatment processes applied to PEEK, PP and PTFE engineering plastics

2.3. Machining

The PEEK, PP, and PTFE plastics were classified into two groups: heat-treated and non-heat-treated, and machinability tests were then conducted. The milling mechanism was substantially affected by the physical and mechanical properties of the polymers. Different cutting set-up conditions were able to optimize the responses. For this purpose, CAM programs were created using Autodesk Fusion 360 CAD/CAM software, incorporating the specified machining parameters (cutting speed, cutting depth, and feed rate) along with the appropriate cutting tools. The machining parameters (cutting speed, feed per tooth, spindle speed, and feed rate) were selected based on Walter Tools' recommendations, using the official Walter Feeds & Speeds database and Machining Calculator tailored for thermoplastics such as

PEEK, PTFE, and PP. Cutting speeds 110 m/min and feed per tooth values of 0.04 mm were taken as reference. Prior to testing, preliminary trials were performed to verify surface roughness, chip formation, and dimensional accuracy. The test specimens from both groups were machined on a HAAS UMC 750 5-axis CNC milling machine. The experimental studies were carried out using cutting tools from Walter. The cutting tools used in the experiments were selected according to the appropriate operation, and the spindle speed and feed rates were calculated based on Walter's catalog data [31]. The cutting tools used in this study consisted of four types of two-flute solid carbide end mills (Ø16 mm, Ø12 mm, Ø10 mm, Ø8 mm), a Ø8 mm reamer, Ø6.8 mm and Ø8 mm HSS drills, an M8 hand tap for internal threading, a Ø6 mm chamfering tool, and a center drill. Additionally, Haimer tool holders were used in the experimental study. Taps, centers, chamfer cutters, and HSS drills were mounted on collet holders with ER collets conforming to ISO 15488 standard [32]. Since high precision and close tolerances similar to micromachining are required, the milling cutters were rigidly mounted in Haimer Shrink Fit holders using the Haimer Shrink Fit device to achieve high performance. A coolant mixture of 95% water and 5% boron oil was used in the experiments. Table 3 presents the machining parameters used in the machinability tests. Autodesk's computer-aided engineering software, Fusion 360, was used to control the machine tool during the manufacture of the experimental samples. To minimize mechanical deformation while machining the other faces of the workpieces, the parts were bolted to the designed fixture. The appearance of the experimental setup for the machining of parts is given in Figure 2. Schematic view of the experimental setup shows in Figure 3.

Table 3. Machining parameters used in machinability experiments

Material	Cutting Parameters		
	Cutting Speed, m/min	**Cutting Depth, mm**	**Feed Rate, mm/rev**
PEEK	201	0.1	0.091
	283		
	301		
	402		
PP	151	0.1	0.091
	553		
PTFE	219	0.1	0.091
	301		
	553		

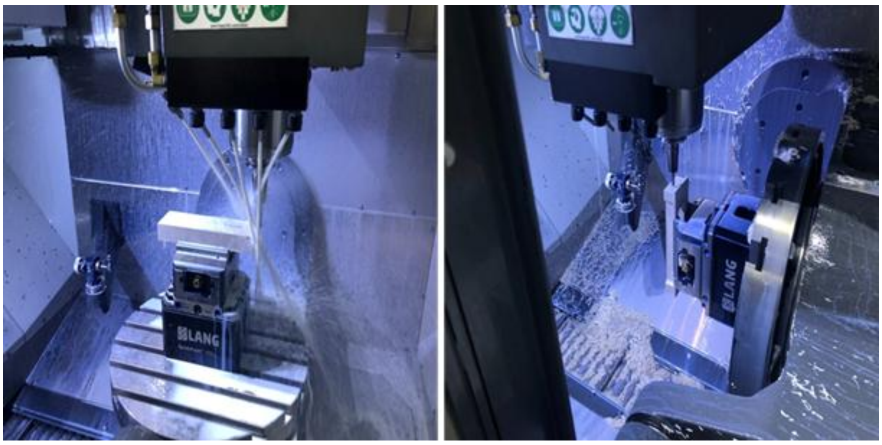

Figure 2. Experimental setup for machining operations

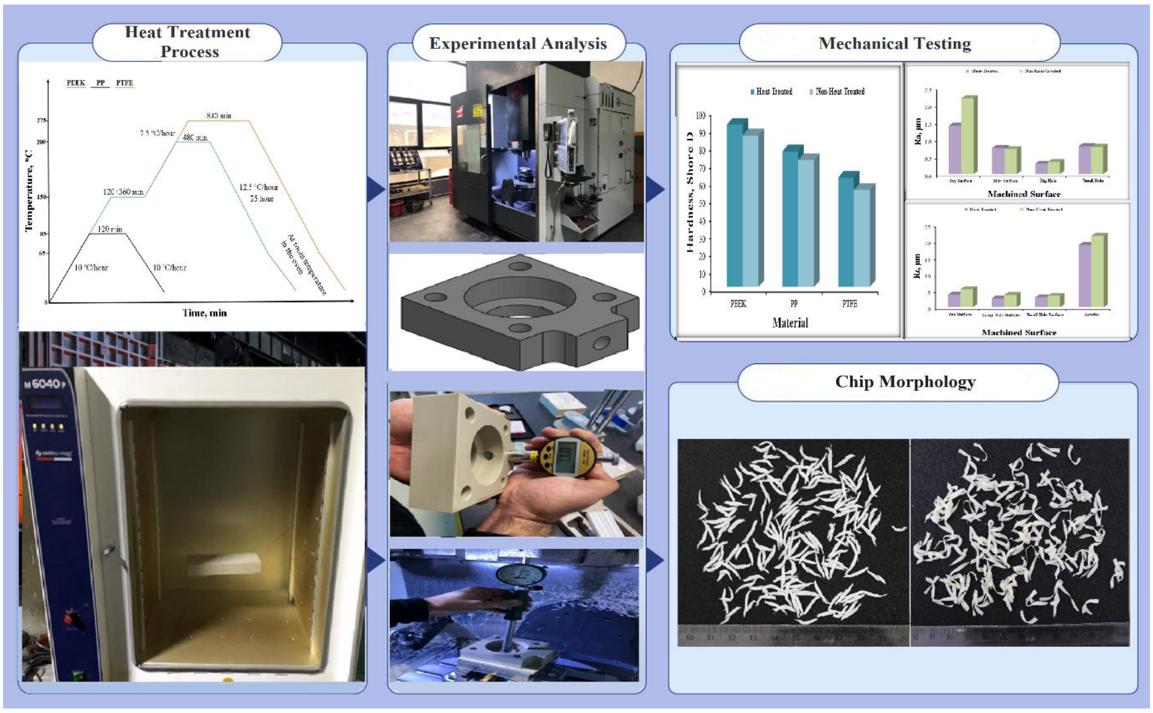

Figure 3. Schematic view of experimental studies

2.4. Characterization Study

Producing the workpiece with the desired quality and required dimensions after machining is crucial to prevent raw material waste. The necessity to improve machining performance and optimize cutting conditions arises during machining processes. To achieve this, factors affecting machinability and those influencing the quality and dimensional accuracy of the workpiece are being investigated by scientists [33], [34]. However, machined samples are prone to deformation due to the nature of their mechanical properties. Shrinkage or expansion may occur in any of the three axes (X, Y, Z) of the machined samples, whether they are heat-treated or non-heat-treated. Therefore, comparing the dimensions of the samples is particularly important in areas where precision is required. Dimensional analysis measurements were performed using a Mitutoyo brand bore gauge, micrometer, and caliper. Additionally, hardness tests of the samples used in the experiments were conducted using a Shore D hardness tester according to ASTM D2240 standard [35]. In hardness measurement, the Loyka Shore D Digital Shoremeter DJ01D with a measurement precision of 0.5 HD was used. For each experimental parameter, five measurements were taken for both dimensional analysis and hardness tests, and the averages were calculated.

The surface roughness measurements were carried out using a Mahr MarSurf m400 brand surface roughness measurement device (precision: 0.3 µm / 140 mm) to determine the quality of the machined surfaces obtained. For each experimental parameter, surface roughness measurements were taken from five different points, and the averages were calculated. Surface roughness is a measure of surface texture and is measured by the vertical deviation of the surface. The arithmetic mean of profile deviations (Ra) and the average roughness height (Rz) values of the workpiece surfaces and the drilled holes were measured. To gain more detailed information about the machinability capability, the chip forms obtained from different machining parameters were also examined. The forms of the chips obtained after machining, both heat-treated and non-heat-treated, were photographed using a Canon EOS 1300D model 18-55MM DC-III camera.

3. RESULTS AND DISCUSSION

Although engineering plastics exhibit superior performance properties, their machining presents significant challenges due to their inherent structure and associated issues. Common difficulties during processing include surface damage from deformation, surface cracks, dimensional inaccuracies in the workpiece, and the low thermal conductivity of these materials, which causes rapid increases in cutting tool temperature. Furthermore, rapid tool wear often occurs due to the abrasive and hard reinforcement elements within the material. Consequently, the selection of appropriate cutting parameters is critical in the machining of engineering plastics. The literature indicates a predominant focus on milling processes, reflecting their relevance to the practical application of these materials. Research has also concentrated on aspects such as the effects of cutting parameters on surface quality and chip morphology. Milling is widely utilized as a finishing process to remove burrs, ensure dimensional accuracy, and achieve high surface quality, as it enables the production of polymer-based engineering plastics close to their net shape [6], [36]. In the machinability experiments, both heat-treated and non-heat-treated variants of PEEK, PP, and PTFE polymers were machined. Figures 4 (a), (b), and (c) illustrate the model representations of PEEK, PP, and PTFE polymers from various perspectives, which are intended for use in the subsequent post-machining tests. Polyetheretherketone (PEEK) is tailored for applications demanding high durability and performance, whereas the lightweight and flexible nature of Polypropylene (PP) necessitates simpler geometric designs. Conversely, Polytetrafluoroethylene's (PTFE) non-stick properties influence the development of geometries aimed at minimizing surface contact. Accordingly, distinct geometries have been selected for this study. In the model drawings shown in Figure 4 (a), (b), and (c), the X-axis represents length, the Y-axis denotes width, and the Z-axis indicates thickness.

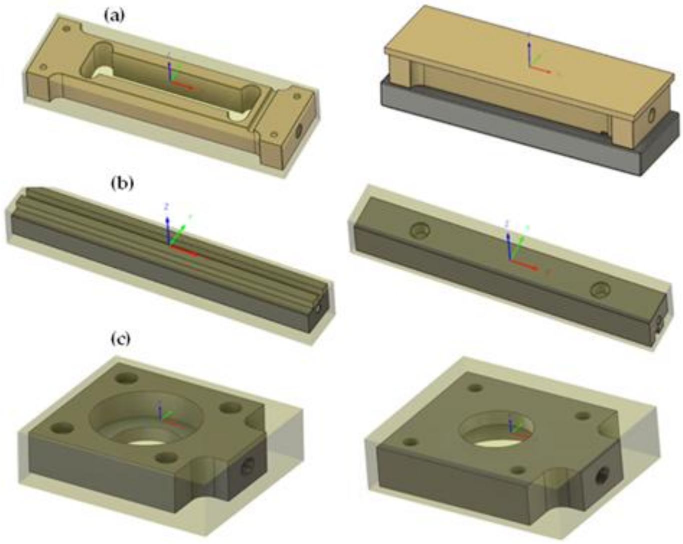

Figure 4. Model drawings of (a) PEEK, (b) PP and (c) PTFE experimental specimens

3.1. Dimensional Measurements

Although polymeric materials can be produced in near-net shapes, their dimensional accuracy must still be ensured by machining to assemble the final products. Due to the high ductility and low melting point of engineering plastics, the selection of tool and cutting conditions is very important for the dimensional tolerance of plastics [24]. The dimensional tolerances specified in the technical drawings were determined in accordance with the general tolerance guidelines outlined in ISO 2768 [37]. This standard was used to define the acceptable deviations for linear and angular dimensions, ensuring the required precision during the manufacturing process.

The engineering plastics PEEK, PP, and PTFE used in dimensional measurement after machining were examined under two categories: heat-treated and non-heat-treated. Dimensional measurements were taken from five different points on the sample, and the average of the obtained values was provided. Table 4 presents the dimensional analysis results of the PEEK, PP, and PTFE experimental samples after machining. The values given after the (±) symbols in the table represent standard deviation values.

Table 4. Dimensional analysis results of PEEK, PP and PTFE experimental samples after machining

Type of Operation	Type of Material	Axis, mm		
		X (length)	Y (width)	Z (thickness)
Non-Heat-Treated	PEEK	225.30 ±0.1	65.10 ±0.05	25.07 ±0.05
	PP	124.78 ±0.05	105.18 ±0.03	38.21±0.02
	PTFE	185.10 ±0.07	22.08 ±0.05	14.90 ±0.05
Heat-Treated	PEEK	224.92 ±0.1	64.98 ±0.05	24.97 ±0.05
	PP	124.85 ±0.05	105.11±0.03	38.12 ±0.02
	PTFE	185.03 ±0.07	22.02 ±0.05	14.94 ±0.05

When examining the dimensional values of the PEEK samples provided in Table 4, the tolerance value for the X length in the design was given as 225±0.1 mm, and the heat-treated PEEK material remained within this value after machining. A deviation of 0.2 mm from the tolerance value was detected in the non-heat-treated PEEK material. Considering the dimensional analyses of the PP samples in Table 4, the desired X length was 124±0.05 mm. The heat-treated PP material was measured as 124.85 mm with a digital micrometer after machining. The non-heat-treated PP material was measured as 124.78 mm in the X length. Regarding the dimensional analyses of the PTFE samples given in Table 4, the desired X length was 185±0.07 mm. The heat-treated PTFE material was measured as 185.03 mm with a digital micrometer after machining, while the non-heat-treated PTFE material was measured as 185.10 mm in the X length [36], [38]. The dimensional tolerances used in the design are generally determined based on functional requirements, the precision of the manufacturing process, and material properties.

Based on the results obtained from the dimensional measurements, the measurement results of the heat-treated PEEK material were found to be closer to the desired tolerance values compared to the non-heat-treated PEEK material. Improvements were also observed in the PTFE material. However, when examining the dimensional analysis results of the PP material shown in Table 4 (non-heat-treated and heat-treated: 124.78-124.85 mm, 105.18-105.11 mm, and 38.21-38.12 mm), no significant change was observed before and after heat treatment. Accordingly, it can be concluded that the effect of heat treatment on the material is limited [38], [39]. When analyzing indirect function measurement, measurements outside the tolerance deviation area are generally not considered errors.

3.2. Hardness Tests

Hardness is one of the most characteristic properties of materials, and it plays a crucial role in the advancement of science, especially as the production of increasingly complex materials becomes possible. It is particularly important in materials that have been hardened through machining and in certain polymers [40]. In material science, hardness is the measure of resistance to localized plastic deformation initiated by abrasion. Generally, hardness and strength are directly related to machinability [41]. Hardness measurements were taken from five different points on the sample, and the average of the obtained hardness values was calculated. The comparison of hardness values according to the heat treatment condition and the engineering material subjected to the process is also shown in Figure 5.

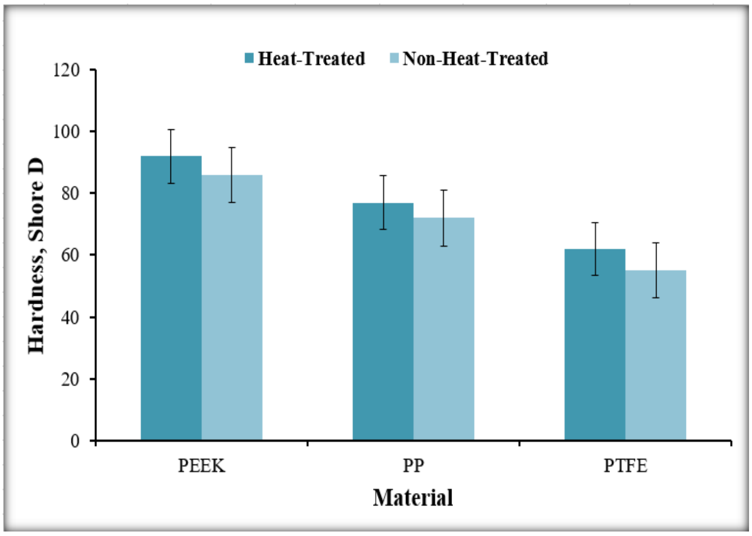

Figure 5. Comparison of hardness results

When examining the results presented in Figure 5, the effect of heat treatment on the mechanical properties of various materials is evident. For the PEEK material, an annealing process was performed by gradually increasing the temperature to 200 °C. The Shore D hardness value of the non-heat-treated and machined PEEK material was measured at 86, while the Shore D hardness value of the heat-treated PEEK material was measured at 92. It was observed that the hardness of the PEEK samples increased by 7% as a result of the heat treatment. The increase in hardness values of PEEK materials as a result of heat treatment has been confirmed by similar results obtained by many researchers such as [42], [43]. The PP material used in the experiments was annealed at 85 °C. The Shore D hardness value of the non-heat-treated PP material was measured at 72, while the Shore D hardness value of the heat-treated material was measured at 77. It was found that the hardness of the PP sample increased by 6% as a result of the heat treatment. The increase in hardness values of PP materials as a result of heat treatment has been confirmed by similar results obtained from literature [17], [44]. For the PTFE material, an annealing process was performed at 275 °C. The Shore D hardness test measured the hardness value at 55 for the non-heat-treated PTFE material, while the heat-treated PTFE material was measured at 62. It was observed that the hardness of the PTFE samples increased by 11% as a result of the heat treatment, indicating that the hardness value was most affected by heat treatment among the materials used in the study. This is explained in the literature by the fact that the temperature and holding time applied to PTFE materials are longer than those for other materials. The use of coolant in PTFE processing is essential for both thermal management and preservation of the raw material properties. Proper and sufficient heat removal helps prevent PTFE from becoming thermally sensitive, which reduces its anisotropic properties and leads to dimensional and functional defects. It can withstand a wide temperature range from -200°C to +260°C. This property is important for high-temperature equipment and processes [11], [43] - [45].

3.3. Surface Roughness Measurements

In all engineering processes, determining surface quality is crucial for the applications of the produced parts. The surface quality of parts obtained after machining is determined by measuring surface roughness values. There are many factors that affect surface roughness, including the structure of the material, the type of cutting tool, cutting parameters and conditions, and the secondary operations the part undergoes [46], [47]. The aim of machining is not only to give the part the desired shape but also to produce it within the expected tolerance range in terms of dimensional and surface roughness [48]. For the long-term use of engineering materials, quality or surface integrity of the workpiece is essential. Surface roughness directly affects the characteristic properties of the part at its application site, such as friction, fatigue resistance, heat transfer, and lubrication. With the development of technology, in addition to dimensional accuracy, the formation and control of surface quality has also gained importance in modern chip removal methods. The aim of chip removal methods is to shape the part as well as to manufacture it within the tolerance limits desired in the manufacturing drawing in terms of geometry, dimension and surface roughness [49] - [51]. In this study, surface roughness was evaluated based on the type of operation and the different surfaces machined. Table 5 presents the Ra and Rz surface roughness test results for PEEK, PP, and PTFE engineering plastic materials. Figure 6 shows the relationship between surface roughness, the type of operation, and the machined surfaces for all plastics.

Table 5. Surface roughness values of the processed surfaces according to the type of processing (μm)

	Type of Operation		Machined Surface			
			Top Surface	**Side Surface**	**Inner Surface**	**Edge Slot**
PEEK	Heat-Treated	Ra	0.814	0.438	0.544	0.574
		Rz	6.166	2.940	3.627	4.242
	Non-Heat-Treated	Ra	0.938	0.496	1.341	0.882
		Rz	8.108	3.565	8.207	6.262
	Type of Operation		**Top Surface**	**Side Surface**	**Big Hole**	**Small Hole**
PP	Heat-Treated	Ra	1.401	0.754	0.299	0.806
		Rz	8.207	4.758	2.574	6.125
	Non-Heat-Treated	Ra	2.190	0.721	0.346	0.783
		Rz	12.77	4.755	2.974	5.489
	Type of Operation		**Top Surface**	**Large Side Surface**	**Small Side Surface**	**Interior**
PTFE	Heat-Treated	Ra	0.461	0.475	0.516	2.311
		Rz	3.835	2.670	3.008	18.88
	Non-Heat-Treated	Ra	0.830	0.588	0.592	2.292
		Rz	5.469	3.736	3.517	21.64

When examining the results presented in Table 5 and Figure 6, it is observed that the reduction in internal stresses in the PEEK material after heat treatment resulted in an improvement in the Ra value of the top surface from 0.938 μm to 0.814 μm. The Ra value of the top surface of the non-heat-treated PP material was measured at 2.190 μm, while the heat-treated PP material was measured at 1.401 μm. The Ra value was measured at 0.830 μm for the non-heat-treated top surface PTFE material, and at 0.461 μm for the heat-treated PTFE material. The most significant reason for the PTFE material's closer tolerance values and better surface roughness compared to the PEEK material can be attributed to its X length. The effect of the length of the machined surfaces on the part can lead to problems such as high tool wear and dimensional errors. According to the top surface roughness values provided in Figure 5, the Ra values of the PEEK, PP, and PTFE materials improved by 15%, 56%, and 80%, respectively, after heat treatment. Similarly, the Rz values of the PEEK, PP, and PTFE materials improved by 31%, 56%, and 43%, respectively, after heat treatment. Surface roughness formation affects the characteristic features such as heat conduction, friction, fatigue resistance and lubrication properties of the material in increasing the quality of the product. The surface quality of the material is also increased by decreasing the workpiece surface roughness value. In general, after heat treatment, an improvement in surface quality was clearly observed on all machined surfaces of PEEK, PP and PTFE materials, except for the side surfaces and small holes of the PP material [14], [17], [39], [52].

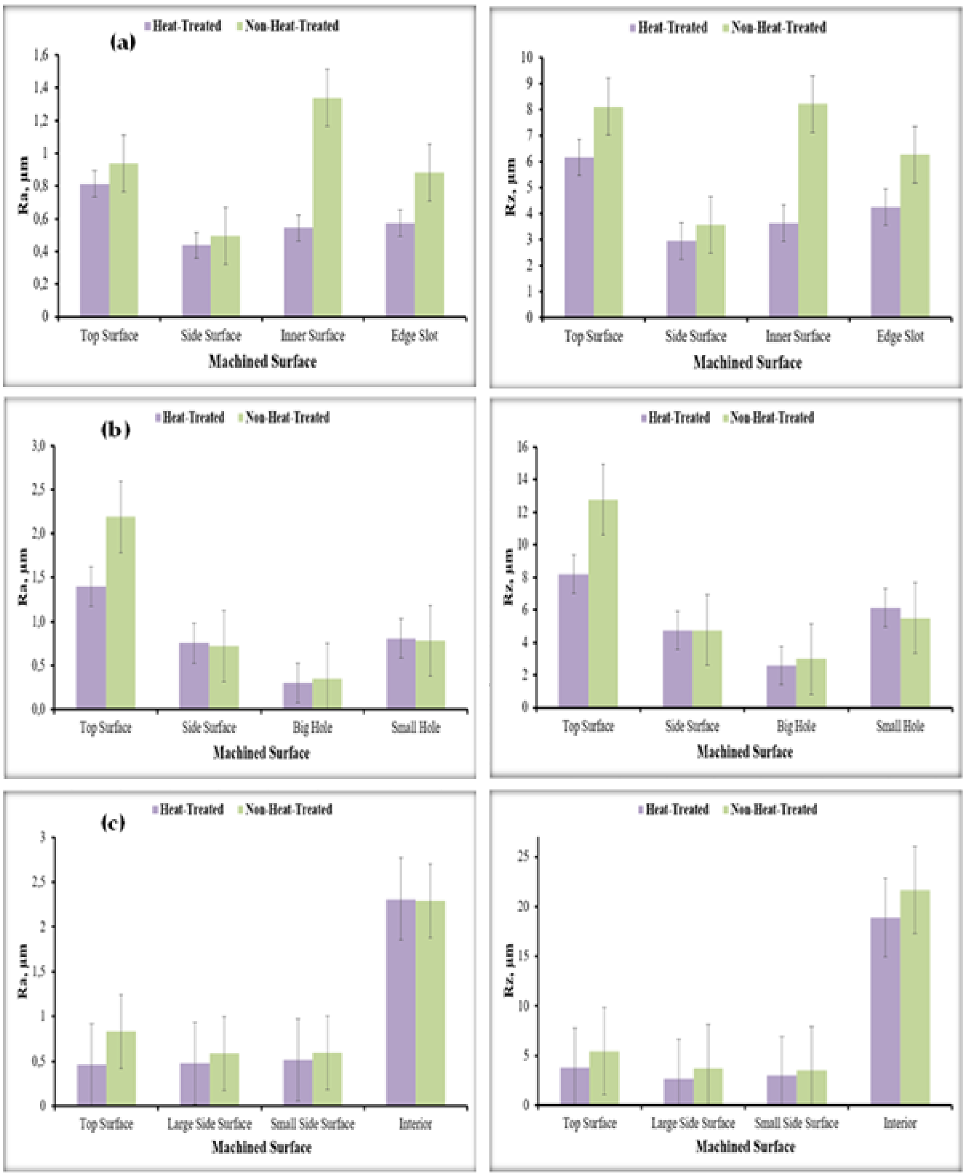

Figure 6. Comparison of surface roughness results: (a) PEEK, (b) PP and (c) PTFE

In the experimental study, the highest Ra and Rz values were measured at 2.19 µm and 12.77 µm, respectively, in the non-heat-treated PP material. Considering these values, the machinability of polymer materials intended to replace metals should also be evaluated within their categories. The parameters that were found to be effective on surface roughness as a result of the experiments include heat treatment, spindle speed, and cutting speed. Although the cutting depth and feed rate were kept constant throughout all experiments, changes in surface roughness were observed due to the changes in cutting speed and the differences in material properties caused by heat treatment. These differences can be explained primarily by the reduction of internal stresses in heat-treated samples and the improved thermal stability, which improves the cutting mechanism even under the same processing parameters. In addition, the surface roughness differences between materials and processing conditions indicate that the microstructural state of the material after heat treatment has a significant effect on machinability. It was determined that fixing the materials onto an additional part during the experiments reduced the risk of deformation of the materials during heat treatment [14], [17], [39], [52], [53]. A few researchers have investigated the relationship between surface roughness and its relevant factors such as thickness and cutting speed in machining polyethylene, polypropylene, and polycarbonate. Experimental studies have shown that as the cutting speed increases, the surface roughness value decreases [54]. Consequently, due to the effect of heat treatment on mechanical properties, improvements in surface roughness values were observed in all heat-treated experimental samples. Although the best surface roughness values were observed in the PP plastic material, significant improvements were also identified in the PEEK material.

3.4. Chip Forms

The chip forms produced from the machined surface after machining provide important information about machinability parameters such as vibration, surface roughness, built-up edge (BUE) formation, and cutting forces [55] - [57]. Chip formation affects the machining process in terms of cutting forces, temperature, tool life, and workpiece surface quality. Additionally, the shape and morphology of the chips influence the thermo-mechanical behavior of the workpiece. For the safety of the machine and to ensure that the quality of the machined surface is not degraded by built-up chips, it is important to keep the chip forms within acceptable limits, ensure their short size, and remove the chips from the environment. Many studies have discussed that short chips are better in terms of cutting conditions and machinability compared to long and difficult-to-break chips [58], [59]. Figure 7 shows the chip forms of all engineering plastics used in the study, both before and after heat treatment.

Figure 7. Chip forms: (a) without heat treatment-PEEK, (b) with heat treatment-PEEK (c) without heat treatment-PP (d) with heat treatment-PP, (e) without heat treatment-PTFE and (f) with heat treatment-PTFE

When examining the chip morphologies of the non-heat-treated and heat-treated PEEK material shown in Fig. 7 (a) and (b), it is observed that the chips of the heat-treated parts are darker in color. This color change is attributed to the heat and holding time during the heat treatment process [60]. Additionally, it was observed that the heat-treated PEEK chips are more clumped together compared to the non-heat-treated chips. However, when evaluated in terms of length, thickness, and diameter, the average length of the heat-treated chips was found to be approximately 0.75 cm, and they were thinner and had a smaller diameter. The average length of the non-heat-treated chips was observed to be about 1 cm. According to the ISO 3685-1977 (E) standard, the heat-treated PEEK chips are classified as short chips, which are considered good [39], [61].

When examining the chip morphologies of the non-heat-treated and heat-treated PP material shown in Fig. 7 (c) and (d), it is observed that the chips of the heat-treated sample are short, comma-shaped, and straight, classified as acceptable. The chip lengths did not change significantly with heat treatment and were measured to be approximately 1 cm on average. The heat-treated chips were found to be thinner, did not show any color difference, and were more clumped together compared to the non-heat-treated chips [17], [39], [52].

When examining the chip morphologies of the non-heat-treated and heat-treated PTFE material shown in Fig. 7 (e) and (f), it is observed that the heat-treated PTFE chips exhibit an imperceptible amount of color change. The chip length was found to decrease from approximately 1.25 cm to 1 cm. It was also determined that the chip diameters and thicknesses decreased. The PTFE chips are classified as short chips, which are considered good [14], [39], [52], [53].

4. CONCLUSIONS

Engineering thermoplastics such as PEEK, PP, and PTFE, which have seen increasing functionality and application areas, have been subjected to heat treatment in this study, and their dimensional integrity and hardness values have been measured. Subsequently, the specimens were machined from different surfaces, and surface roughness measurements and chip forms were examined. The general results obtained are presented below.

- It has been found that the dimensional measurement values of PEEK and PTFE engineering plastic materials are closer to the desired tolerance values. As a result, heat treatment has improved the dimensional integrity of PEEK and PTFE plastics.
- The hardness values of all the engineering plastic materials used in the study increased after heat treatment. This increase in hardness was found to be 7%, 6%, and 11% for the PEEK, PP, and PTFE samples, respectively.
- Following heat treatment, the Ra values of the PEEK, PP, and PTFE engineering plastic materials improved by 15%, 56%, and 80%, respectively, and the Rz values improved by 31%, 56%, and 43%, respectively.
- It was determined that fixture usage during experiments reduced the risk of deformation of the materials during heat treatment.
- It was also found that the chip forms of all the engineering plastic materials machined in the study were classified as short chips, which are considered good, after heat treatment. The heat treatment was found to affect the length, shape, thickness, diameter, and color of the chips.
- In conclusion, this study showed that the annealing heat treatment, increased the ductility, eliminated internal stresses, ensured dimensional stability, improved mechanical properties, and with the increased hardness value, reduced the surface roughness value, which is one of the most important criteria affecting machinability, thereby improving the surface quality of the machined parts.
- Engineering plastics such as PEEK, PP, and PTFE exhibit diverse machinability characteristics due to their different structural and thermal properties. The results of this study highlight that heat treatment has a significant role in optimizing machining outcomes by improving hardness, dimensional accuracy, and surface quality.
- Overall, the findings suggest that the application of appropriate pre-machining heat treatment can standardize chip formation and enhance machinability across different polymer types, providing a valuable guideline for industrial applications where precision and surface integrity are critical.

Declaration of Ethical Standards

The authors declare that the study complies with all applicable laws and regulations and meets ethical standards.

Credit Authorship Contribution Statement

The authors contributed equally to the study's conception and design.

Declaration of Competing Interest

The authors declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Not applicable.

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