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An Efficient Method to Fabricate the Mold Cavity for a Helical Cylindrical Pinion

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Abstract: An efficient method was proposed to fabricate the mold cavity for a helical cylindrical pinion based on a plastic torsion forming concept. The structure of the spur gear cavity with the same profile as the end face of the target helical gear cavity was first fabricated by low-speed wire electrical discharge machining (LS-WEDM). Then, the structure of the helical gear cavity could be obtained by twisting the spur gear cavity plastically around the central axis. In this way, the fabrication process of a helical cylindrical gear cavity could be greatly simplified, compared to the fabrication of a multi-stage helical gear core electrode and the highly difficult and complex spiral EDM process in the current gear manufacturing method. Moreover, several experiments were conducted to verify this novel processing concept, and a theoretical model was established to show the relationship between the machine torsion angle and the helical angle of a helical gear. Based on this theoretical model, the experimental results showed that it is feasible to precisely control the shape accuracy of a helical cylindrical pinion mold cavity by adjusting the machine torsion angle.

Keywords: injection mold; helical cylindrical pinion; plastic torsion forming; LS-WEDM

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1. Introduction

With the rapid development of some emerging fields of science and technology such as electronic information, the trend of product miniaturization is becoming increasingly popular. Thus, small modulus gears are now widely used in aircraft, communication facilities, traffic vehicles, intelligent instruments, appliances, etc. In particular, plastic gears are getting more and more attention in recent years due to their light weight, low noise, and inherent lubricity [1,2]. For plastic gear manufacturing, injection molding is the main method and the mold cavity is crucial for the gear injection molding process [3]. In order to reduce micro-cell formation in the gear and produce more accurate plastic gears, Yoon et al. proposed a new injection molding process, the pressurized mold, which is designed to suppress the nucleation of micro-voids [4]. Ni et al. used micro powder injection molding (μPIM) to fabricate the micro gear cavity. The results showed that the micro gears can be successfully fabricated under an injection pressure of 70 MPa and 60% injection speed [5]. An effective method to control the non-linear shrinkage of micro-injection molded small module plastic gears by combining multi-objective optimization with Moldflow simulation is proposed. The accuracy of the simulation model was verified in a micro-injection molding experiment using reference process parameters [6]. In order to reduce the excess costs of the molds used to produce parts in injection molding and the problems of wastes that occur during production in hobbing, Tunalioglu et al. analyzed the wear resistance of plastic spur gears produced by the Fused Deposition Modeling (FDM) method [7]. In order to determine the service life of gears, wear tests were carried out in the Forschungsstelle fur Zahnrader und Getriebebau (FZG) type test device at the same load and rotational speeds. Polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PETG) thermoplastic polymer materials were used in the production of gears. Singh et al. produced ABS, HDPE, and POM gears by the injection molding method, and their thermal and wear behaviors were investigated [8]. While ABS and HDPE gears completed 0.5 and 1.1 million cycles, respectively, before failure, they claimed that the POM gear completed 2 million cycles without any signs of failure. Duzcukoglu and Imrek increased the tooth width in PA 66 gears, delaying the occurrence of thermal damage in the single-tooth region [9,10]. Experiments show that the appearance of heat damage is delayed for width-modified gear teeth compared with unmodified gear teeth. Kalin et al. investigated the tribological properties of POM gears at different temperatures and torques [11]. In a word, the machining method for a spur gear mold cavity is quite stable and reliable, but fabricating a mold cavity for a helical gear with a high-precision is still a big challenge.

LS-WEDM is a general method for machining micro spur gears or their mold cavities, and its machining quality can reach Grade 5 for the DIN standard. Unfortunately, there is no evidence that this method can be used for machining micro helical mold cavities [12]. Limited by the complex enclosed space, the helical cylindrical pinion cavity cannot be fabricated by LS-WEDM directly like the micro spur gears and its mold cavities. The common process is to first fabricate the helical gear core into several rough and fine processing sections by hobbing, milling, and other cutting methods (Figure 1a) and then the helical cylindrical pinion mold cavity can be fabricated by the spiral EDM using the obtained helical gear core as the tool electrode [13]. Considering that the discharging gap will change its size at the rough and finish machining steps in the spiral EDM process, it is quite difficult to accurately compensate for the machining error in this process. Moreover, chip removal will become more difficult in the spiral discharge machining process, which can cause a more serious electrode loss for the multi-stage helical gear core. It should also be mentioned that the discharge machining process for a helical cylindrical cavity is quite time-consuming and more and smaller metal debris would be generated, which is detrimental to maintaining a clean processing environment. Wang et al. forward the forging process of spiral bevel gear with large modulus, including blanking, uptuning-punching compound, rolling, and final forging. It was found that the tooth shape of the lower die produces uneven deformation under the action of thermal coupling, and as the height of the tooth shape of the lower die decreases, the spiral angle of the center point of the helix decreases, and the tooth profile becomes narrower [14]. Qi et al. proposed a forming method for straight bevel gear, which used a special mold with a flash edge and a convex to manufacture straight bevel gear, and used deform-3D V6.1 to optimize the forming load and die wear [15]. Xia et al. proposed using a positive extrusion process to form a four-leaf aluminum alloy spiral surface rotor and combined deform-3D V6.1 with numerical simulation to study the influence of extrusion temperature, extrusion speed, extrusion ratio, and other parameters on the extrusion process [16]. Li et al. put forward a combination process including hot forging, upsetting finishing, and radial extrusion of gears and conducted simulation and experimental research to analyze the flow law of metals in the extrusion process and the influence of finishing parameters on surface quality and the stress–strain distribution in the extrusion process [17]. Moreover, it is still a challenge to predict the machining error in the fabricating process of gear structure. Ma et al. built a prediction model of free tooth splitting error in the axial rolling of a straight gear, and characterized the mathematical relationship between the tooth spacing error of a free tooth splitting axial rolling workpiece and the initial diameter of the workpiece, the initial phase of the rolling gear teeth and the contact degree. Based on the theory of gear meshing, the assumption of plane strain, and the principle of equal volume, the estimation model of workpiece tooth forming height at any time is constructed. The geometric design method of the axial rolling wheel is also proposed. The structure of the axial rolling wheel is divided into the cutting section, finishing section, and exiting section. The cutting section, finishing section, and exiting section are designed from the angles of the force of rolling wheel teeth, root stress, slip rate, and tooth surface scratches [18,19].

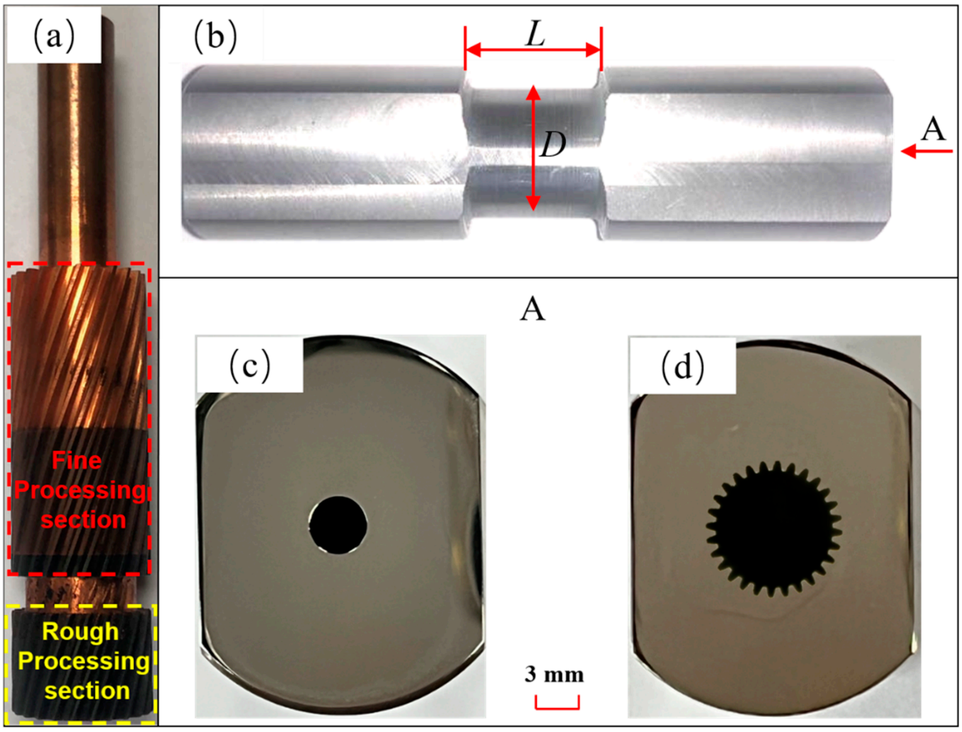

Figure 1. Conventional machined electrode and plastic torsion samples: (**a**) a helical gear core electrode; (**b**) the size view of a torsion sample; (**c**) the torsion sample with a through-hole; (**d**) the torsion sample with a spur tooth cavity.

In a word, there is a lack of a more effective way to fabricate the cavity of the helical cylindrical pinion mold by the current machining methods. Therefore, it is urgent for the industry to develop a new approach to fabricate the structure of the helical cylindrical pinion cavity.

In this paper, an efficient method was proposed to fabricate the mold cavity for a helical cylindrical pinion based on a plastic torsion forming concept. A mathematical model was established for the relationship between the machine torsion angle and the helix angle on the gear cavity reference circle. By analyzing and comparing the torsion experiment and calculation results at different helix angles, the established mathematical model was found valid.

2. Research Methodology and Experiment Details

2.1. Proposed Concept

According to the profile data of the helical gear cavity end face, its spur gear cavity was first machined by LS-WEDM. The spur gear cavity was then twisted plastically by a torsion machine to obtain the targeted helical gear cavity. Compared with the highly difficult and complex steps for the gear cavity machining in the spiral EDM process, this novel method was based on a more simple and more reliable 2D machining concept, which greatly improved the machining reliability and efficiency. It should be mentioned that the high-precision LS-WEDM was also adopted in this novel method to obtain the spur gear mold cavity, which is crucial for ensuring the forming accuracy of its helical cylindrical pinion cavity. Thus, this novel fabricating method for a helical gear cavity shows its promising application in the involved industry.

2.2. Theoretical Background

As shown in Figure 1b, the torsion sample could be divided into three sections. The two ends were the clamping sections to facilitate clamping the sample piece on the torsion machine chuck, and the middle was the torsion section. A wire-cutting threaded hole (Figure 1c) was initially processed on the axis of the torsion sample. According to the end surface profile data of the helical gear cavity, the spur gear mold cavity (Figure 1d) was first fabricated by LS-WEDM, and then the helical gear cavity could be obtained from the torsion section by twisting the spur gear mold cavity slowly. As shown in Figure 2a, the torsion sample could be further divided into three different deformation zones after the torsion based on its plastic deformation characteristics: (1) Helical gear zone (uniform deformation zone): l_m was the length, and β_m was the reference circle helix angle, which was found constant in this zone, which indicated that the materials twisted and deformed uniformly in this zone. A helical cylindrical gear mold cavity could be obtained from this part. (2) Spur gear zone: there was no plastic deformation in this zone, and the internal cavity structure still maintained its complete spur gear cavity. (3) Transition gear zone: the internal cavity shape contained both spur and helical gears in this zone. This zone deformation played a transitional role between the helical gear zone and the spur gear zone to guarantee the continuity of the material deformation in the whole torsion sample. l_{em} represented the length of the intersection zone between the transition gear zone and torsion section and l_{eo} meant the length of the intersection zone between the transition gear zone and clamping section. l_{e} was the total length of the transition gear zone ($l_{\mathrm{e}} = l_{\mathrm{em}} + l_{\mathrm{eo}}$). β_e was the reference circle helix angle of the transition gear zone, which changed continuously in the range of 0~β_m along the axial direction of the torsion sample.

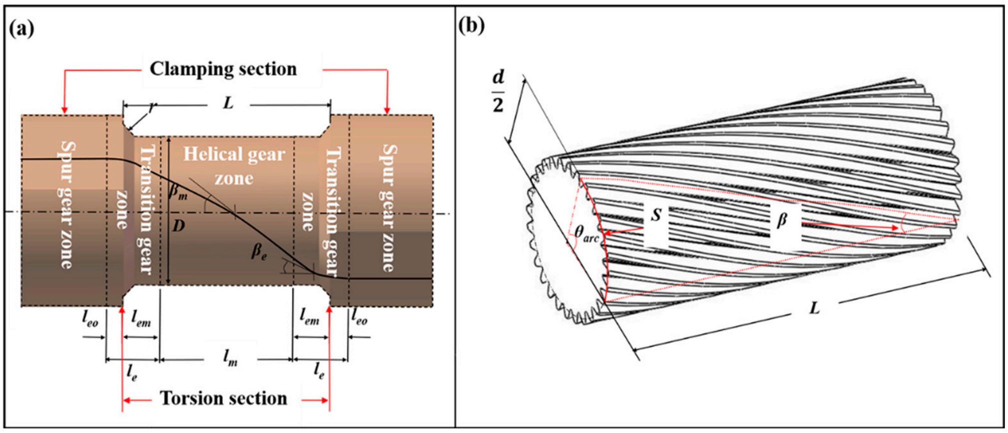

Figure 2. Analysis of the torsion forming for the gear cavity: (**a**) different deforming zones; (**b**) the geometrical relationship in the torsion section.

In order to analyze the deformation law of the helical gear cavity in the torsion section, the torsion section part was taken for analysis (Figure 2b). d was the diameter of the reference circle on the end face of the helical gear cavity and L was the length of the torsion section. Considering the torsion section theoretically included both the helical gear zone (uniform deformation) and the transition gear zone (non-uniform deformation), β represented the approximate helix angle in the torsion section. Based on the forming characteristics of the spiral involute surface, the relationship between the circumferential travel S of the tooth line on the reference circle of the torsion section, the machine torsion radian θ_{arc}, and the reference circle helix angle β was as follows:

$$S = \theta_{arc}\frac{d}{2} = Ltg\beta \tag{1}$$

After converting radian units (θ_{arc}) into angle units (θ), the machine torsion angle θ could be calculated as follows:

$$\theta = \frac{2Ltg\beta}{d} \times \frac{180}{\pi} \quad (2)$$

From Equation (2), the reference circle helix angle β of the helical gear cavity could be also calculated from the machine torsion angle θ directly in the torsion section.

Considering a part of the transition gear zone might be located in the torsion section, the helix angle β calculated by Equation (2) would not be completely consistent with the helix angle β_m in the helical gear zone with a uniform deformation, which indicated that there might be some deviation in controlling the helix angle β_m directly by the machine torsion angle θ. However, Equation (2) still provided a kind of theoretical relationship between the operating parameters of the torsion machine and the characteristic parameters of the helical gear cavity. If it could be proved that the error between the predicted β and the β_m is acceptable or controllable, this new method proposed would be quite promising for fabricating the helical gear cavity in the industry.

2.3. Experiment Setup

The torsion sample material was S136 steel, the length of the torsion section of the sample L = 15 mm, and the diameter of the torsion section D = 15 mm. An LS-WEDM machine (AP250L, Sodick Co., Ltd., Kanagawa, Japan) was used to fabricate the spur gear cavity with the highest machining accuracy of 0.001 μm and the best surface roughness of Ra0.1. A pulse width of 0.5 μs, a pulse interval of 15 μs, a peak current of 0.1 A, and a wire speed of 2 mm/min were used in the LS-WEDM process. An electronic torsion testing machine (CTT1000, Xinsansi Co., Ltd., Hangzhou, China) was adopted for the plastic torsion forming to obtain the helical gear cavity. Based on the helical gear cavity obtained, a series of injection molding experiments were conducted to verify the novel fabrication method for a helical cylindrical pinion. First, the POM granules were dried at 100 °C for 3 h. An injection molding machine (HA1700, ShengDa machinery equipment company, Wenzhou, China) was used and the injection parameters were as follows: Injection temperature was 200 °C, injection pressure was 110 MPa, and pressure holding time was 8 s. A small gear testing machine (GTR-4LS, Osaka Precision Co., Ltd., Osaka, Japan) was used to determine the quality of the helical cylindrical pinions.

The design parameters of the helical cylindrical gear cavity were chosen as follows: the number of teeth z = 28, the normal module m_n = 0.2, the pressure angle α = 20°, and the helix angle β = 20°. The diameter of the end reference circle d = 5.959 mm, and the diameter of the end addendum circle d_a = 6.359 mm. According to the end face profile data of the helical gear cavity, several spur gear cavity samples were machined by LS-WEDM, and then they were twisted around the central axis with the machine torsion angles (θ) of 20°, 40°, 60°, 80°, 100°, 120°, and 140°, respectively. After the torsion experiments, each sample was cut into five sections and each cutting surface was located 3 mm away from the nearest interface between the clamping section and the torsion section as shown in Figure 3a. From the experimental observations, this cutting method could guarantee that each cutting section included only one tooth shape feature: helical gear shape, spur gear shape, or transition gear shape.

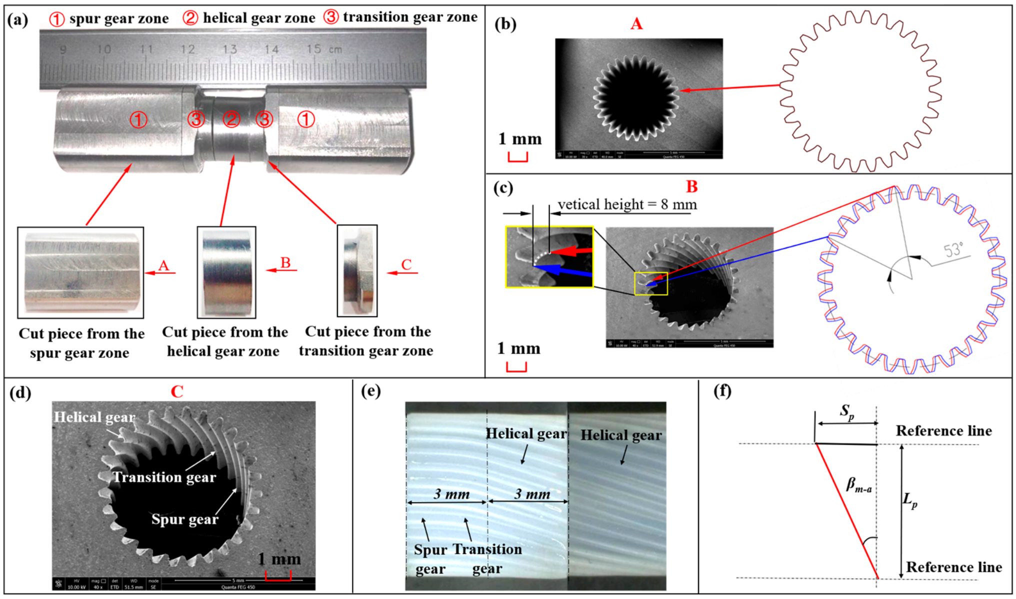

Figure 3. Torsion forming result for the gear cavity and its silicone copy: (**a**) different cut pieces from the torsion sample; (**b**) a cut piece from the spur gear zone; (**c**) a cut piece from the helical gear zone; (**d**) a cut piece from the transition gear zone; (**e**) a silicone copy; (**f**) the spiral tooth line measurement.

3. Result and Discussion

Figure 3b,c showed the cutting cavities in the spur gear zone without any plastic deformation and the helical gear zone with a large plastic deformation with the machine torsion angle θ of 100°. As shown in those two figures (Figure 3b,c), the end face contours were in good consistency. Figure 3d showed the cutting cavity in the transition gear zone, and its shape was represented by filling the cavity with silicone resin (Figure 3e left). Using the same method, the cavity shape of the helical gear zone could be also obtained as shown in the right of Figure 3e. It could be clearly seen from the above figures (Figure 3b–e) that the torsion sample really could be divided into three different zones: the helical gear zone with a uniform deformation, the spur gear zone without any deformation, and the transition gear zone.

In order to analyze the evolution law of the spiral tooth line from the cavity, one of the tooth surfaces from the silicone gear was painted using black ink and then the silicone gear was rolled along a reference line on paper. The axial travel of the tooth line (L_p) and the circumferential travel of the tooth line (S_p) could be measured, and the torsional angle (θ_p) of the tooth profile in the circumferential direction could be calculated as follows:

$$\theta_p = 2\frac{S_p}{d_a} \times \frac{180}{\pi} \tag{3}$$

where d_a was the diameter of the addendum circle.

In fact, θ_p was also the torsion angle for the cut piece from the helical gear zone. At the assumption that the entire torsion section was located at the helical gear zone, the equivalent torsion angle θ_e for the entire torsion section could be determined by the following equation:

$$\theta_e = \frac{L}{L_p}\theta_p \tag{4}$$

The helix angle on the addendum circle $\beta_{m\text{-}a}$ in the helical gear zone could be calculated as:

$$\beta_{m-a} = arctg\left(\frac{S_p}{L_p}\right) \times \frac{180}{\pi} \tag{5}$$

From Equation (2) above, the helix angle on the reference circle (β_m) in the helical gear zone could be determined:

$$\beta_m = arctg\left(\frac{\theta_e d}{2L} \times \frac{\pi}{180}\right) \times \frac{180}{\pi} \tag{6}$$

Based on the above theoretical formulas and the experiment data, the calculated and measured values for the helical angles with different machine torsion angles are shown in Table 1. The results showed that the machine torsion angle θ and equivalent torsion angle θ_e were quite close, which suggested that the proportion of the transition gear zone probably should be very limited. This could also be verified from the silicone copy obtained from the cut piece from the transition gear zone (Figure 3e). In the silicone copy of the transition gear zone with a length of about 6 mm, the part with the uniform helical gear cavity occupied almost half of this zone (Figure 3e), which indicated that there was no transition zone in the torsion section actually ($l_{\mathrm{em}} \approx 0$ or $l_{\mathrm{e}} \approx l_{\mathrm{eo}}$) (Figure 2a). That is, the uniform deformation occurred in almost the entire torsion section, which suggested that this section could be used as the helical gear mold cavity directly, and the whole spur gear zone and almost the entire transition gear zone were located at the clamping section. Moreover, the difference between the calculated value (β) and the measured value (β_m) for the helix angle was less than 3% for the conventional range of 8~25°, which indicated that the accuracy of the helix angle for the target helical gear cavity, calculated by Equation (2), was sufficient. From Table 1, $\beta_{m\text{-}a}$, β_m, and β only increased by 3~4° as θ increased by 20°, which also indicated that it would be convenient and feasible to control the manufacturing accuracy of the helical tooth line of the cavity by the machine torsion angle θ.

Table 1. Measured and calculated crucial parameters for a spiral tooth line.

machine torsion angle θ (°)	20	40	60	80	100	120	140
axial travel of a tooth line L_p (mm)	9.732	9.747	9.614	9.572	9.563	9.452	9.632
circumferential travel of a tooth line S_p (mm)	0.762	1.421	2.100	2.745	3.482	4.152	4.908
torsion angle of a tooth line θ_p (°)	13.731	25.605	37.840	49.463	62.743	94.816	88.438
equivalent torsion angle θ_e (°)	21.163	39.405	59.040	77.512	98.415	118.730	137.726
helix angle on the addendum circle in the helical gear zone $\beta_{m\text{-}a}$ (°)	4.477	8.295	12.322	16.002	20.007	23.715	27.001
helix angle on the reference circle in the helical gear zone β_m (°)	4.496	7.780	11.568	15.042	18.840	22.374	25.525
helix angle on the reference circle in the torsion section β (°)	3.967	7.896	11.751	15.502	19.122	22.590	25.891

The results also suggested that the length (L) and diameter (D) of the torsion section had an important influence on the plastic torsional process. For a targeted helical gear cavity, increasing the D value could decrease the limit torsion angle (θ_{limit}) of the torsion sample. When the machine torsion angle (θ) was higher than θ_{limit}, cracks and other defects were more likely to occur on the surface of the torsion sample. As the L value was constant, a smaller θ was needed for a larger addendum circle diameter (d_a) and reference circle diameter (d) of the end face in Equation (2). Therefore, the parameters D and d_a should be adjusted carefully and a larger D was more favorable to increase θ_{limit}. Based on the good plasticity of S136 steel, its torsion-forming process could be completely carried out at room temperature. For d_a < 10 mm and the helix angles within 8~25°, the helical cylindrical gear cavity could be obtained by one-time twisting using the S136 steel material. For helix angles over 20°, intermediate annealing treatment was probably needed.

To further verify the novel gear mold fabricating method proposed in this paper, a series of injection molding experiments were carried out based on a complete plastic helical cylindrical gear injection mold (Figure 4). From Equation (2), θ of 104.980° was chosen to achieve the helix angle of 20°. The left-hand and right-hand gear cavities were twisted, respectively. Then the obtained two cavities were assembled into the plastic injection system. The result showed that the quality of the left and right helical cylindrical pinions was sufficient, which suggested that this novel method would be quite promising in solving the bottleneck problem in the helical gear fabricating process for the related industry.

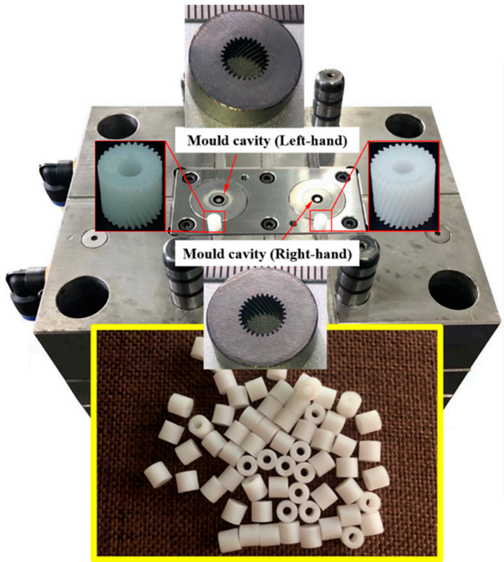

Figure 4. Injection mold system of a plastic helical cylindrical gear.

4. Conclusions

In this paper, a new method for manufacturing a helical gear cavity was proposed. LS-WEDM was used to form a spur gear cavity and then a helical gear cavity could be obtained by twisting the spur gear cavity. Several equations were derived to predict and evaluate the precision of the helical gear geometry. The results showed that this novel method would probably be promising for helical gear manufacturing in the future.

(1) A new method for the efficient and controllable manufacturing process of the helical cylindrical gear cavity was proposed. The experimental results showed that almost the whole torsion section was located in the helical gear zone with uniform deformation, which could be used as the cavity of the targeted helical gear mold directly, and the whole spur gear zone and almost the entire transition gear zone were located at the clamping section.

(2) A mathematical model was established for the relationship between the machine torsion angle and the helix angle on the reference circle, and the result showed that the difference between the helix angle calculated by the mathematical model and its measured value was close, which indicated that it is feasible to precisely control the helix angle of the helical cylindrical gear cavity by adjusting the machine torsion angle. Moreover, the helix angle on the reference circle only increased by 3~4° when the machine torsion angle increased by 20°, which was favorable for the accuracy control of the helical gear profile.

(3) For d_a < 10 mm and helix angles within 8~25°, the helical cylindrical gear cavity could be obtained by one-time twisting using the S136 steel material. For the helix angles over 20°, intermediate annealing treatment was probably needed.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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