

사출성형기 스크류의 다층코팅을 통한 도광판의 성형품질 향상

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Enhancement of the Molding Quality of Light Guide Plates by means of Multi-Coating Surface Treatments of the Injection Molding Screw

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Abstract: The effects of different surface treatments of an injection molding screw have been investigated using light guide plates as a representative precision component. The quality of the fabricated light guide plates was compared for different screw coatings, using the stripping performance, surface microstructure and adhesion strength as criteria. In addition, the results obtained using different combinations of screw coatings were analyzed in order to identify the optimum screw surface treatment method for the large scale production of polycarbonate light guide plates. It was found that light guide plate parts fabricated using a screw with a TiAlN/Cr multi-coating had the best performance, with a defect percentage of only 0.11%, much lower than the value of 19.21% obtained using a screw with a conventional hard chrome coating.

Keywords: multi-coating, screw surface treatment, injection molding quality, light guide plate.

Introduction

Precision injection molding is a key technology in the precision manufacture of devices such as light guide plates (LGP) and microfluidic chips. An important stage in precision injection molding, which can affect the accuracy and mechanical properties of the resulting components, is part plasticization.^{1,2} In this process, inadequate surface treatment of the screw can cause a variety of defects in LGP, including black discoloration and formation of yellow streaks.^{3,4} In general, the part thickness is less than 0.5 mm and a microstructural array exists on the surface, so that injection molding processing of LGP is very different from that of conventional parts.⁵⁻⁸ As a result of the intense abrasion and corrosion of the screw surface, surface failure is commonly observed, which may create gaseous

decomposition in the products⁹ leading to the observed black discoloration and yellow streaks on the surface, unless the screw and screw tip have been subjected to an appropriate surface treatment. Surface failure may also lead to melt decomposition and promote melt carbonization due to overheating as the melt tends to adhere to the surface of screw. In other cases, the gas produced undergoes heating and burning and results in blackening of the product. If the melt adhering to the screw or coating film is stripped from the screw substrate, this can also result in black discoloration and yellow streaks.⁹ Unfortunately, such defects significantly influence the transparency and uniformity of the parts produced. Therefore, surface treatment of injection molding screws used in the fabrication of LGP is desirable in order to enhance the wear and corrosion resistance, both by preventing the coating from peeling off the substrate and avoiding melt adhesion on the surface of the screw.

In recent years, hard chrome coatings have generally been employed in industry for the surface treatment of injection

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molding screws and barrels. Even better performance has been obtained by various approaches such as nitriding the steel barrel, applying tungsten carbide–cobalt coatings by thermal spraying techniques, and applying chrome nitride by physical vapor deposition (PVD).^{10,11} Titanium-based hard coatings have also been deposited on steel substrates by means of a radio frequency sputtering process, and afforded a significant improvement in wear resistance of the melting zone inside a screw–barrel system.¹² Nickel–tungsten alloy plating and PVD can also dramatically improve stripping properties, corrosion resistance and smoothness.^{13–16} PVD of TiN and TiAlN coatings has been shown to significantly reduce the adhesion strength between polycarbonate (PC) and the coatings.^{13,17} In general, hard films prepared by PVD and chemical vapor deposition offer better wear protection in comparison with the standard coatings used for screws.¹⁵ Detailed studies of the structure and properties of the “basic” AlTiN and TiAlCrN coatings have resulted in some metallurgical design principles for the hard PVD coating of hard cutting materials.¹⁸ However, despite the success of these approaches, comparative wear data which could assist in the selection of an appropriate coating technique, have rarely been reported.

In this work, a systematic study of the effects of different surface treatments of a screw is reported. Our aim is to find ways to improve and optimize the stripping properties and adhesion strength by appropriate screw surface treatment technology. To our best knowledge, nano-multilayered coating technology, which has been extensively studied in the area of super-alloys and hardened tool steels,^{19,20} is employed for the first time in the surface treatment of screws used in the precision injection molding of plastic optical components. Three coating features, namely the stripping between the polymer and coating film, the surface microstructure of the coating film, and the adhesion strength between the metal substrate and the coating film were analyzed in order to identify the best surface coating treatment methods for use in the large scale industrial fabrication of PC LGP.

Experimental

In order to compare stripping stress between the polymer and various coating films, we built a stripping performance test platform as shown in Figure 1. The metallic testing block was composed of SKD61 steel and was identical to material used to make the special screw. Prior to surface coating, the steel block was mirror polished, followed by ultrasonic cleaning

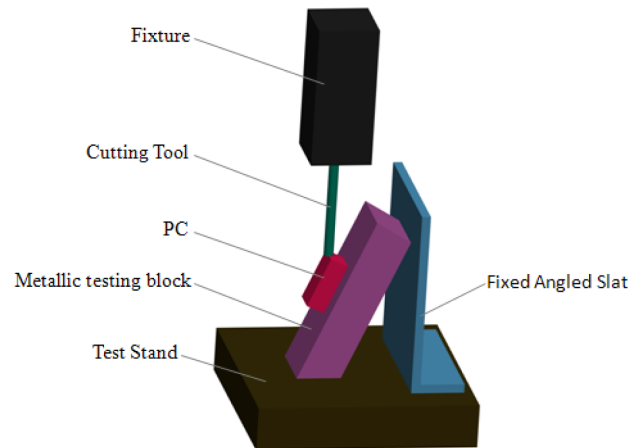


Figure 1. Stripping performance test platform.



(a)



(b)

Figure 2. PVD TiAlN coated screw in injection molding machine and molded LGP parts: (a) PVD TiAlN coated screw; (b) molded LGP.

with purified water for 10 min, ultrasonic cleaning with acetone for 15 min, and finally ultrasonic cleaning with alcohol solution for 15 min. After the block surfaces were coated by various methods, rectangular PC sheets were fixed on their top surface and they were then heated in an oven to 280 °C and kept at that temperature for 4 h. This ensures that the PC became fully molten and bonded to the metal block after cooling. A cutting tool moving downwards with a constant speed of 1 mm/s in the drive of a universal tester provided a suitable load. In this way, the stripping performance of PC and the coating film was measured in the form of an adhesion force.

Atomic force microscopy (AFM: Dimension V SPM, Veeco,

USA) was used to investigate the surface profile of various coating films. In this way, images of the 3D surface microstructure could be created. The adhesion strength between the metal substrate and the coating film was measured using a material surface properties tester (MFT-4000, Zhongke Kaitke Industrial and Trading Co., Ltd, Lanzhou, China). An all-electric injection molding machine (Tianrui VE900, Ningbo Zhafir Plastics Machinery Co., Ltd., China) equipped with screws having various coatings including conventional plated hard chrome, PVD TiN, PVD TiAlN and PVD TiAlN/Cr was employed to produce the PC (LC1500, NATURAL ED 76366) used in the fabrication of the LGP (shown as Figure 2).

Results and Discussion

Stripping Performance of the Polycarbonate Sheet and Coating Films. The stripping performance of the PC sheet and various coating films is shown in Table 1. The results show that chromium hemi trioxide produced by a thermal spraying treatment process (sample 3) showed the lowest average stress value, that is to say, it affords the best stripping performance. However the coating film, together with the PC specimen peeled away from the metallic block during the experiment, and so this film is clearly unsatisfactory; the same problem was observed with sample 2. However, samples 1, 5 and 6 afforded greatly improved stripping performance compared with the uncoated metallic block (sample 7) and these coating surfaces remained intact and smooth after testing.

These results were compared those obtained with another PC material (Bayer 2805) with higher viscosity in order to investigate whether the material properties have an influence on the stripping stress. As shown in Figure 3, both PVD TiN and brushed electroplated nickel–tungsten alloy showed superior stripping performance to those of a conventional hard

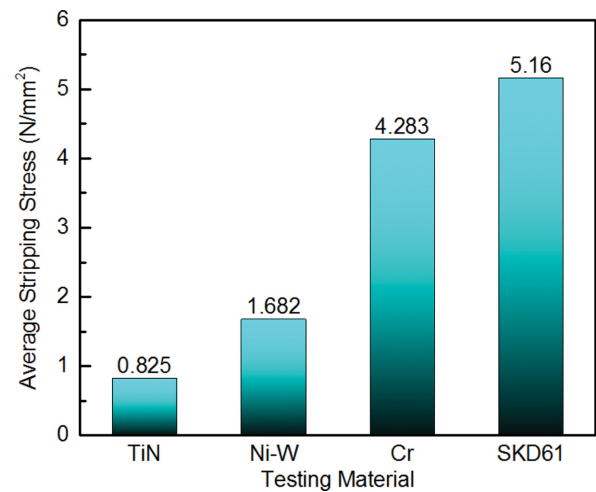


Figure 3. Average stripping stress for different test materials.

chromium coating and a non-coated SKD61 block, similar to the results in Table 1. However the stress values were larger than the corresponding values for the lower viscosity PC material. Furthermore experimental studies indicated that the brushing electroplating approach is much more difficult to employ in the case of a complex screw surface. Therefore, PVD of TiN and TiAlN is the recommended method for coating the screw for LGP injection molding.

Analysis of Coating Properties. Different surface treatment methods of a metal substrate result in variations in hardness and surface microstructure. These factors determine the stripping performance of a coating film because the microscopic surface texture—including crystal growth, particle size, the arrangement of crystals, and the presence or absence of large grooves—affects the strength of adhesion between the substrate and the coating film. Therefore, the influence of the surface roughness of the substrate and the thickness of coating film on the surface quality and adhesion strength of coatings

Table 1. Stripping Performance of the Polycarbonate Sheet and Various Coating Films

Sample number	Test material	Treatment process	Stripping force (N)	Area (mm ²)	Average stripping stress (N/mm ²)
1	Nickel	Brushing electroplating	507	900	0.563
2	Tungsten carbide	Thermal spraying	548	900	0.609
3	Chromium hemi trioxide	Thermal spraying	161	900	0.179
4	Nanophase material	Brushing electroplating	701	900	0.779
5	Nickel tungsten	Brushing electroplating	573	900	0.637
6	TiAlN	PVD	430	900	0.478
7	SKD61	No coating	1155	900	1.283

Table 2. Surface Qualities of Coating Films on Substrates with Different Roughness

Substrate roughness (μm)	0.4	1.6	3.2	6.3
R_a (nm)	9.35	21.5	51	89.9
R_q (nm)	17	30.3	74.5	117
R_{max} (nm)	295	330	650	1078
Critical adhesion strength (N)	30.71	30.17	17.26	14.65

Table 3. Surface Qualities of Coating Films with Different Thickness

Thickness of coatings (μm)	0.1	1	5	10
R_a (nm)	4.31	9.35	5.29	6.05
R_q (nm)	6.02	17	10.7	8.11
R_{max} (nm)	74.8	295	154	65.2
Critical adhesion strength (N)	16.06	30.71	33.32	31.26

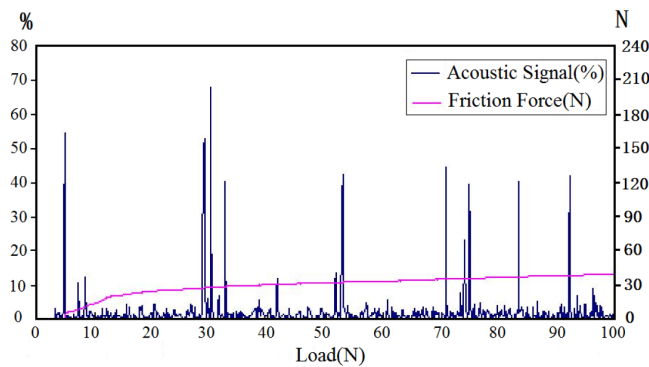


Figure 4. Acoustic signal and friction force measured with a material surface properties tester (substrate roughness=1.6 μm).

were investigated.

Four cylindrical substrate samples with different surface roughness were prepared and coated with 1 μm thick film PVD TiAlN. The coated surface quality and adhesion strength for substrates with different roughness are shown in Table 2. As the surface roughness of the substrate increased, the values of R_a (the arithmetic average of the absolute values of the surface height deviations measured from the mean plane), R_q (the root mean square average of the height deviation taken from the mean image data plane) and R_{max} (the maximum vertical distance between the highest and lowest data points in the image following the plane) of the coating film increased significantly, and the critical adhesion strength (measured with a material surface properties tester) decreased monotonically (Figure 4). Therefore, the surface roughness of the screw substrates should be as low as possible in order to give coatings with enhanced overall performance.

TiAlN coatings with different thickness were also prepared on substrates with the same surface roughness, 0.4 μm . The results, in Table 3, show that surface quality can be improved by increasing the coating thickness up to a certain point. A thin film with thickness of 0.1 μm gave the lowest adhesion strength of all the samples. However, the adhesion strength began to decrease when the thickness exceeded 5 μm . A pos-

sible reason for this is that the residual stress of the coating becomes greater as the coating thickness increases, which leads to cracking and delamination between the substrate and coating film, resulting in lower film adhesion strength. Considering both surface quality and adhesion strength, the optimum PVD TiAlN coating thickness lies in the range 1–5 μm .

Multi-coating Surface Treatment. Although a PVD TiAlN coating with a thickness of 5 μm and a substrate roughness of 0.4 μm has good stripping performance and high adhesion strength, it is still insufficient for LGP injection molding, since this process requires both high adhesion strength and an extremely smooth surface of the screw in order to prolong its service life. Therefore, multi-films have been proposed to reinforce the adhesion strength between the PVD TiAlN coating and the substrate (SKD61 screw). We chose Cr or Ti as the cushion layer between TiAlN and the substrate, since their hardness is lower than that of the TiAlN coating but higher than that of SKD61, and they have matching crystal lattices.

Figure 5 shows the strength of adhesion between the substrate and the coating film, and clearly indicates that the adhesion strength of multi-films greatly exceeds those of a single film (TiN or TiAlN). From Figures 6 and 7, the results show

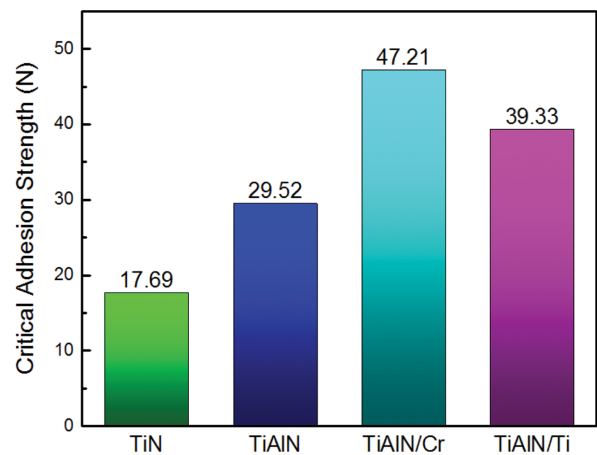


Figure 5. Adhesion strength between the substrate and coatings.

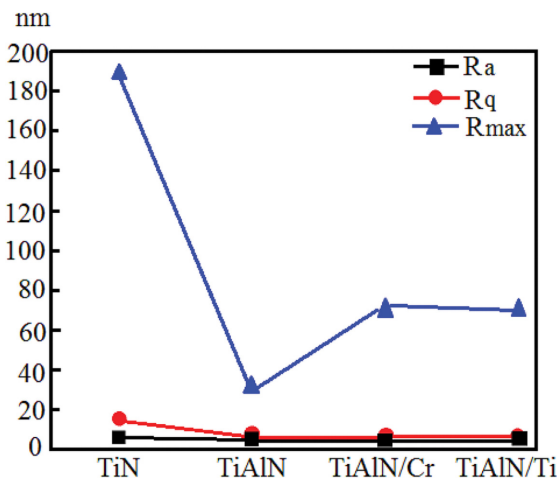


Figure 6. Comparison of the surface quality of different coatings.

that the TiN coating had the largest size of crystal particles ($R_{max}=189$ nm), the TiAlN/Cr coating had the second largest size of crystal particles ($R_{max}=73.0$ nm), the TiAlN/Ti coating had the third largest size of crystal particles ($R_{max}=69.9$ nm) and the TiAlN coating had the smallest size of crystal particles ($R_{max}=32.1$ nm). As shown in Figure 7(b), the TiAlN coating afforded excellent surface quality as a result of its smoothness, with the average roughness of the surface, R_a , as low as 4.38 nm. However, the R_{max} values of the TiAlN/Cr coating and the TiAlN/Ti coating were slightly worse than that for

TiAlN. On the other hand, the R_{max} values of the TiAlN/Cr and TiAlN/Ti coatings were much lower than that of the TiN coating, and their R_a and R_q values were very similar to that of the TiAlN coating. Nevertheless, owing to their better adhesion with the substrate, the lower stripping stress with PC, and the smoother surface of the coatings, multi-films are a potentially useful approach for the treatment of the special screw used in LGP injection molding.

Industrial Testing of LGP Injection Molding. In order to confirm the benefits of multi-coating surface treatment of the screw, almost 10000 LGP parts were fabricated. Three parameters were used to evaluate the overall performance of the various coating films: the sequence number of the molded part when black discoloration appeared for the first time, the average defect percentage (the percentage of molded parts with black discolorations or yellow streaks, as shown in Figure 8), and the surface quality after testing, including whether the coatings were exfoliated or corroded or heavily worn.

The industrial testing results, in Table 4, showed that the TiAlN/Cr coating afforded the best performance with the appearance of defects being delayed the longest, the lowest defect percentages and the best surface quality of the post-test screw, and the performance was far superior to that of the hard chrome coating. In addition, it was found that once the first defective part emerged, wear of the coatings became much more severe and more defective parts with black discoloration

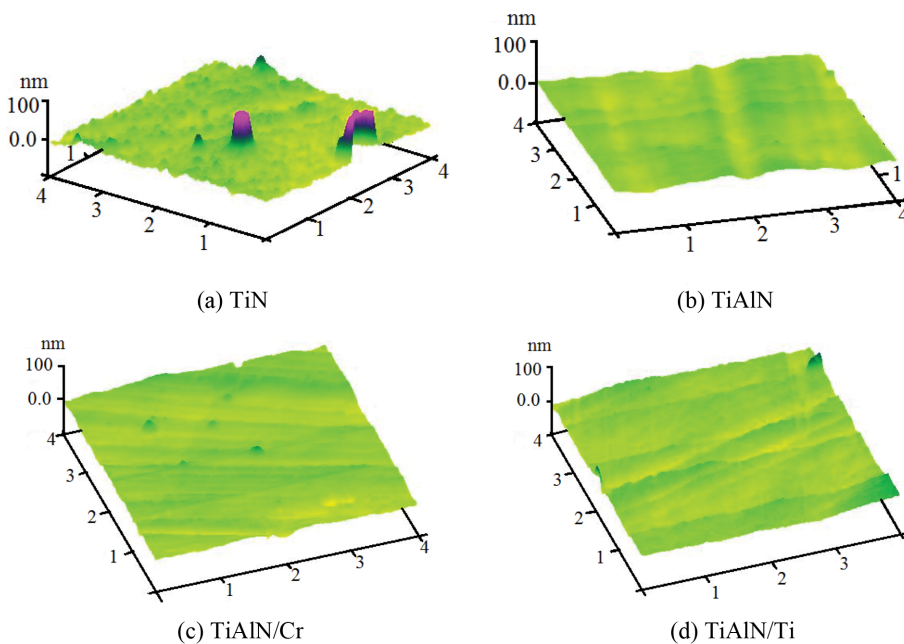
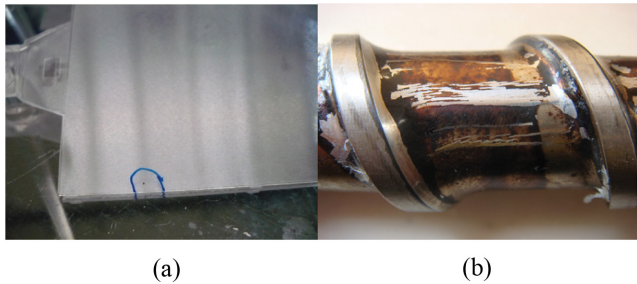
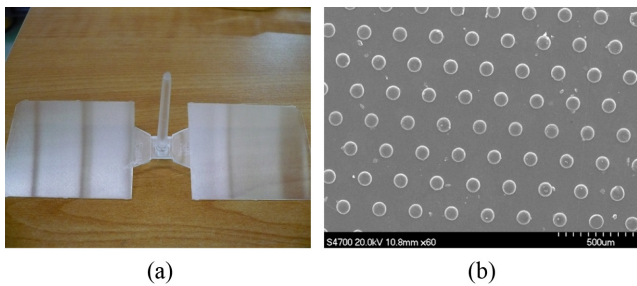


Figure 7. Surface micro-morphologies of various coating films.

Table 4. Industrial Test Results for LGP Injection Molding

Coating type	Sequence number of first defective part	Average defect percentage (%)	Surface quality of the post-test screw
Hard chrome	410	19.21	Severe degradation, change in color
TiN	823	0.46	Slightly broken surface
TiAlN	1098	0.19	Intact and no degradation
TiAlN/Cr	2076	0.11	Intact and no degradation

**Figure 8.** Defects observed in the process of LGP injection molding: (a) black discoloration of the product; (b) yellow streaks on the screw.**Figure 9.** Non-defective parts: (a) the surface microstructure; (b) of the injection molded LGP.

were formed in subsequent molding cycles. Figure 9 shows views of non-defective parts and the surface microstructure of the injection molded LGP, which has a good microspheres structure. However, since the melt adheres to the surface of the screw, especially in the case of the screw with a hard chrome coating, the surface screw became yellow and the melt partially detached as shown in Figure 8(b), leading to the black discoloration shown in Figure 8(a). This destroys the microspheres structure and adversely affects the optical properties of the LGP.

Conclusions

An experimental study was carried out to investigate the quality of optical components prepared by precision-injection-molding, with a particular focus on the effects of surface treat-

ment of the screw. Multi-coatings were employed for the first time in the surface treatment of the screw. The influence of the surface roughness of the substrate and the thickness of the coating film on the surface quality and adhesion strength of the coatings were also investigated. It was found that, compared with a hard chrome film, both TiN and TiAlN coatings afforded improved surface quality and significantly reduced the bonding force between the surface and polycarbonate. The adhesion strength of the coating decreased rapidly with increasing roughness of the substrate. However, the thickness coating should be within a certain range in order to maintain strong adhesion with the substrate. The use of multi-coatings, including TiAlN/Cr and TiAlN/Ti, greatly increases the adhesion strength between substrates and coatings due to the cushion effect of coating with Cr and Ti. According to industrial test results, the average defect percentage of LGP molded with a TiAlN/Cr coated screw was as low as 0.11%, a significant improvement compared with the corresponding value of 19.21% obtained with a conventional hard chrome coated screw.

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