EVALUATION OF SCREW DESIGN PARAMETERS ON FLOW AND PRODUCT QUALITY IN PLASTIC INJECTION MOLDING

Van Thanh Hoang*, Duc Binh Luu, Hoang Ha Cao

The University of Danang - University of Science and Technology, Vietnam

*Corresponding author: hvthanh@dut.udn.vn

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Abstract - In the plastic industry, the plastic injection molding process is becoming more and more popular and developed. The plastic injection molding process can produce parts from simple to complex. To ensure the quality of the product after the plastic injection molding process, we need to evaluate the influence of design parameters on the flow quality and product quality. In particular, the screw of the plastic injection molding machine will directly affect the flow quality of the plastic and lead to the quality of the injection molded product. This study will evaluate the influence of some factors of the screw and its impact on the flow quality and product quality, thereby being able to design the screw of the injection molding machine and further improve the quality of the plastic.

Key words - Injection molding; injection molding machine; screw; flow quality; shear stress.

1. Introduction

In the field of plastics, injection molding technology is increasingly being applied thanks to its ability to produce components ranging from simple to complex geometries. To ensure product quality after the injection molding process, it is essential to evaluate the influence of design parameters on both flow quality and product quality [1], [2], [3]. Injection molding is a technology for manufacturing plastic products and components by injecting molten plastic material into a mold. The material is fed into a heated chamber, thoroughly mixed (using a screw system), and injected into the mold, then cooled and solidified to take the shape of the mold cavity [4], [5].

To ensure the molding process proceeds with the highest precision, components must be meticulously designed: selecting materials, determining the geometry and technical requirements of the part, and carefully calculating mold materials and machine parameters. This creates the flexibility of the injection molding technology.

Injection molding offers advantages such as high efficiency, accuracy, low cost, and the ability to manufacture components with complex geometries. Thanks to these advantages, injection molding has become a popular method for mass production of various plastic products in the automotive, electronics, sports equipment, medical devices, optical lenses, and other industries.

However, polymers, when melted in the injection unit, undergo changes in temperature, pressure, and shear stress, which alter their properties and affect the quality of the molded parts. Many studies have shown that the quality of the flow and the final product depends on factors such as shear stress generated by the rotating screw, screw design, and control parameters like rotational speed. These factors not only have individual effects but also interact with each other [6], [7].

Among them, the design parameters of the screw in injection molding machines-including geometry (screw flight depth h, screw flight crest diameter D, taper angle Ψ, length L, screw pitch t, helix angle φ), rotational speed, and clearance between the screw and barrel-play a crucial role in directly influencing the quality of the plastic melt flow. Flow quality is assessed by factors such as shear rate, plastic throughput, melt pressure, homogeneity of the plastic, and melt temperature. These screw design parameters affect the processes of conveying, compressing, and melting the plastic, thereby impacting the flow quality and the plastic within the cylinder.

This study evaluates the influence of screw design parameters on the quality of plastic melt flow and the quality of plastic in the barrel, aiming to provide a scientific basis for more effective screw design. Although screw design has been extensively studied, with existing works focusing on calculations, simulations, and experiments, and the technology for manufacturing injection molding machines has been perfected with strict processes, this study introduces novelty through analyzing the interactive relationships between design parameters (such as h with shear rate and taper angle Ψ with the length of the compression section L_2) and using visual calculation charts to support practical design, which differs from previous studies that mainly relied on CFD simulations. The screw parameters of the injection molding machine directly affect the quality of the plastic melt flow and the quality of injection-molded products [8], [9]. This study evaluates the influence of screw parameters and their impact on flow and product quality, thereby enabling the design of injection molding machine screws and further improving product quality.

2. Research content and calculations

2.1. Technical requirements

This study aims to design the screw and evaluate the effects of its parameters on flow quality and product quality.

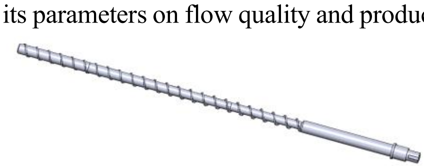

Figure 1. *The model used for conducting the research*

Material: Extrusion screws are typically made from wear-resistant steel, hardened steel, or special alloys to ensure high durability and wear resistance. In this study, the material selected is 38CrMoAlA.

The screw in an injection molding machine must be designed to ensure optimal operational efficiency and high product quality. The main requirement is to optimize design factors, including screw geometry (flight depth h, screw diameter *D*, taper angle *Ψ*, length *L*, screw pitch *t*, helix angle *φ*), the relative position between the screw and the barrel, and rotational speed, to achieve stable flow quality and products with high accuracy, surface finish, and consistency. The study focuses on evaluating the design parameters of the screw to improve the efficiency of conveying, compressing, and melting the plastic, rather than optimizing each factor individually.

2.2. Screw design calculations

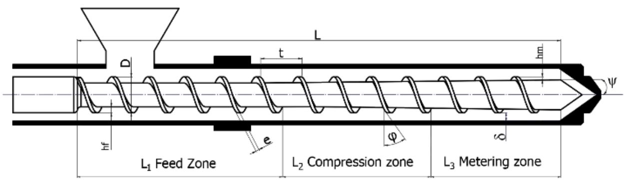

Figure 2. *The parameters of the plastic feeding screw*

Selected machine: Clamping force: 40 tons, maximum injection volume: 64 cm³, screw diameter *D* = 30 mm.

Selected injection pressure: 10,000 N/cm² = 1,000 kg/cm²

F = P.A = 1000.π (2.5²/4) = 4908.7Kg = 49087 N

Cylinder holding volume: $V_{XL} = K_1.V_d$ (1)

Where: V_d: Injection volume;

K_1= Holding coefficient (1.25 ÷ 1.3);

V_{XL}= 1.25 x 64 = 80 cm³.

Plastic flow rate into the mold: $Q = \frac{V_{XL}}{t} = 66$ (cm³/s)

Cylinder holding volume can also be calculated as:

$$V = \frac{\pi}{4}.d^2.H = K_2.\frac{\pi}{4}.d^3(\text{cm}^3) \quad (2)$$

Where: d: Inner diameter of the cylinder (cm);

H: Screw stroke (cm);

K_2: Stroke coefficient, K_2 = 2 ÷ 3.

Screw stroke:

$$\text{H} = \frac{V_{XL}}{\frac{d^2.\pi}{4}} = \frac{80}{\frac{3.12^2.\pi}{4}} \quad (3)$$

H =10.46 cm= 105 mm

Screw parameters:

- Screw diameter: D = 30 mm.
- Screw length:

L = (20 ÷ 35) x D = 35 x D = 35 x 30 = 1050 mm

- Clearance between screw tip and cylinder inner diameter:

δ = 0.8÷1.2mm

- Flight thickness: e = 0.1 x D = 0.1 x 30 = 3 mm
- Screw pitch: t = D = 30 mm
- Flight helix angle (for granular material): φ = 15°
- Screw rotational speed:

$$n = \frac{42.K.\cos\alpha}{\sqrt{D}.\sin\alpha.\sin(\alpha+\theta)}(\text{RPM}) \quad (4)$$

Where:

D: Screw diameter (cm); K: Coefficient, select K = 0.5;

θ: Friction angle between material and screw, degrees;

θ = arctg*f* with *f* being the friction coefficient between the material and the screw.

Friction coefficients for some plastics with steel H.L. Vien, 2003 [1]: PE = 0.25; PVC = 0.25; PMMA= 0.35; PS = 0.35; PA (Nylon) = 0.25

Select *f*=0.35 → θ = arctg*f* = 19.29°.

α: Screw groove helix angle, degrees.

$$\tan\alpha = \frac{t}{\pi.D} = \frac{30}{\pi.30} = 0.318 \rightarrow \alpha = 17.64°$$

Substitute the coefficients into the formula to calculate the screw rotational speed:

$$n = \frac{42\times 0.5.\cos 17.64°}{\sqrt{3}\times\sin 17.64°\times\sin(17.64°+19.29°)} = 65(\text{RPM})$$

Material conveying speed along the screw:

$$v = \frac{S\times n}{60} = \frac{30.10^{-3}\times 65}{60} = 0.0325\ (\text{m/s}) = 3.25\ \text{cm/s}$$

Machine capacity: $N = 47.D^2.S.n.\rho.\mu.K$ (5)

Where: D: Screw diameter, m;

S: Screw pitch, m;

n: Screw speed, RPM;

ρ, Material density; ρ = 1.18g/cm³ = 1180kg/m³;

K: Coefficient for cross-sectional reduction due to the helix angle, K = 0.7.

Machine output:

$N = 47.D^2.S.n.\rho.\mu.K$

$N = 47\times 0.03^2\times 0.03\times 65\times 1180\times 0.4\times 0.7 = 27\ (\text{kg/h})$

After selecting the design approach and calculating the parameters, the authors created a 3D sketch of the injection molding machine screw using design software, as shown in Figure 1.

3. Survey and results

3.1. Relationship between shear stress and screw flight depth

The relationship between shear stress and shear rate is as follows:

$$\mu = \frac{\tau}{s} \quad (6)$$

Where:

μ (Pa.s): Viscosity coefficient of the molten plastic material;

τ: Shear stress;

S: Shear rate.

According to the relationship between shear rate and flow rate Q:

$$S = \frac{V}{h} \tag{7}$$

Where: V is the flow velocity of the plastic (mm/s) and h is the screw flight depth (mm).

From the screw flow rate equation:

$$V = \frac{Q}{A} \tag{8}$$

Where: Q: Plastic flow rate (mm^3/s);

A: Flow gap area, approximately $W.h$;

Combining (6), (7), and (8), we have:

$$S = \frac{Q}{W.h^2} \tag{9}$$

From here, the relationship between shear stress τ, screw flight depth h, and screw speed n can be expressed as:

$$\tau = \frac{\mu}{k.h^3}\left(\frac{\pi.D.n.\cos\theta.k.h^2}{60} - \frac{k.h^4.(P_1 - P_2)}{12.\mu.L}\right) \tag{10}$$

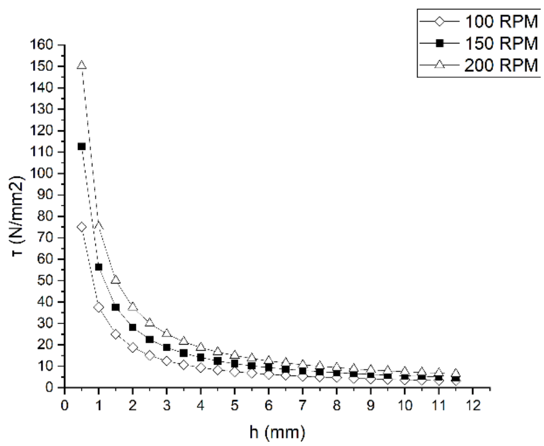

Figure 3. *The correlation between stress (τ) and flight depth of the screw (h)*

The analysis results of the relationship between screw flight depth h and shear stress show that when h decreases from 3.0mm to 1.5mm, the shear rate S increases significantly, improving the plastic mixing ability. However, if h is too small (below 1.5mm), high shear stress may cause plastic degradation. This indicates that h needs to be considered in conjunction with other factors such as flow rate and pressure to achieve optimal efficiency.

The chart showing the relationship between shear stress τ and screw flight depth h indicates that τ decreases as h increases. For small h values (from 0.5mm to about 3.0mm), the stress decreases rapidly, but the rate of decrease slows as h continues to increase. In addition, screw speed also has a significant effect, with a speed of 200 RPM generating higher τ values compared to 150 RPM and 100 RPM. Higher speeds increase friction and cutting force in the compression zone of the screw, leading to higher shear stress.

Specifically, screw flight depth h and screw speed n (RPM) need to be optimized to balance the efficiency of mixing, compression, and plastic uniformity. High speed is suitable for high-viscosity plastics to generate strong shear force, while low speed is appropriate for plastics with low melting temperatures to avoid overheating.

3.2. Relationship between screw flight depth and shear rate

The formula for calculating shear rate is based on the original formula for shear rate, as changes in depth h lead to different shear rates in different zones.

$$S = \frac{\pi.D.n}{60.h} \tag{11}$$

$$S = f(h)$$

Where: S: Shear rate;

D: Screw diameter;

h: Screw flight depth;

n: Rotational speed;

$f(h)$: Function relating depth h and shear rate.

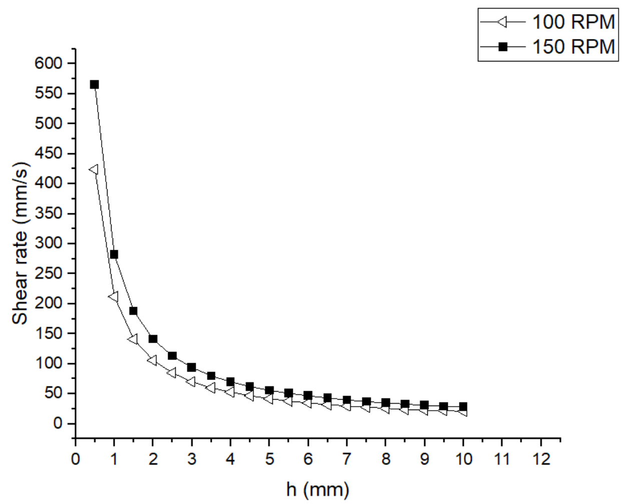

Figure 4. *The relationship between screw flight depth (h) and shear rate (S)*

Shear rate S is determined by screw diameter D, rotational speed n, screw flight angle φ, and screw flight depth h. Results show that when h decreases from 3.0mm to 1.5mm, shear rate S increases significantly (from about $50s^{-1}$ to $100s^{-1}$ at $n = 150$ RPM), improving plastic mixing. However, if h is too small (below 1.5mm), shear rate S exceeds $120s^{-1}$, which may cause thermal degradation of plastic, especially for heat-sensitive plastics like PVC. Conversely, large h (2.5–3.0mm) reduces shear rate S to below $60s^{-1}$, resulting in poor mixing.

To balance mixing ability and avoid degradation, the optimal value for h should be in the range of 1.8–2.0mm in the melting zone. This ensures shear rate S is in the range of $70–90s^{-1}$, suitable for common plastics such as PE, PVC, and PS, and supports the ideal shear rate without damaging the plastic. In the feeding zone, h can be larger (2.5–3.0mm) for efficient plastic feeding and gradually decreases through the compression zone (2.0–2.5mm) to maintain a reasonable shear rate S.

The chart showing the relationship between shear rate S, screw flight depth h, and screw speed demonstrates important characteristics of the plastic compression and mixing process. Shear rate S drops sharply as h increases from 0.5mm to about 3.0mm and decreases more slowly at larger h values. The most significant drop occurs at the initial stage when h is small, due to the compression zone generating high shear and friction. As h increases, the larger space reduces the shear force, leading to a gradual decrease in shear rate.

For screw design, screw flight depth h needs to be optimally adjusted to balance shear rate and mixing efficiency, ensuring uniform plastic quality without causing degradation. In operation, rotational speed should be flexibly adjusted: high speed is suitable for high-viscosity plastics to increase shear force and uniformity, while low speed is a safe choice for easy-flowing or heat-sensitive plastics.

3.3. Correlation between screw diameter and screw flight depth

The formula for calculating the plastic flow rate in the cylinder is determined as follows:

$$Q = \frac{\pi.D.n.\cos\theta.W.h}{2} - \frac{W.h^3.(P_2 - P_1)}{12.\mu.L} \quad (12)$$

Where: Q: Plastic flow rate in the cylinder (mm^3/s);

D: Screw diameter (mm);

W: Distance from the screw profile to the inner wall of the cylinder (mm);

h: Screw flight depth (mm);

P_2, P_1: External and internal cylinder pressures (atm);

With: W = k.h

The relationship between screw diameter D, screw flight depth h, and screw speed is given by:

$$D = \frac{60}{\pi.n.\text{Cos}\,\theta.k.h^2}.\left(Q + \frac{k.h^4.(P_1 - P_2)}{12.\mu.L}\right) \quad (13)$$

The correlation between screw diameter D and screw flight depth h affects the flow efficiency of plastic in injection molding machines. Based on the shear rate S and flow rate Q formulas, the relationship between D and h is determined as follows: when D increases (for example, from 25mm to 30mm), shear rate S increases due to the larger D, while smaller h (from 2.5mm to 1.5mm) further increases S. However, the plastic flow rate depends on the area $D.h$, so if h is too small, the flow rate may decrease even if D is large. Analysis results show that when D = 30mm and h = 2.0mm, the shear rate reaches about $80s^{-1}$, which is good for plastic mixing. If h drops below 1.5mm with D = 30mm, shear rate S exceeds $100s^{-1}$, risking plastic degradation, especially for heat-sensitive plastics. Conversely, large h (2.5mm) with D = 25mm reduces shear rate S below $60s^{-1}$, resulting in poor mixing.

The chart showing the relationship between screw diameter D, screw flight depth h, and screw speed reveals several important trends in the plastic compression and conveying process. As screw diameter D increases, screw flight depth h gradually decreases, which applies to both 100 RPM and 150 RPM speeds. However, the decrease in h occurs faster at 150 RPM than at 100 RPM, especially at small D values.

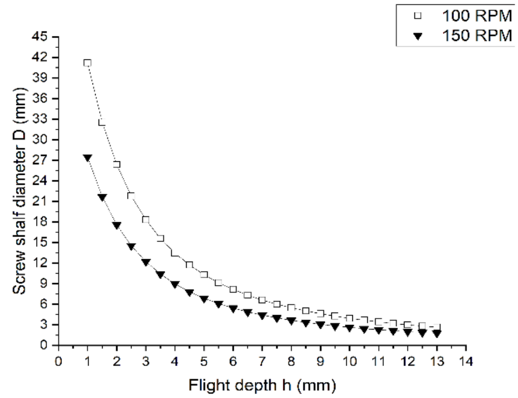

Figure 5. *The correlation between diameter (D) and screw flight depth (h)*

The chart helps determine the optimal size for the screw and flight based on diameter D and speed. A screw with a large diameter and low speed requires a deeper flight to efficiently process plastic. When higher output is needed, a screw with a larger diameter and higher speed can be used, but the flight depth should be reduced to avoid excessive shear force. These adjustments will optimize the mixing and compression process, ensuring efficient flow and plastic quality.

3.4. Correlation between screw taper angle and length L_2

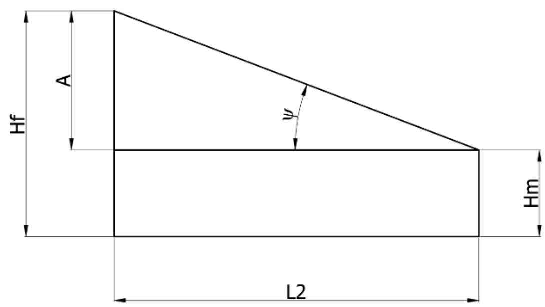

Figure 6. *Diagram for calculating the shaft section length L_2 and the screw shaft taper angle*

$$A = Tan(\Psi) \times L_2 \quad (14)$$

In the design of the compression section of the screw, where the plastic is compressed and melted before moving to the melting section, the taper angle Ψ and the length of the compression section L_2 are two important parameters affecting plastic compression efficiency. Specifically, the taper angle Ψ represents the inclination of the groove in the compression section, while L_2 is the length of this section; both are applied to the screw's compression section. The pressure formula in the compression section is calculated based on the taper angle Ψ and length L_2, with a small Ψ helping to gradually increase pressure, while a sufficiently long L_2 ensures complete plastic compression.

Analysis results show that when Ψ < 0.01rad and L_2 = 350–400mm (equivalent to 1/3 of the total screw length L), it is suitable for effective plastic compression without causing overpressure. Therefore, the optimal values for Ψ and L_2 are proposed as Ψ < 0.01rad and L_2 = 350–400mm for the compression section, ensuring stable plastic compression and supporting flow quality for plastics such as PE, PVC, and PS.

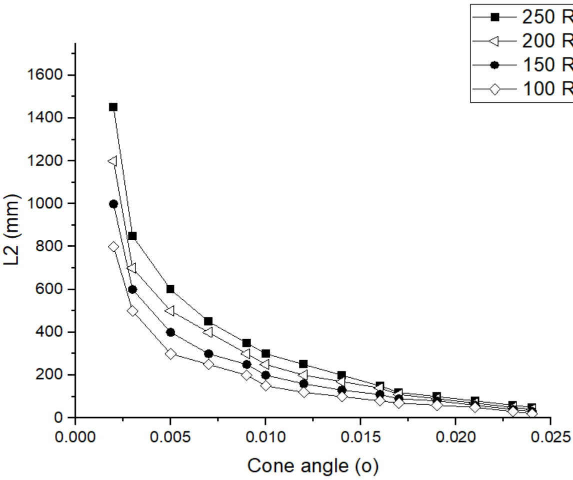

Figure 7. *Chart showing the relationship between the taper angle and the length L_2*

The chart showing the relationship between taper angle Ψ and screw length L_2 indicates a clear trend. When taper angle Ψ increases, screw length L_2 decreases. In the initial stage, when the taper angle is small (close to 0), L_2 decreases rapidly. However, when the taper angle exceeds a certain level (about $\Psi > 0.01$), the reduction rate of screw length slows down and gradually stabilizes.

Specifically, in the initial stage ($\Psi < 0.01$), screw length changes significantly; each slight increase in taper angle causes a considerable reduction in length, indicating that at small taper angles, screw length strongly depends on the taper angle value. After the taper angle exceeds $\Psi > 0.01$, length L_2 gradually stabilizes, and the chart flattens, indicating that at this stage, changing the taper angle no longer significantly affects the length of the screw's compression section. In design, increasing the taper angle reduces screw length, helping save space, reduce the mass of the screw and machine, and may improve plastic processing efficiency. However, when the taper angle is too large, the pressure on the screw surface increases, potentially leading to higher wear risk and requiring more durable materials during manufacturing. The taper angle Ψ needs to be optimally selected to ensure the compression section length L_2 meets the plastic loading and melting requirements. At the same time, a balance must be achieved between processing efficiency and screw durability throughout its service life.

3.5. Correlation between depth A and compression ratio r

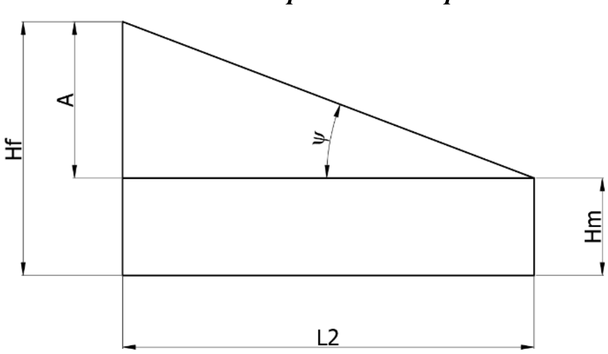

Figure 8. *Diagram for calculating the depth A*

From the diagram, we have:

$$A = H_f - H_m \tag{15}$$

$$\frac{H_f}{H_m} = 2\text{-}2.5 \tag{16}$$

From (15) and (16), the relationship is derived as follows:

$$A = H_m(r - 1) \tag{17}$$

The chart showing the relationship between screw depth A and compression ratio r indicates several clear trends in the plastic compression and conveying process. Screw depth A increases as compression ratio r increases, but the degree of increase depends on the initial values indicated by the curves. In particular, the curves of metering zone depth H_m show differences in the increase of screw depth as the compression ratio increases.

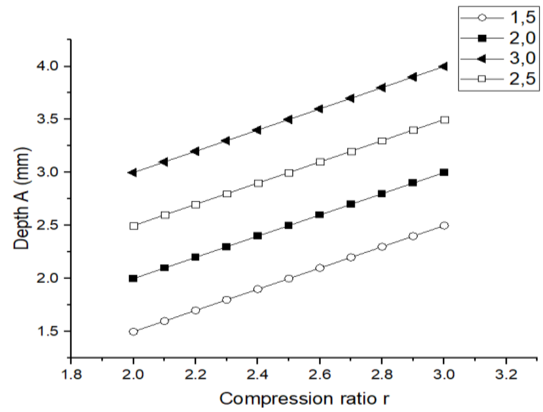

Figure 9. *Chart showing the relationship between depth A and compression ratio r*

In design, screw depth is important for the ability to compress and process material. If depth A is small, the machine operates at low pressure, suitable for low-viscosity plastics or those not requiring high pressure. However, when depth A is large, the screw can process material at higher pressure, suitable for high-viscosity plastics or when strong compression is needed.

Compression ratio r reflects the ratio between the pressure at the end and the beginning of the screw, directly affecting material compression. When compression ratio r increases, the material is more tightly compressed, requiring the screw to have a greater depth A to handle and maintain stable flow.

3.6. Results

A detailed analysis of screw design factors in injection molding machines, including screw flight depth h, screw diameter D, taper angle Ψ, compression section length L_2, rotational speed, and screw structure. The goal is to improve the quality of plastic flow and plastic quality in the cylinder by balancing these factors. Specifically, the analysis of shear stress and shear rate S shows that screw flight depth h significantly affects plastic mixing ability. The optimal value of h must be appropriate to ensure shear stress S is within the allowable range to increase plastic holding capacity, maintain pressure and compression efficiency, and avoid plastic degradation. For screw diameter D, when D increases, shear rate S increases due to a larger contact area, improving plastic flow and mixing ability. A larger contact area also increases shear stress, which may cause plastic degradation if not combined with an appropriate screw flight depth. However, if D is small, shear rate and flow decrease, leading to low pressure and poor mold filling, resulting in poor product quality. Each type of plastic has a different viscosity depending on its characteristics. For each type of plastic, a certain shear rate range is required to ensure mixing, uniformity, and plastic quality. For low-viscosity plastics (e.g., PE, PS, PA, PP, etc.), their characteristic is easy flow, and they usually do not require a high shear rate, but too high a shear rate can easily cause plastic degradation. For medium and high-viscosity plastics (e.g., PC, PMMA, ABS, etc.), higher shear rates are needed to ensure uniform mixing. Increasing the shear rate can be achieved by adjusting the screw diameter, screw depth, or both to increase the contact area. However, adjustments must be appropriate to avoid excessive shear rate causing plastic degradation.

The correlation between screw taper angle and length L_2 focuses on the design of the compression section, determining that the optimal taper angle Ψ and compression section length L_2 optimize the plastic compression process, ensuring stable pressure and efficient plastic conveying.

4. Conclusion

The results obtained from this study indicate that the technical parameters of the screw have a significant impact on the quality of plastic during the injection molding process. Adjusting these parameters affects the melting capability, mixing uniformity, and the stability of plastic flow within the cylinder. Therefore, this research can serve as a valuable reference for the design, improvement, and manufacturing of screws for injection molding machines, aiming to enhance operational efficiency and the quality of molded plastics. Furthermore, the evaluation of screw parameters and their influence on flow characteristics and plastic quality in the cylinder will contribute to increasing molding efficiency and improving the performance of injection molding machines in production.

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