Experimental research on laser micro-texture friction coefficient of V-clamp Mold

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Abstract. The friction pair between the V-clamp stamping mold and the blank directly affects the forming quality of the V-clamp. The goal of this paper is to optimize the mold friction coefficient of V-clamp with laser micro-texturing technology. To validate the texture area occupancy rate and the depth of morphological depression, the actual working condition was simulated, and the friction test was conducted. The experiment results implies that, in the case of the same morphological depression depth, the friction increase effect achieved the best with 15% texture area occupancy rate and the friction reduction effect worked best while 50%; the sample with 15% area occupancy rate and with the morphological depression depth 7.192μm had the best friction reduction effect. The research results provided a basis for surface optimization of V-clamp stamping mold.

1. Introduction
V-clamp is widely used in the pipeline connection of automotive exhaust systems.[1] Due to the existence of complex features such as bosses and arc surfaces, cracking and wrinkling during the clamp forming process frequently occurred. Failure form, which seriously affected the performance.[2] [3] The friction coefficient between the V-clamp stamping mold and the blank has great influence on the forming quality of the clamp. This paper used experimental methods to study the friction coefficient (between the mold and the blank). According to the setting parameters of the actual condition stamping of V-clamp, the effect of laser micro-texture on friction coefficient was studied, and focused on the influence of the texture area occupancy rate (TAOR) and the morphological depression depth (MDD) on friction coefficient.[4] It could provide the basis for the optimal design of V-clamp mold surface.

2. Experiment

2.1. Experimental equipment

2.1.1. Multi-functional friction and wear testing machine. The experimental equipment is the MFT-5000 multi-functional friction and wear testing machine of Rtec Instruments, CA, USA. The equipment adopts modular design, including rotation module, reciprocating module, ring block module and upper drive module. The user can match the required module as needs. This experiment needed to simulate the actual stamping conditions of the V-clamp, so it was performed on the
The high-speed reciprocating module is usually used for testing ball disk, ball plate, pin plate, piston ring bushing, etc. The driving device is installed on the XY platform. The MFT equipment can run the reciprocating drive and the XY platform simultaneously, and can be programmed independently, the stroke of the module can be adjusted. The sample is installed on the reciprocating module with a standard universal fixture, or through the four positioning holes on the top of the reciprocating module. The stroke and speed can be adjusted as required, and the accurate stroke is measured by a high-resolution LVDT displacement sensor. The maximum stroke is 30 mm and the maximum frequency is 70 Hz.

2.1.2. Other auxiliary equipment. The following auxiliary equipments were also used in this experiment

(1) CNC ultrasonic cleaner
   The KH-500DE CNC ultrasonic cleaner was used to clean the friction coefficient measurement sample, and remove surface oil.

(2) 3D morphology detection equipment
   The sample surface micro-texture morphology was detected by nanofocus 3D high resolution confocal microscope.

2.2. Experiment material

2.2.1. Experiment materials and dimensions. Due to the sliding friction pair of surface contact between the mold and the material sheet in the forming process of V-clamp, in order to simulate actual working conditions, the pin-plate sample of surface to surface contact was adopted. The upper sample was a Cr12MoV cylindrical pin with a diameter of 6 mm and a height of 20 mm, with a surface hardening treatment and a hardness up to 65HRC. The lower sample was a SUS304 block with size of 35 mm × 25 mm × 2 mm (length × width × height). The sample dimensions are shown in Figure 2.
2.2.2. Lubricating oil. The 460-drawing oil was used in the experiment because it is also used in the mass production process of V-clamps. This lubricating oil is mainly used for metal stamping and drawing processing, with excellent abrasion resistance and extreme pressure resistance. It can effectively reduce workpiece burrs and strains during the molding process but also improve the surface finish of the workpiece, prevent mold damage and burning, extend the mold life.

2.3. Experiment scheme for friction coefficient measurement and sample preparation
Under the requirements of the mold on the friction coefficient and lubricating state, this experiment measured the influence of the TAOR and the MDD on friction coefficient. Samples with different parameters was prepared first.

2.3.1. Preparation of samples with different texture area occupancy rates
When the laser micro processing system processed micro-textures on a plane, it is a planar square lattice processing. In order to realize the controllable processing of laser micro TAOR, a calculation model of micro TAOR is established, as shown in Figure 3.

In Figure 3, D is the diameter of a single point of the micro-texture, L is the row spacing of two adjacent two rows of micro-textures, and K is the column spacing of two adjacent two columns of micro-textures. Thus, the calculation formula of the TAOR is as follows:

$$f = \pi \left( \frac{D^2}{4KL} \right) \times 100\%$$  \hspace{1cm} (1)
For easy operation during the experiment, set the row spacing and column spacing to the same value, that is, \( L = K \). At this time, the calculation formula of the TAOR is as follows:

\[
f = \pi \left( \frac{D^2}{4L^2} \right) \times 100\%
\]

(2)

The experiment was performed with an IPG fiber laser in a laser micro-intelligent processing system. According to the simulation results and experiment requirements, M-shaped morphology was selected (laser process parameters: laser power of 50W, pulse width of 5000\( \mu \)s, morphology parameters: diameter of 285\( \mu \)m, height of 3.646\( \mu \)m, MDD of 3.546\( \mu \)m). The TAORs were 5\%, 10\%, 15\%, 30\%, and 50\%. The processing parameters are shown in Table 1. After the sample processing was completed, the surface micro-texture morphology was observed with the objective lens of nanofocus 3D high-resolution confocal microscope with 5 \( \times \) magnification, as shown in Figure 4.

![Figure 4. Surface morphology of samples with different texture area occupancy (5 \( \times \) magnification).](image)

| Texture area occupancy rate f (%) | Spacing L (\( \mu \)m) | Rows | Rows |
|----------------------------------|---------------------|------|------|
| a 5                              | 1130                | 7    | 7    |
| b 10                             | 799                 | 9    | 9    |
| c 15                             | 652                 | 11   | 11   |
| d 30                             | 461                 | 15   | 15   |
| e 50                             | 357                 | 18   | 18   |
2.3.2. Preparation of samples with different depths of morphological depression. Under the requirements of the experiment friction coefficient, the micro-texture MDD as a single parameter, the influence of the MDD on friction coefficient has been investigated. On the basis of the results of the laser micro-texture process test and Zhu Yaqiong's research on the surface micro-texture elastohydrodynamic lubrication performance, [5] it was found that for the TAOR of 7% to 20% has the most obvious effect. [6] Therefore, in this experiment the TAOR of the samples at different MDDs was 15%, the processing and morphological parameters are shown in Table 2.

| Laser power density (W/mm²) | Pulse width (µs) | Diameter (µm) | Height (µm) | Depression depth (µm) | Spacing (µm) | Rows | Columns |
|-----------------------------|------------------|---------------|-------------|-----------------------|--------------|------|---------|
| a                           | 2.55×10⁴         | 5000          | 285         | 3.646                 | 3.546        | 652  | 11      | 11      |
| b                           | 5.60×10⁴         | 11000         | 406.2       | 3.07                  | 5.7          | 929  | 8       | 8       |
| c                           | 3.57×10⁴         | 15000         | 396.9       | 3.865                 | 7.192        | 908  | 8       | 8       |
| d                           | 4.58×10⁴         | 15000         | 400.4       | 3.79                  | 9.608        | 916  | 8       | 8       |
| e                           | 4.58×10⁴         | 23000         | 420.3       | 4.16                  | 11.61        | 962  | 8       | 8       |

The surface micro-texture morphology was detected with the nano focus 3D high-resolution confocal microscope after the sample processing was completed, are shown in Figure 5.

2.4. Experimental steps for determination of friction coefficient

2.4.1. Pre-experiment preparation. Under the experiment requirements, the upper sample surface was cleaned with CNC ultrasonic cleaner for 10 minutes to remove the oil stains. The sample was taken out and blown dry with a blower. The sample surface morphology was detected by nanofocus 3D high-resolution confocal microscope to observe whether the morphology parameters met the experiment requirements.

2.4.2. Sample clamping and parameter setting. The sample was clamped into the MFT-5000 to simulate the actual forming condition of V-clamp. Set up procedure, the loading force was set as 80 N, the corresponding pressure 2.8 MPa, the upper sample was fixed, the lower sample reciprocated, the stroke 20 mm, the reciprocating frequency 0.5 Hz, and the linear speed 20 mm/s. Applied 4 ml the 460-drawing oil to the sample surface evenly, to ensure that the oil-rich state was maintained during the experiment. The friction coefficients were collected synchronously during the experiment, and stopped the experiment after the values were stabilized.

2.4.3. Experiment data collation. The sample was taken out and cleaned with the CNC ultrasonic cleaner for 10 min to remove the oil stains, and blown dry with a blower. The sample was packed into the sample bag and labeled. By sorting out the test data, plotted the friction coefficient curve under different parameters, analyzed the investigated of each parameter on the friction coefficient, and determined the optimal parameters.
3. Experiment results and analysis of friction coefficient

3.1. Influence and analysis of texture area occupancy rate on friction coefficient
The curve of variation friction coefficient, made of Cr12MoV cold work mold steel material, the with different M-shaped morphology TAOR and smooth sample, as shown in Figure 6.
Figure 6. With different texture area occupancy and smooth sample friction coefficient variation curve.

From Figure 6 is concluded:
(1) When the sample TAOR was 5%, the average friction coefficient was slightly larger and fluctuated less than that of the untextured sample, and the operation was stable; when the TAOR was 10% and 15%, the friction coefficient and fluctuation were both large, and the runtime was long; when the TAOR was 30% and 50%, the average friction coefficient decreased gradually, and the operation was stable and the fluctuation was small; when the TAOR was 50%, the average friction coefficient was smaller than that of the untextured sample.

(2) M-shaped morphology within the range of test parameters, as the TAOR increased, the average friction coefficient increased first and then decreased, and the fluctuation of the friction coefficient also increased first and then decreased.

Because the surface of the newly processed friction pair had roughness, as the TAOR increased, the roughness increased, and the geometry of the texture point had convex peaks and sharp corners, the surface microscopic peaks and valleys were embedded in each other. Under the friction, the convex peak was sheared, and the abrasive debris was mixed into the lubricant and mixed on the sample contact surface. The increase of TAOR led to the increase of sample shear stress and the increase of abrasive debris on the sample contact surface. Therefore, as the TAOR increased, the average friction coefficient and the fluctuation increased; As the TAOR continued to increase, on the one hand, due to the aggregation of adjacent texture points, on the other hand, the center of M-shaped morphology had a sag area, so that there were more oil storage units, the ability to absorb abrasive debris was enhanced, the friction and wear of the abrasive particles was reduced, and the lubricating effect of the sample surface was improved. So, the average friction coefficient reduced and the fluctuations decreased.

In summary, within the range of test parameters, the samples with M-shaped morphology with TAOR of 15% had the best friction increasing effect, but the friction coefficient fluctuated greatly; with TAOR of 50% had the best friction reduction effect and the smallest fluctuation.

3.2. Influence and analysis of the depth of texture morphological depression on friction coefficient

The curve of variation friction coefficient is shown in Figure 7. The samples made of Cr12MoV cold work mold steel material, and with different MDD and smooth.
From Figure 7 is concluded:

Under the condition of 15% TAOR, within the range of test parameters, as the MDD increased, the average friction coefficient decreased first and then increased, and the fluctuation of the friction coefficient also decreased first and then increased.

When the MDD increased from 3.546μm to 7.192μm, the space in the depression area at the center of the micro-textured morphology increased gradually, that is, the oil storage space became larger, the quantity to absorb abrasive debris was increased, and the friction and wear on the sample surface was reduced. Therefore, improved the friction coefficient, shortened the run-time, the average friction coefficient and the fluctuation were reduced, and the operation was stable; when the MDD continued to increase, the average friction coefficient increased. At this time, the MDD was too large to extrude the lubricant oil from the textured cavity. At the same time, the melting and concretion around the micro-textured morphology increased the shear strength and roughness of the sample surface, so the average friction coefficient gradually increased.

In summary, the samples with MDD of 7.192μm had the best friction reduction effect and the smallest fluctuation.

4. Conclusion

The laser micro-texture with different parameters was processed on the V-clamp mold material Cr12MoV, with the V-clamp material SUS304 formed a surface-to-surface contact pin-plate friction pair, the lubricating was 460-drawing oil. By setting experimental parameters to simulate the actual working conditions of V-clamp stamping, and the influence of different texture area occupancy rates (M-shaped morphology) and different depths of morphological depression on friction coefficient have been investigated, and compared them with the smooth sample. Concluded as follow:

1) Within the range of experiment parameters, the higher the texture area occupancy rate of M-shaped morphology sample, the average friction coefficient increased first and then decreased, and the fluctuation of the friction coefficient also increased first and then decreased; the sample with area occupancy rate of 15% had the best friction increasing effect, but the friction coefficient fluctuated greatly; with area occupancy rate of 50% had the best friction reduction effect and the smallest fluctuation.
(2) Under the condition of 15% texture area occupancy rate, within the range of experiment parameters, as the morphological depression depth increased, the average friction coefficient decreased first and then increased, and the fluctuation of the friction coefficient also decreased first and then increased; the sample with depression depth of 7.192μm had the best friction reduction effect and the smallest fluctuation.

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