

Investigating Wear and Predicting Lifetime of the Roller Cavities for the Net-shape Blade Rolling

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Investigating wear and predicting lifetime of the roller cavities for the net-shape blade rolling

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Abstract: The die undergoing severe loads which induces inevitably wear in the pressure forming process, and the wear of die arouses obsessions about the die's service lifetime. In order to obtain the geometrical shape transformation caused by wear and predict the service lifetime for a pair of rollers in net-shape blade rolling process, this paper quantified the distributions and evolutions of the local wear over roller cavities based on the local contact load responses, and predicted the lifetime which related to wear by a mathematical models. Firstly, the net-shape blade rolling process and the local contact load responses were summarized. Then, an improved wear model was provided based on the Archard formula, and the impact factors of the model was standardized by a regression analysis experiment. The transient wear distributions and evolutions over the roller cavities were enumerated, and the wear distribution for one rolling cycle was calculated based on wear accumulation effect. Finally, a lifetime prediction model was proposed to predict the service lifetime of the rollers according to the wear accumulation effect, and an experimental verification was carried out to validate the model. The results showed that the wear model and lifetime prediction model can be used for investigating the wear and lifetime prediction of the roller cavities for the net-shape blade rolling process.

Keywords: net-shape rolling blade, roller cavities, local contact pressure, local sliding, wear model, lifetime prediction model

1. Introduction

The manufacturing accuracy of components is sensitive to the geometrical shape of die cavity in pressure forming process, this feature is particularly obvious to the rolling process of the net-shape rolling blade [1]. Hence, a batch of compressor blades with the high accuracy and good uniformity requires a pairs of roller cavities with the stable geometry profiles and persistent mechanical performance in blade manufacturing industry [2]. However, the roller cavity surfaces suffers the cyclic deformation resistance from the blank, which induces unknown wear over the roller cavity surfaces in blade rolling process [3]. The unknown wear over the cavity surfaces arouses obsessions about the roller's service life and the formed blade's precision [4-5]. Hence, investigating the wear and predicting the service lifetime a pair of roller are significant for ensuring the manufacturing accuracy of the blades.

The analytical, numerical and experimental methods has been combined to investigate the wear and predict service life for a variety of pressure forming process. For aspects of the mould wear studying, Torres et al. [6] used FEM to simulate hot metal shearing process and found a good correlation between

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the stress distributions on the tool and wear location observed on tool shape. Luo et al. [7] investigated the wear characteristics of the die in a process of the hot forging turbine blade, the influences of the temperature on the wear evolution and distribution were discussed. Galakhar et al. [8] studied adhesive wear between a hardened tool steel sliding against a mild steel wheel, and investigated wear mechanisms of material transfer in a cold roll forming processes. Zhang et al. [9] studied the influences of the processing parameters on the mold wear and optimized the parameters in cross wedge rolling process, the optimized parameters could prolong the mold life greatly. Wang et al. [10] developed a thermal–mechanical coupled simulation model for two-roll cross wedge rolling, and investigated the influence of the cooling condition on the wear of rollers. The location of the maximum wear was marked, and the good cooling could reduce wear effectively. Bataille et al. [11] characterized the wear of the working rollers during a hot rolling milling process, a non-destructive methodology was proposed to measure the topography of the working roller, and a wear criterion was defined in order to determine the maximal wear. Pereira et al. [12-14] investigated the contact pressure and local sliding over the die radius in a stamping process, and the possible trends of wear over the radius were predicted. Jin et al. [15] studied the contact condition and wear of roller in cold rolling, the distribution of local contact pressure and sliding were quantized, and the relative wear was predicted based on contact responses. Cui et al. [16] studied the wear mechanisms of AISI D2 steel trim die and their effects on plastic deformation. For aspects of the lifetime predicting, Dukwen et al. [17] investigated the wear mechanisms of glassy carbon tools for fused silica molding and predicted the mold lifetime based on the critical size of a notch. Kim et al. [18] developed two methods for estimating the service life of dies in hot forging process, the plastic deformation of the die and calculating abrasive tool wear were used to predict life respectively. The influences of the initial die temperature and forming velocity were discussed. Yin et al. [19] proposed a calculation model to predict wear of the fine-blanking die during its whole lifetime based on BP neural network. The model was validated by a case study, the results showed that the calculation model had a very good agreement with the real manufacture. Kozjek et al. [20] predicted the fatigue life of die for forging brass ball based on finite element analysis, the fatigue cracks was the main failure mode and a recommended load cycles was provided. According to above analysis, wear service lifetime characteristics of the pressure forming dies are still less reported, especially in the industry of manufacturing component with a complex shape, small machining allowance and high precision requirement.

Consequently, this paper aimed to reveal the distributions and evolutions of the wear over the roller cavities in net-shape blade rolling process, and predict the service lifetime of a pair of roller based on the wear distributions. The organization of the paper is as follows, the Section 2 introduced organization of this paper and summarized the previous research which were bases for this study. In Section 3, an improved wear model was proposed and standardized, and the wear distributions and evolutions over roller cavities were quantized. In Section 4, a lifetime prediction model was proposed and the cycle time of a pair of roller was predicted and validated. Finally, conclusions are provided in Section 5.

2. Research Methods

2.1. Outline for investigating wear and predicting lifetime of the net-shape blade rolling cavities

This paper investigated the wear and predicted the severe lifetime of the rollers for net-shape blade rolling, a wear model and a lifetime predicting model were proposed respectively. The flowchart of the study is showed in Fig 1. The contact load responses over

the roller cavities were already achieved at previous research. An improved wear model was proposed and standardized, and the wear distributions and evolutions of the roller cavities were investigated based on the contact responses and the wear model. Then, a lifetime predicting model was proposed to calculate the number of the rolling cycles, and an experiment was carried out to validate the wear model and lifetime prediction model.

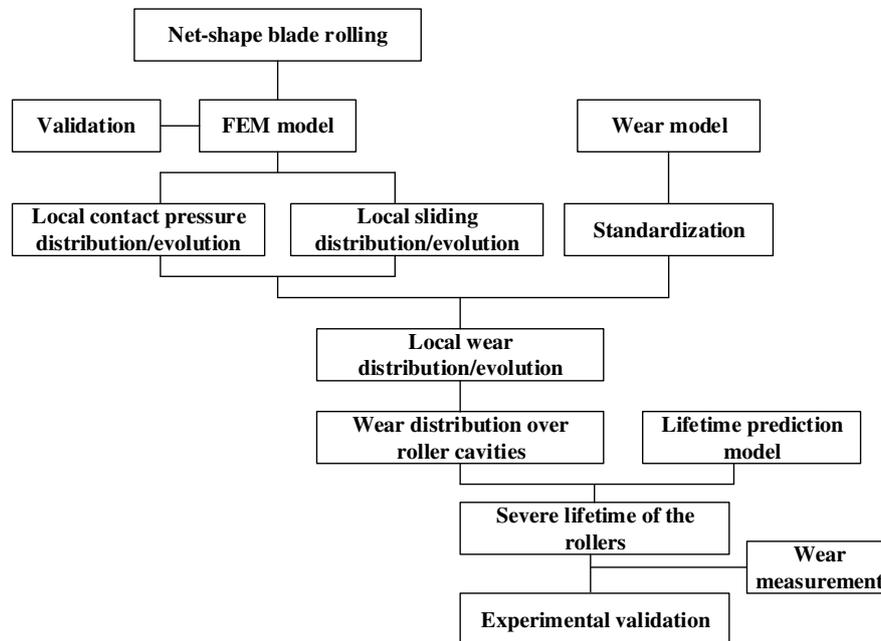


Figure 1. Flowchart for investigating wear and predicting lifetime of the net-shape blade rolling die

2.2. The physical model and the contact responses of the net-shape blade rolling process

In net-shape blade rolling process, the roller cavity surfaces squeezing the work blank with the rotation of rollers, and the blank occurred plastic deformation by the squeezing action. Fig. 2 shows a typical compressor blade and rollers, and a schematic of the blade rolling process. The material of the blade is GH4169 superalloy. The blade is a typical thin-walled component, the cross section curves of the blade demonstrate as severe bending and twisting, shown as Fig. 2(a). The material of the rollers are Cr12MoV. The profiles of the roller cavities have a topological refinement with the blade. The roller cavity surfaces were fabricated at a pair of roller brackets, a pixelate picture of the rollers is showed in Fig. 2(b). Fig. 3(c) shows a schematic section of the net-shape blade rolling process, the rollers and the blade has been shown at horizontal layout. The blank gradual entrance to the rolling bite, and the contact interface between rollers and blade change constantly with the rotating rollers. On account of the irregular shape of blade, and the region and magnitude of the contact load responses on cavity surfaces are changed constantly. Hence, the contact load responses are complicated.

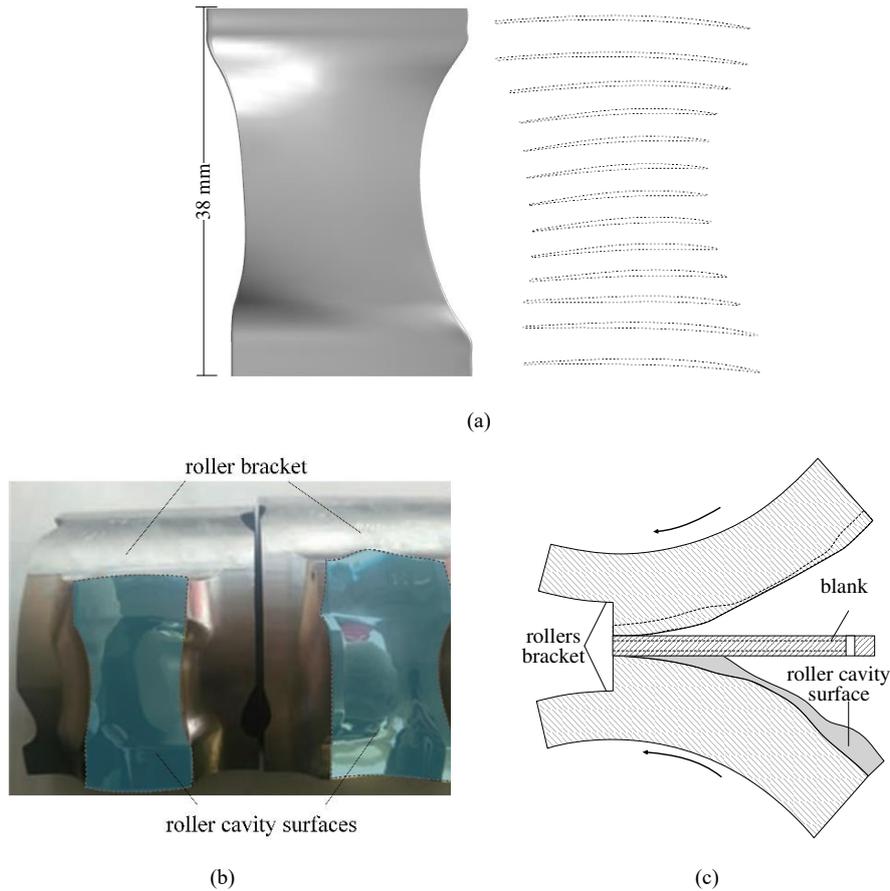


Fig. 2 The physical model of net-shape blade rolling process. (a) CAD model of the blade and representative cross section curves, (b) the rollers for rolling blade, (c) a schematic section of the net-shape blade rolling process

In blade rolling process, the rollers undergoes squeezing and friction in the rolling process, the contact load responses over the roller cavity surfaces including three portions: the contact pressure which overcome the plastic deformation resistance of the blank, the shear stress which overcome the friction resistance, and the local micro-slip at contact interfaces. The authors had been quantified the local contact pressure and local sliding over the rolling bite in symmetric rolling process, and the results shown in Fig. 3 [15]. Nay, the authors had been quantified the distributions and evolutions of the contact pressure and local sliding in net-shape blade rolling process by FEM, and the results shown in Fig. 3 and Fig. 4 [21].

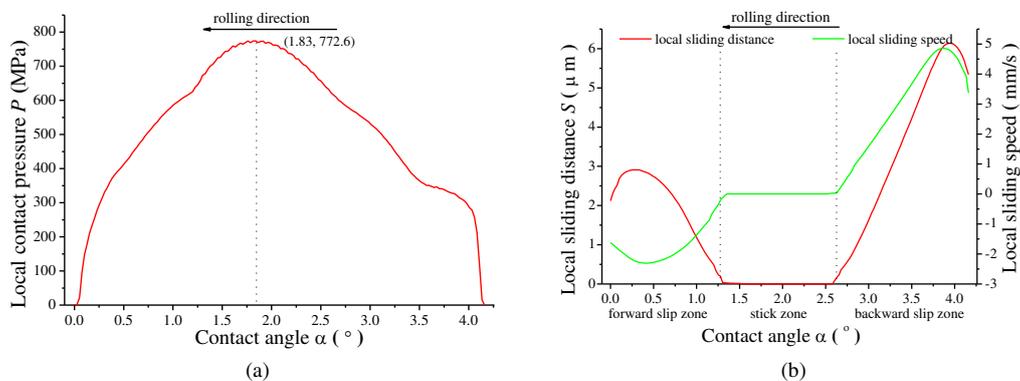


Fig. 3. Distribution of the contact pressure and local sliding over the rolling bite in symmetric rolling process [15].

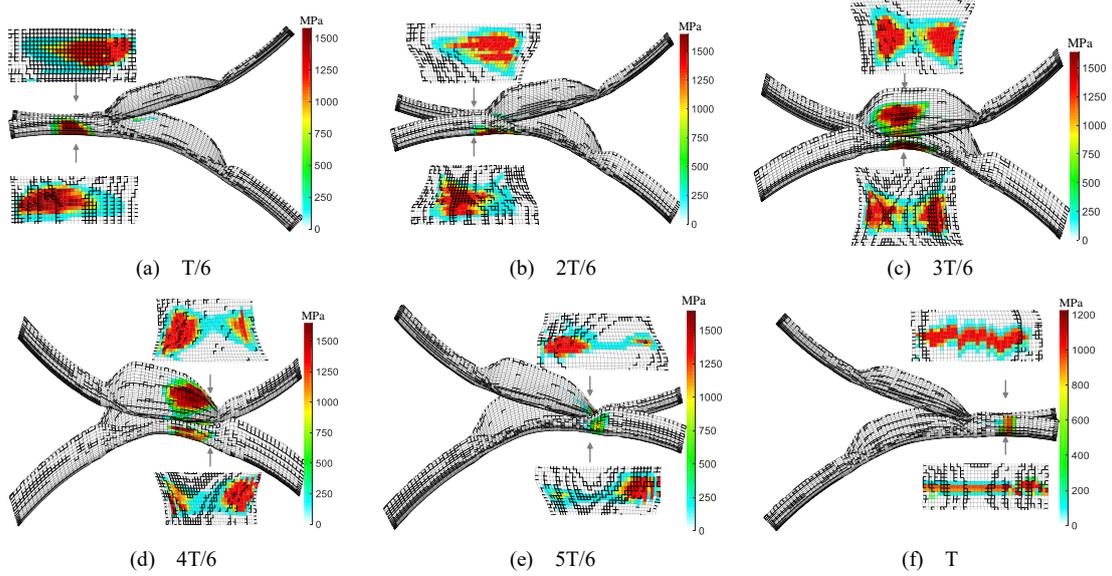


Fig. 4. The contact pressure distribution at six different instances during the blade rolling process [21].

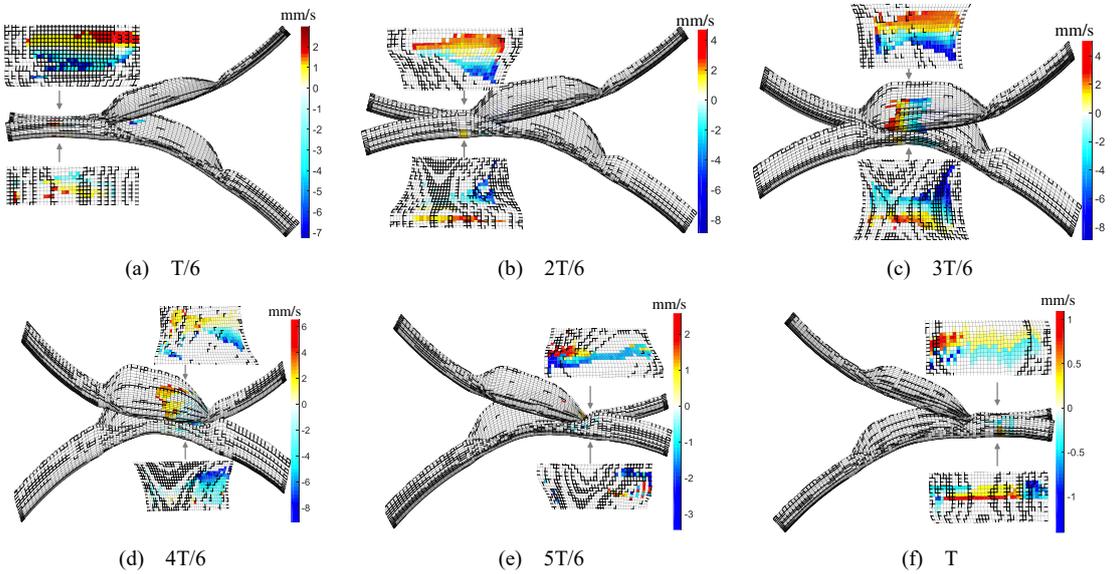


Fig. 5. The local sliding at six different instances during the blade rolling process [21].

3 The wear distributions and evolutions over roller cavities

3.1 An improved wear model

The manufacturing accuracy of the net-shape rolling blade is sensitive to the geometric shape of roller cavities. In order to calculate the wear distribution and evolution, an improved wear model was proposed based on the Archard wear model,

$$h = K \frac{P^m S^n}{H} \quad (1)$$

where h is local wear depth on roller cavities surface (mm), K is the wear coefficient, P is the local contact pressure (MPa), S is the slip distance (mm), H is the hardness of the material (HV), m is the impact factor of the contact pressure, and n is impact factor of the slip distance.

According to the simulation results in Section 2.2, the contact interface, the contact pressure and the local sliding are changed constantly. In order to investigate the local wear over the roller cavities, the time T for the blade rolling process was divided into N time periods, the corresponding contact

pressure could be recorded by the same way in Section 2.2, the corresponding sliding distance could be calculated by the time period and sliding velocity in Section 2.2. Hence, the total wear depth was the summation of the wear in every time period, and the arithmetic can be presented as follow,

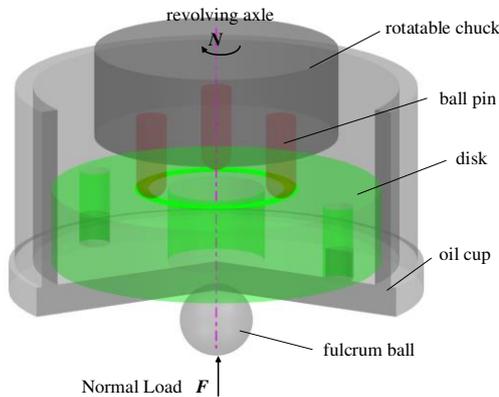
$$h = \sum_1^N h_i \quad (2)$$

$$h_i = K \frac{p_i^m (v_i \Delta t)^n}{H} \quad (3)$$

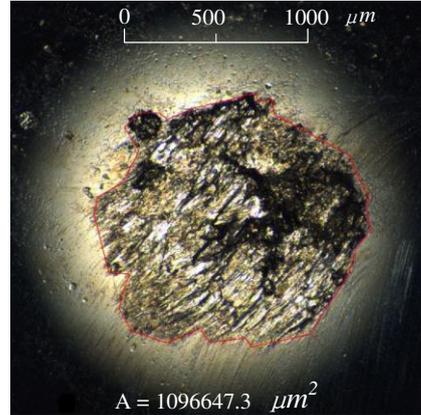
where h_i is the local wear depth of roller cavities in the i period (mm), p_i is the local contact pressure in the i period (MPa), v_i is the local sliding velocity in the i period (mm/s), Δt is the time difference for two adjacent transients (s).

3.2 The standardization of the impact factors in the wear model

The wear not only depends on the contact pressure and the local sliding, but also impacts by the impact factors of the contact pressure and the local sliding. In order to investigate the wear depth over the roller cavities, the wear model was standardized based on a pin-disk wear test. The testes were implemented on a MMW-1 wear testing machine. The schematic diagram for the test is showed in Fig. 6(a). Three ball pins were clamped on a rotatable chuck symmetrically, the pins were rotated with the chuck and slide on a disk, and the turning radius was 12.5mm. The disk was jointed in an oil cup, the cup was floated on a fulcrum ball. In the testing process, the fulcrum ball was hold up by a lever which loading the contact loads. The contact interface was lubricated by the grease, and the liquid level achieved at the top surface of the disk opportunely. The size of wear spots at the tip of the ball pins were measured by an Alicona IF-0400 surface morphometer, one of the wear spot is showed as Fig. 6(b). The loading parameter and measured results are showed in Table 2. In addition, the hardness of the surface has significant influence on wear, hence, the pin and the disk were carried out the same heat treatment process with the roller and blank in the blade rolling, and the surface hardness informations are showed in Table 3.



(a) schematic diagram for wear testing



(b) a wear spot

Fig. 6 wear testing by pin-disk experiment

Table 2 the loading parameters and the size of wear spot

No.	Normal Load F (N)	Rotation speed N (r/min)	Contact area of wear spot A (10^{-6} mm^2)	Mean value of contact area \bar{A} (10^{-6} mm^2)
1	100	50	0.147	0.149
			0.165	
			0.135	
			0.695	
2	200	100	0.635	0.642
			0.596	

			1.097	
3	300	200	1.403	1.273
			1.319	

Table. 3 the surface hardness and roughness of the pin and disk

	Materials	Surface hardness (HRC)	Surface roughness (μm)
ball pin	Cr12MoV	45-45	≤ 0.6
disk	GH4169	61-65	≤ 0.6

The diameter of the pin was 5mm, the pins were rotated with the chuck and the turning radius was 12.5mm, the testing time was 180 seconds. The contact pressure between the pins and disk was calculated by formula 4, and the sliding velocity was calculated by formula 5.

$$P = \frac{F}{A_{total}} = \frac{F}{3\bar{A}} = \frac{4F}{3\pi\bar{d}^2} \quad (4)$$

$$v = 2\pi R \times \frac{N}{60} \quad (5)$$

$$\bar{H} = \frac{\bar{V}}{\bar{A}} = \frac{\pi \left[r - \sqrt{r^2 - \left(\frac{\bar{d}}{2}\right)^2} \right]^2 \left[r - \sqrt{r^2 - \left(\frac{\bar{d}}{2}\right)^2} \right]}{\frac{\pi\bar{d}^2}{4}} = \frac{4 \left[r - \sqrt{r^2 - \left(\frac{\bar{d}}{2}\right)^2} \right]^2 \left[r - \sqrt{r^2 - \left(\frac{\bar{d}}{2}\right)^2} \right]}{\bar{d}^2} \quad (6)$$

where P is the contact pressure(MPa), F is the normal load(N), A_{total} is the summation of three contact spot(10^{-6} mm^2), \bar{A} is the mean value of contact spot(10^{-6} mm^2), \bar{d} is the mean diameter of the contact spot(mm), v is the relative sliding velocity(mm/s), R is the turning radius of the pins(mm), N is the rotate speed of the rotatable chuck(r/min), \bar{H} is the wearing depth of the pins(mm), \bar{V} is the wearing volume of the pins(mm^3), r is the radius of the pins(mm).

According to the testing parameters and the testing results, the wearing depth was regressed and fitted as follow,

$$\bar{H} = 1.34115 \times 10^{-11} \times P^{1.38217} \times (vt)^{0.85419} \quad (7)$$

where t is the testing time(s).

According to the formula 7, the wear depth is the function of the contact pressure, sliding velocity and time. The formula represents the wear between pins (Cr12MoV) and disk (GH4169), and can be used for investigating the wear of the roller cavities for net-shape blade rolling process.

3.3 The wear of roller cavity surfaces

(1) The local wear distributions and evolutions

According to Section 2.2, the contact interface and contact loads were change constantly in blade rolling process. The wear distributions in a single increment and the wear evolutions were calculated based on the Formula 3, the contact pressure and the local sliding distribution. Following the same method, the magnitude of wear over the roller cavities were calculated and plotted to present the contact pressure distribution, and 6 uniform transients wear distribution of the roller cavities were enumerated to present the evolution of wear. The wear distribution and evolution over the cavity surfaces be show in Fig. 7. The wear distributions over roller cavities for a single increment near T/6 are showed in Fig. 7(a). The severe wear occurred at the center of the forward and backward slip zones, the wear depths in the backward slip zones were more serious than that in the forward slip zones, the similar results was presented in cold rolling process[15]. The maximum wear over top and bottom roller cavities are 3.04 nm and 2.13 nm respectively, the maximum wear over top cavity is slightly bigger than that of bottom cavity, because of the blank bending and extruding toward the suction surface of blade. The wear distributions over roller cavities for a single increment near 2T/6 are showed

in Fig. 7(b), the maximum wear over top and bottom roller cavities are 3.87 nm and 3.88 nm respectively, the section of blade distorted seriously and the obvious sliding occurred at this stage, hence, the maximum wear depth was greater. The wear distributions over roller cavities for single increments near $3T/6$ and $4T/6$ are showed in Fig. 7(c) and Fig. 7(d). The wear distribution presented as a butterfly shapes, the wear depths in the backward slip zones were more serious than that in the forward slip zones. The maximum wear over top roller cavities are 3.36 nm and 3.37 nm, the maximum wear over bottom roller cavities are 3.34 nm and 3.47 nm respectively. The wear distributions over roller cavities for single increments near $5T/6$ and T are showed in Fig. 7(e) and Fig. 7(f). The maximum wear over top roller cavities are 2.46 nm and 1.03 nm, the maximum wear over bottom roller cavities are 2.57 nm and 1.10 nm respectively. The rolling reduction was reduced gradually, the contact pressure and sliding velocity which presented in Section 2.2 were decreased, hence, the slightly wear occurred at this stage.

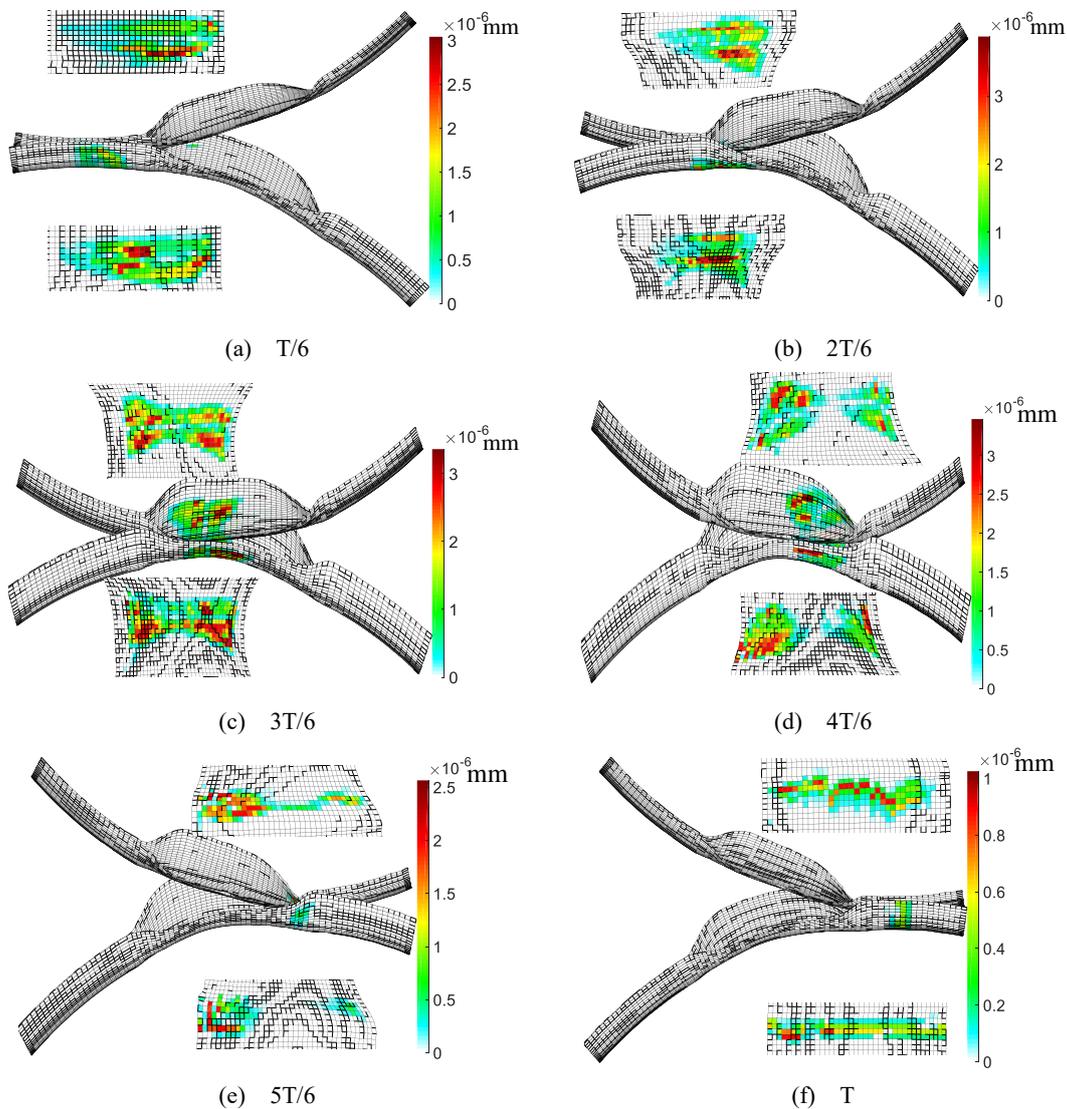


Fig. 7. The wear distributions over roller cavities and evolution in the rolling process

According to the contact load responses, the greater wear appeared at the center of the forward and backward slip zones. The wear in the backward slip zones were more serious than that in the forward slip zones, due to the obvious sliding in the forward slip zone[15]. The striking wear presented at the stage when the blade deformed tempestuously. According to the wear evolution, the maximum wear

depth decreased gradually in 6 individual increment because the reduction of blade was reduced in rolling process.

(2) *The wear distribution over roller cavities surface*

The wear depth distribution over roller cavities in every increment can be calculated by formula 3 and formula 8, the wear depth distribution was the summation in all increment based on accumulation effect of wear. The wear depth distributions over roller cavities in one rolling process cycle are showed in Fig. 8. The maximum value of the local wear depths are 28.10 nm and 28.74nm over the top and bottom roller cavities respectively. The distinct wear presented at the corresponding regions that the sections of blade are serious twisting and bending, because the bigger thickness reduction and deformation induced severe contact pressure and sliding.

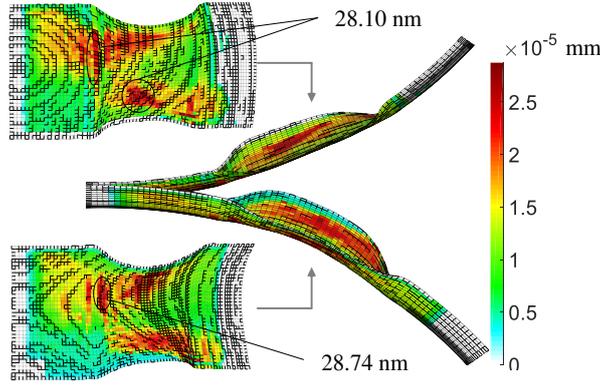


Fig. 8. The wear depth distributions over roller cavities in one rolling process cycle

4 predicting the lifetime based on the wear of the roller cavities

The wear over roller cavities are accumulated gradually with recycling employment of the rollers. The distinct wear changes the geometric profile of the roller cavities, and influences the molding precision of the formed blade. Investigating the wear accumulation and predicting the service lifetime are significant for ensuring the forming accuracy of a batch blades.

4.1 The lifetime prediction model

In order to predict the service lifetime of the rollers, a lifetime predicting model was proposed as follow,

$$N = \min (N_{top}, N_{bottom}) \tag{8}$$

$$N_{top} = \frac{h_{tolerance}}{h_{top}^{max}} \tag{9}$$

$$N_{bottom} = \frac{h_{tolerance}}{h_{bottom}^{max}} \tag{10}$$

where N is the number of usage or the lifetime for a set of rollers, N_{top} is the lifetime of the top roller, N_{bottom} is the lifetime of the bottom roller, $h_{tolerance}$ is the tolerance for the forming precision, h_{top}^{max} is the maximum wear depth of the top roller for one rolling process cycle, h_{bottom}^{max} is the maximum wear depth of the bottom roller for one rolling process cycle.

The contour tolerance of the section is 0.025mm for the blade in this paper. According to the Fig. 8, the maximum wear depth of the top and bottom roller are 28.10 nm and 28.74 nm respectively. Hence, the lifetimes of the top and bottom rollers are 889 and 869 cycle, and the lifetime for a set of rollers is 869

cycle.

4.2 The validation of the roller's lifetime

The wear distribution are non-uniform over roller cavities, the shape of cavities are complex free surfaces, and it's difficult to match and estimate the local wear of the cavities after usage, shown as Fig. 9(a). In order to validate the lifetime prediction model and the predicting results, 4 cross sections were arranged at the roller cavities along rolling direction, the diagram is presented as Fig. 9(b). Moreover, the corresponding cross sections of the used rollers were measured and planed by a trilinear coordinates measuring instrument, shown as Fig. 9(c), and the measured section curves were matched with the theoretical section curves.

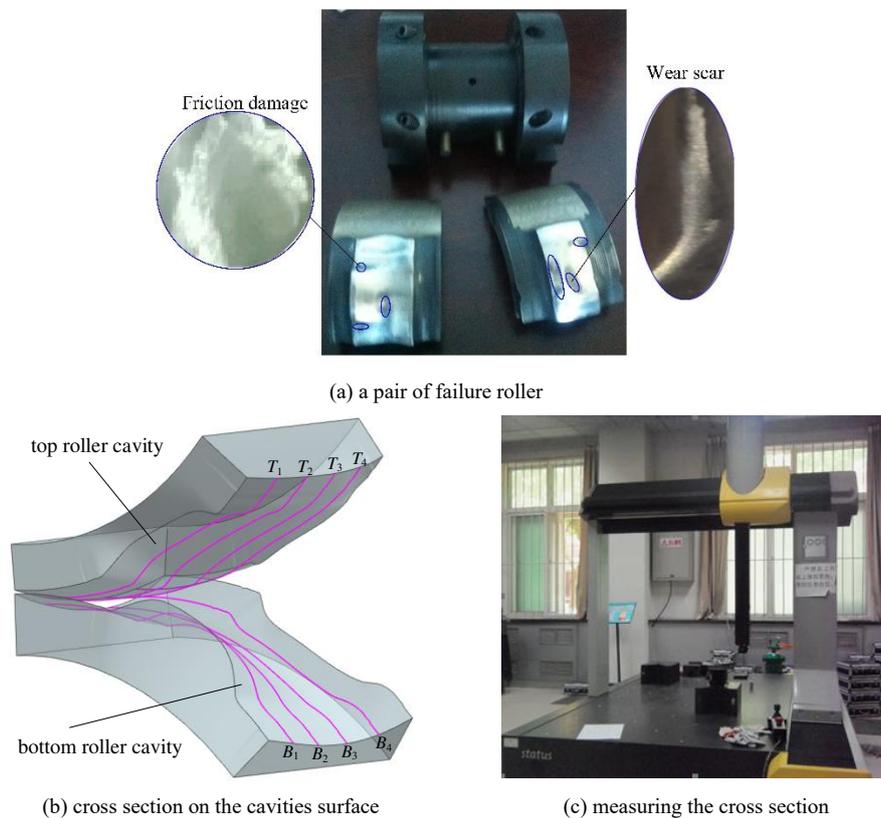


Fig. 9 arrangement and measurement of the cross section over the failure roller cavity surfaces

In order estimate the local wear, the theoretical and measured section curves were compared. The curves were disperse into 100 points respectively, the deviation of corresponding points characterized the local wear of the same location, the diagram of the solution method is presented as Fig. 10.

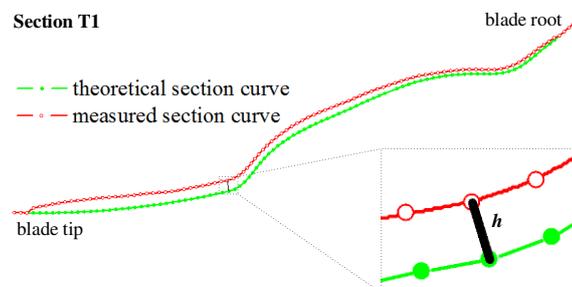


Fig. 10 the diagram of solution method for the cross section

A set of rollers was measured after 800 rolling cycle processes, and 4 groups of wear distributions on the section curves are presented in Fig. 11. The wear distributions over roller cavities presented similar

tendency, and all of the contour errors were smaller than 0.025mm. According to formula 8, the predicting lifetime was 869 cycles, the tested roller was serviced 800 cycles. Hence, the relative error was 8.63%, and the model and the results were credible.

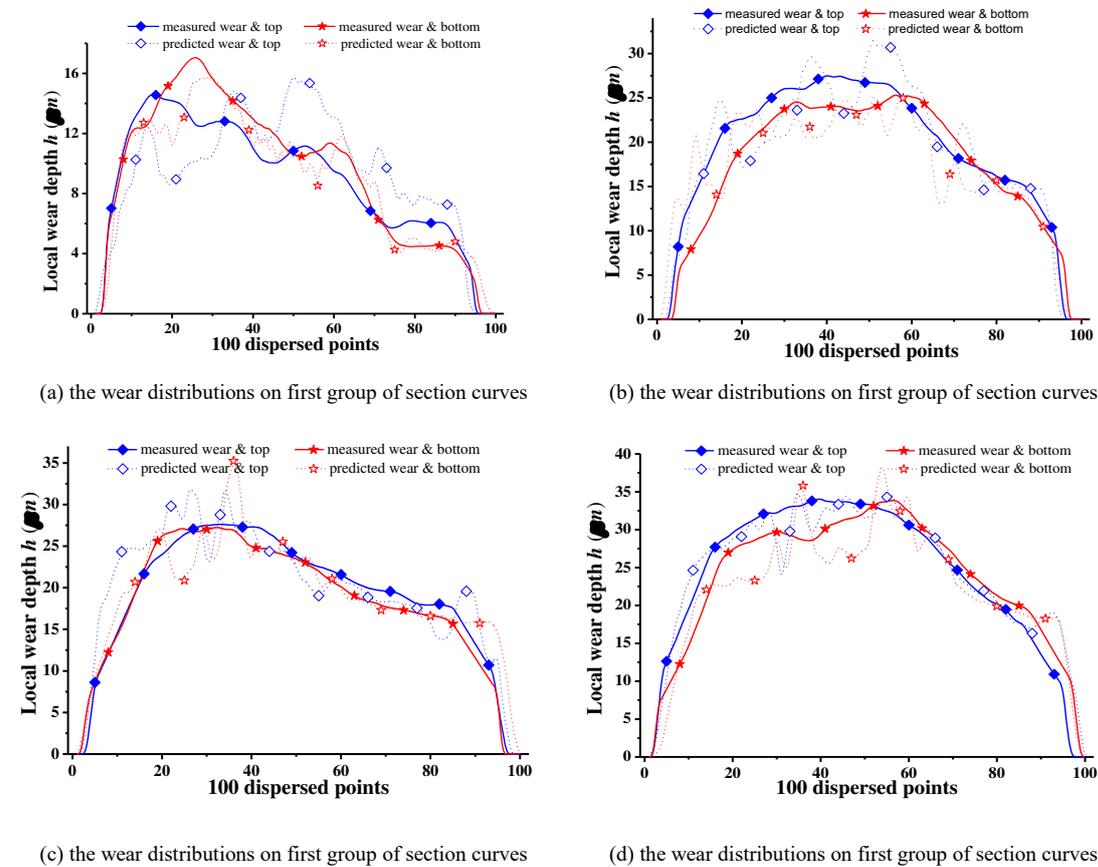


Fig. 11 the wear distributions over roller cavities

5. Conclusions

In this work, the local wear and lifetime prediction of roller cavities were discussed for net-shape blade rolling process. An improved wear model and a lifetime prediction model were proposed to investigate the local wear and predict the service lifetime respectively. It was the first study to quantify the distributions and evolutions of the local wear for rolling irregular components. The major findings are summarized below,

1. An improved wear model was proposed and developed to calculate wear over the roller cavities, and the corresponding influence coefficients in the formulas were regressed based on a pin-disk experiment.
2. The transient local wear distributions and evolutions over roller cavities were investigated quantitatively based on the local contact loads and the wear model. Meanwhile, the distributions of wear depth over roller cavities for one rolling process cycle were calculated by summarizing all the transient wear distributions.
3. A lifetime prediction model was proposed to predict the service lifetime for a pair of rollers based on the profile integrity of the roller cavities. The model was validated by an experiment. The wear distributions between the predicted and measured wear depth showed a good agreement, the model can

be applied to predict die lifetime for other pressure forming processes.

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Author Contributions: Qichao Jin designed, conducted the research and wrote the manuscript, Wenhui Wang discussed the research and rechecked the results, Ruisong Jiang and Lei Guo discussed the research and revised the manuscript.

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Code availability: Not applicable.

Declarations

Ethics approval: The authors understand and approve the ethical responsibilities of the authors.

Consent to participate and publish: The authors declare that they participated in this paper willingly and the authors declare to consent to the publication of this paper.

Conflicts of Interest: The authors declare no conflict of interests regarding the publication of this paper.

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