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An Experiment Study on Surface Roughness in High Speed Milling NAK80 Die Steel

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Abstract. The paper introduces that the high speed milling experiments on NAK80 die steel was carried out on the DMU 60 mono BLOCK five axis linkage high speed CNC machining center tool by the TiAlN coated tools, in order to research the effect of milling parameters on surface roughness R_a. The results showed that the R_a value increased with the decrease of milling speed v_c, increased with the axial depth of milling a_p, and feed per tooth f_z and radial depth of milling a_e. On the basis of the single factor experiment results, the mathematics model for between surface roughness and milling parameters were established by linear regression analysis.

1 Introduction

NAK80 is a kind of pre-hardening plastic die steel, which is mainly made to produce some mirror polishing mold, automobile parts electrical discharge machining and so on. High Speed Machining Technology plays important part in application of mold processing, which could largely increase the producing efficiency and quality of mold.in this case, for NAK80 die steel, developing the research of high speed milling is really important. Surface roughness is one of the parameters that influence parts surface processing quality. It influences the parts' fitting property, endurance, fatigue resistance, corrosion resistance, contact stiffness and so on. Besides, it also influences parts' working life, stability and reliability.

By consulting literature, it could be deferred that scholars have researched on surface roughness of high speed milling steel: Z. Y. Hu [1] and W. W. Liu [2] have all received parameters about milling parameters' influence on surface roughness from experimental study on high speed milling GH4169 nickel-base superalloy. Meanwhile, W.W. Liu ,etc [3]created empirical formula of surface roughness based on SPSO; P. Koshy, etc [4] carried on high speed milling test on AISI D2 tool steel and researched on selection of tool wear mechanism and milling parameters, D. A. Axinte, etc [5] carried on high speed milling experimental research on AISI H13 hot die steel. From this, they received milling parameters' influence on surface roughness, micro-structure, micro-hardness and residual stress. Moreover, they established relevant experimental mathematical model; J. J. Chen, etc [6] researched on milling parameters' influence on surface roughness and established relevant surface roughness mathematical model; S. Y. Wang ,etc [7] created surface roughness predicted model based on experimental research on high speed milling 45 steel, C. F. Yao, etc [8] carried on high speed milling test on TC11 titanium alloy and analysed milling parameters' influence on surface roughness and three-dimension surface topography; F. Su ,etc [9] carried on experimental research on 718 die steel and established regressive mathematical model on surface roughness. So far, the research on surface roughness of NAK80 die steel has not been found.

The author carried on the high speed milling experiments on NAK80 die steel was carried out on the DMU 60 mono BLOCK five axis linkage high speed CNC machining center tool by the TiAlN coated tools and researched on milling parameters' influence on surface roughness and established mathematical model on relationship between surface roughness and milling parameters. Before high speed milling processing NAK 80 die steel, surface roughness could be appropriately predicted to select proper milling parameters. This importantly guide the practical production.

2 Experimental Tests

2.1 Specimens

NAK80 die steel had dimensions of 80 × 30 ×30mm^3, 80 × 35 ×30 mm^3, 80 × 40 ×30mm^3 and 80 × 45 ×30mm^3. Some main chemical component of NAK80 die steel as follows: C is 0.28~0.40%, Si is 0.20~0.80%, Mn is 0.60~1.00%, Mo is 0.30~0.55, Cr is 1.40~2.00%, Ni is 0.80~1.20%. Some main physical mechanical properties as follows: density is 7.8g/cm^3, elasticity modulus is 205GPa, extension strength is 1100MPa, yield strength is 980 MPa, hardness is HBS356, ductility is 0.13, Original state is anneal.

2.2 Milling experiments

Surface milling experiments were conducted on a high-speed machining center tool (DMU 60 mono BLOCK produced by Germany DMG company).The machine spindle is capable of running up to 18000 rpm, the maximum feed rate of (X, Y, Z) is 30m/min, the maximum power of three-dimensional Heldenhain iTNC 530 control system The power of the spindle drive motor is 35kW.

Coolant fluid was not used in the milling tests. The experimental setup is illustrated schematically in Fig.1. The cutting tools of SNNDVIK's TiAlN coating cemented carbide indexable blade were used ,whose type is 490R-140408M- PM 4220, The cutter holder type is A1B05-4022100, which is overall face milling cutter handle, its diameter is 63mm, it has five blade. The surfaces milling was carried out on the 80 × 30 mm^2, 80 × 35 mm^2, 80 × 40 mm^2 and 80 × 45 mm^2 surfaces in a up- milling mode. A series of tests were performed using different peripheral milling speeds, axial depths of milling, feeds per tooth and radial milling depths to study their influences on the milling performances. Detailed milling parameters used were listed in Table 1.

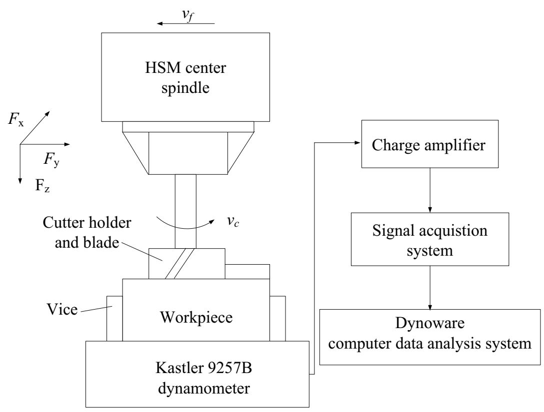

Figure 1. Schematic illustration of the processing.

Table 1. Parameters used in milling of the NAK80 die steel.

milling parameters	Value
Peripheral milling speed v_c (m/min)	198, 296, 394, 495, 594
axial depth of milling a_p (mm)	0.1, 0.2, 0.3, 0.4, 0.5
feed per tooth f_z (mm/z)	0.01, 0.02, 0.03, 0.04, 0.05
axial depth of milling a_e(mm)	30, 35, 40, 45

2.3 Force measurement and ground sample evaluation

Milling forces were measured using a piezoelectric dynamometer (Kistler 9257B), the radial cutting depth direction F_x, feed direction F_y, axial direction F_z. were measured. The force signals were fed to a 5067A1 type charge-amplifier and 5697A1 type data collection system. Under each set of parameters, the grinding process was repeated at least three times to obtain the average values of grinding forces.

A surface profilometer (Mahr Products, XR20) was used to measure surface roughness of milling ground along the directions parallel and perpendicular to the milling direction, three measurements were taken at different locations, the mean values was calculated. R_a (//) is used to show surface roughness that is parallel to milling direction, R_a (⊥) is used to show surface roughness that is perpendicular to milling direction. The selected measurement parameters were sampling length is 0.8mm, evaluated length is 4.0mm, measured length is 5.6mm.

2.4 Experiment method

The single factor experiment method [10] applied to carry on high speed milling experiment. Through the analysis of experiment results, the author received the influence of milling parameters on surface roughness. Meanwhile, the surface roughness mathematical model was established. When milling speed is larger than 300m/min, it could be named high speed milling [1]. The surface roughness values of measuring were listed in Tab. 2.

Table 2. The measuring surface roughness values.

Milling parameters				R_a(//)(μm)	R_a(⊥)(μm)
v_c	a_p	f_z	a_e		
198	0.2	0.02	30	0.683	0.651
296	0.2	0.02	30	0.628	0.603
394	0.2	0.02	30	0.581	0.551
495	0.2	0.02	30	0.549	0.455
594	0.2	0.02	30	0.456	0.417
495	0.2	0.01	30	0.252	0.229
495	0.2	0.03	30	0.361	0.371
495	0.2	0.04	30	0.375	0.437
495	0.2	0.05	30	0.429	0.458
495	0.1	0.02	30	0.441	0.388
495	0.3	0.02	30	0.560	0.517
495	0.4	0.02	30	0.681	0.601
495	0.5	0.02	30	0.754	0.651
495	0.2	0.02	35	0.453	0.505
495	0.2	0.02	40	0.581	0.626
495	0.2	0.02	45	0.642	0.735

3 Result and discussion

3.1 The influence of milling parameters on surface roughness R_a

The influence rule curve of the milling speeds v_c on measured surface roughness results of the R_a (//) and R_a (⊥) are presented in Fig.2. It could be seen that the R_a values decrease with increases, It's mainly because as increases, milling forces F decreases[11]. This could make frequency produced by tool system of processing far away from inherent frequency of tool system. This could decrease of eliminate vibration, thus the R_a values were decreased, and the processing quality of milling surfaces could be increased. Fig 3 is the influence rule curve of the axial milling depth a_p on measured surface roughness results of the R_a (//) and R_a (⊥) . It could be seen that as the R_a values increase with the a_p increases, the R_a values are approximate linear improving. The reason is that the milling forces F increase with the a_p increases [11]. The friction and extrusion between flank surface of cutting tools and machined surface were intensified. Therefore, the values increase, but the milling surface quality decreases. Fig 4 is the influence rule curve of the feed per tooth f_z on measured surface roughness results of the R_a (//) and R_a (⊥) . It could be seen that as the R_a values increase with the f_z increases,. The reason is that as increases, the milling layer' s thickness increases with f_z increasing, the metal plastic deformation's volume of the finished surface increases, the milling forces F increases[11].so, the surface roughness values increase with the f_z increase. The influence rule curve of the axial depth a_e on measured surface roughness results of the R_a (//) and R_a (⊥) is drew in Fig 5. It could be seen that the R_a values increase with the a_e increases .The reason is that the milling area and the milling forces increase[11], thus, the surface roughness values increase and the milling surface quality decreases ,and the a_e is the most influence on the surface roughness values among milling parameters.

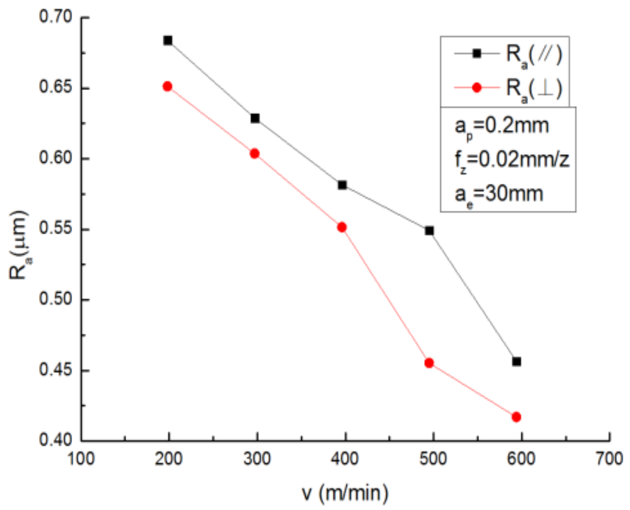

Figure 2. Impact of milling speed on surface roughness.

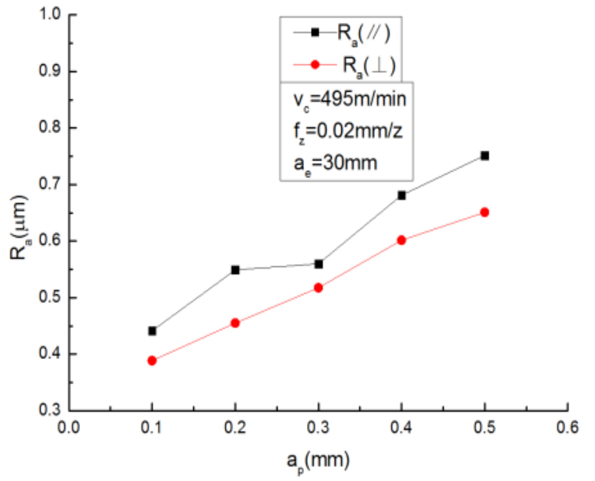

Figure 3. Impact of axial milling depth on surface roughness.

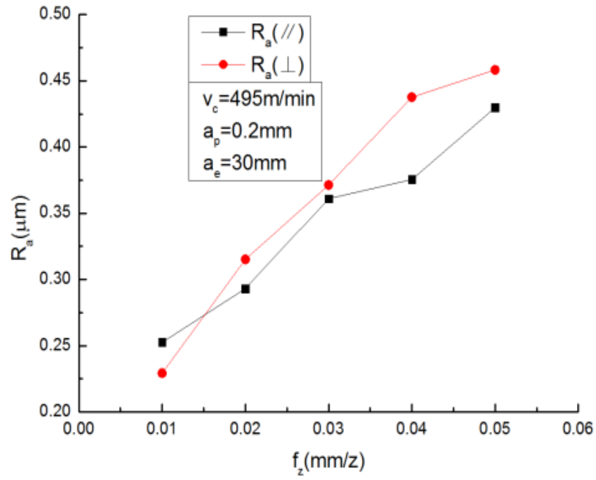

Figure 4. Impact of feed per tooth on surface roughness.

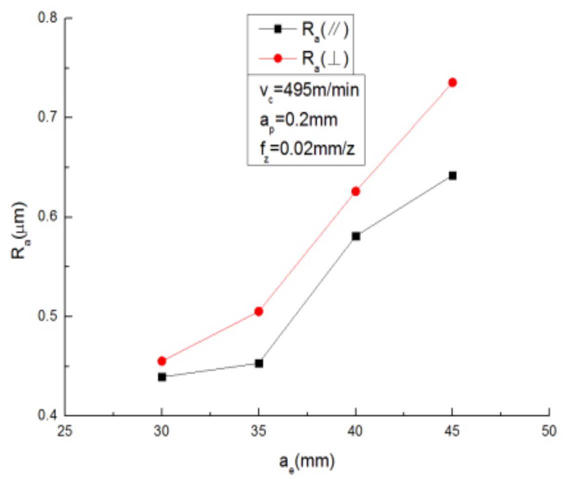

Figure 5. Impact of radial milling depth on surface roughness.

3.2 Establishment and verification of the prediction mathematical model of surface roughness R_a

Lots of research results show that surface roughness and milling parameters have complex index relationship, for high speed milling, mathematical expression of high speed milling could be expressed as

$$R_a = C_a a_p^{b_1} v_c^{b_2} f_z^{b_3} a_e^{b_4} \qquad (1)$$

where a_p is axial depth of milling ,mm. v_c is peripheral milling speed ,m/min. f_z is feed per tooth, mm/z. a_e is radial milling depth, mm. C_a is comprehensive coefficient of milling condition. b_1, b_2, b_3 and b_4 are the influence parameters of each milling parameters， which are decided by the factors of work-piece material and cutting condition.

As for single factor experiment method, it needs to transform Eq.[1] to followed 4 mathematical expression in order to obtain Eq.[1]:

$$R_a = C_a^{a_p} a_p^{b_1} \qquad (2)$$

$$R_a = C_a^{v_c} v_c^{b_2} \qquad (3)$$

$$R_a = C_a^{f_z} f_z^{b_3} \qquad (4)$$

$$R_a = C_a^{a_e} a_e^{b_4} \qquad (5)$$

It is very difficult to get mathematical solution of exponent equation of Eq.[2], Eq.[3], Eq.[4] and Eq.[5]. The common method is to take the both sides logarithm of Eq.[2], Eq.[3], Eq.[4] and Eq.[5]. So, exponent equation could be transformed to linear equation and solve the equation. For example, for Eq.[2], the process is as follows:

$$\log R_a = \log C_a^{a_p} + b_1 \log a_p \qquad (6)$$

make $\log R_a = y$ ， $\log(C_a^{a_p}) = b_0$ ， $\log a_p = x_1$. therefore, surface roughness exponent equation could be transformed into linear equation:

$$y = b_0 + b_1 x_1 \qquad (7)$$

The unary linear regression mathematical model was established as follows:

$$\begin{cases} y_1 = \beta_0 + \beta_1 x_{11} + \varepsilon_1 \\ y_2 = \beta_0 + \beta_1 x_{21} + \varepsilon_2 \\ \quad\cdots\cdots \\ y_n = \beta_0 + \beta_1 x_{n1} + \varepsilon_n \end{cases} \qquad (8)$$

where ε_i is random variable error, for Eq.(8), the form of matric could be expressed as:

$$Y = X\beta + \varepsilon \qquad (9)$$

where, $Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_n \end{bmatrix}$ 、 $X = \begin{bmatrix} 1 & x_{11} \\ 1 & x_{21} \\ \cdots & \cdots \\ 1 & x_{n1} \end{bmatrix}$ 、 $\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix}$ 、 $\varepsilon = \begin{bmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \end{bmatrix}$. The parameter β is estimated by the least square method, hypothesis b_0 and b_1 are respectively the least square estimation of parameterβ_0, β_1, thus, regression mathematics model is:

$$\hat{y} = b_0 + b_1 x_1 \qquad (10)$$

where, $\hat{y}$ is statistical variable. b_0 and b_1 are regression coefficient, and could be calculated by $b = (X'X)^{-1} X'Y$.

According to measured surface roughness results of the $R_a(//)$ and $R_a(\perp)$ by single factor experiment, each regression coefficient could be solved by using origin software , then the each coefficient in Eq.[2], Eq.[3], Eq.[4] and Eq.[5] could be solved in return.

After solution, The mathematical models of the surface roughness R_a (//) , R_a ($\perp$) between single milling parameters are as follow: R_a(//) $= 0.710 a_p^{0.39794}$,R_a(//) $= 2.782 v_c^{-0.33208}$,R_a(//) $= 0.753 f_z^{0.32674}$, R_a(//) $= 0.057 a_e^{0.54742}$,R_a($\perp$) $= 0.485 a_p^{0.32301}$,R_a($\perp$) $= 2.169 v_c^{-0.31714}$, R_a($\perp$) $= 1.072 f_z^{0.44095}$, $R_a(\perp) = 0.003 a_e^{1.29914}$.

The coefficient C_a value in Eq.[1]could be solved according to the $C_a^{a_p}$, $C_a^{f_z}$, C_a^{v} and $C_a^{a_e}$ value , For example, The steps of solving C_a were as follow:

$$R_a = C_a^{a_p} a_p^{b_1} = C_a^1 a_p^{b_1} v_c^{b_2} f_z^{b_3} a_e^{b_4}$$

Thus $$C_a^1 = \frac{C_a^{a_p}}{v_c^{b_2} f_z^{b_3} a_e^{b_4}} \qquad (11)$$

where, v_c, f_z, a_e are fixed values when a_p changes.
In addition, the solve is done as follows:

$$R_a = C_a^{v_c} v_c^{b_2} = C_a^2 a_p^{b_1} v_c^{b_2} f_z^{b_3} a_e^{b_4}$$

Thus $$C_a^2 = \frac{C_a^{v}}{a_p^{b_1} f_z^{b_3} a_e^{b_4}} \qquad (12)$$

where, a_p, f_z, a_e are fixed values as v_c changes.

$$R_a = C_a^{f_z} f_z^{b_3} = C_a^3 a_p^{b_1} v_c^{b_2} f_z^{b_3} a_e^{b_4}$$

Thus $$C_a^3 = \frac{C_a^{f_z}}{a_p^{b_1} v_c^{b_2} a_e^{b_4}} \quad (13)$$

where, a_p, v_c , a_e are fixed values when f_z changes.

$$R_a = C_a^{a_e} a_p^{b_4} = C_a^4 a_p^{b_1} v_c^{b_2} f_z^{b_3} a_e^{b_4}$$

Thus $$C_a^4 = \frac{C_a^{a_e}}{a_p^{b_1} v_c^{b_2} f_z^{b_3}} \quad (14)$$

where, a_p, v_c , f_z are fixed values when a_e changes.

In addition, The coefficient C_a value could be solved according to $C_a = \frac{C_a^1 + C_a^2 + C_a^3 + C_a^4}{4}$, thus $R_a = C_a a_p^{b_1} v_c^{b_2} f_z^{b_3} a_e^{b_4}$ could be received. After solution, the mathematical models of surface roughness $R_a(//)$ and $R_a(\perp)$ are as follow:

$$R_a(//) = 2.711 a_p^{0.39794} v_c^{-0.33208} f_z^{0.32674} a_e^{0.54742} \quad (15)$$

$$R_a(\perp) = 0.210 a_p^{0.39301} v_c^{-0.31714} f_z^{0.44095} a_e^{1.29914} \quad (16)$$

The measured values and prediction values calculated by model was compared so as to verify prediction accuracy of mathematical model Eq.[15], Eq.[16]. By calculation, prediction error is 3.20%~24.60%, it shows that the mathematical models have higher accuracy and could be used to predict surface roughness of high speed milling NAK80 die steel.

4 Conclusion

The conclusions could be deferred from high speed milling experimental research on NAK80 die steel:

Through the analysis for test results, the influence rules of milling parameters on surface roughness could be known: the surface roughness R_a increases with peripheral milling speed v_c decreases, and radial milling depth a_e, axial depth of milling a_p and feed per tooth f_z increases. However, influence degree is different, and the is the most impact.

As for obtaining better finished surface quality, smaller radial milling depth a_e and feed per tooth f_z could be selected. Besides, higher milling speed v_c and smaller axial depth of milling a_p could be selected.

Based on unary linear regression analysis method, the author carried on numerical fitting analysis on experimental data and established mathematical model for relationship between surface roughness and milling parameters in case of high speed NAK80 die steel. Moreover, the author verified the model and proved the established model is available.

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