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Surface Affected Character Analysis based on Field Characteristic Parameter

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Abstract

Surface affected layer characteristic is an important index to check machined surface integrity, which has great influence on work piece fatigue and wear resistance. Based on the definition of four filed characteristics parameters-filed gradient, field impact depth, filed mean value and field peak value, the combination of quantitative and qualitative description of high-speed milling process physical field is realized. According to finite element analysis method, characteristic parameters of stress filed and temperature filed in the process of hardened steel high-speed milling are calculated, and the field characteristic parameters changing regulation under different cutting parameters is analyzed. Based on micro hardness experiment results of the surface layer and sub surface layer materials of machined surface obtained from experiment and the surface residual stress distribution obtained from data simulation, surface affected layer character, such as residual stress and hardness changing, forming mechanism and altering regulation is discovered based on filed characteristic parameter analysis. The results show that the residual stress along the depth direction is compression stress, the stress field peak value and the temperature field gradient have greatest influence on residual stress among these filed characteristic parameters; stress field peak value can be used as the symbol of strain rate hardening, which is the main factors affecting pieces hardening along the layer depth direction.

Keywords: *Field of characteristic parameters; Hardened steel; affected layer; micro hardness*

1. Introduction

Currently, medium and high-speed cutting and machining technology has been widely used in automobile mold manufacturing enterprises at home and abroad, which becomes the mainstream machining technology of hardened steel mold for automobile covering work pieces. Surface affected layer as the outermost surface of work, has great impact on the physical and using performance of work piece [1, 2]. Therefore, studying on thermodynamics essence of work piece material plastic deformation in the high speed cutting process, and exploring the surface affected layer thermal distribution essence formed in the process of cutting and machining of mold steel materials, have significant meaning to improve mold fatigue properties and mold life [3, 4]. However, only relying on experiments, it will not only consume much time, but also increase experimental cost and the temperature and stress-strain are hard to obtained precisely in manufacturing process. Therefore, dynamic displaying the temperature and stress-strain distribution of cutting deformed area using the method of data simulation technology, can overcome the shortcomings of experimental research method, and provide an effective method for high speed cutting and machining research.

Umbrel-lo did research on the surface affected layer formation mechanism of high-strength steel AISI 52100 in hard cutting process; it shows affected layer thickness

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increases with the increasing of cutting speed and hardness of the work piece [5]. Zhang studied on the hard milling surface generation mechanism of high-strength steel AISI H13 [6]. Han did research on the metal phase transition mechanism of machined surface of AISI 1045 alloy steel in cutting process, it is found that even below the austenitizing temperature, the machined surface can also generate white layer [7]. M'Saoubi *et al.*, and Stolorz *et al.*, did detailed study on the machined surface affected layer of high-strength steel in hard cutting [8, 9].

At present, among the widely used finite element simulation analysis, most of them are limited in representation description of simulation results, and seldom do quantitative and qualitative analysis on the area with the most dramatic field variables. Therefore, using the thinking processing method of “discrete-continuous-discrete”, the characteristic parameters of stress filed and temperature field distribution are brought forward; stress field, temperature field and residual stress field distribution in work piece cutting process is simulated, and manufacture hardening testing parameter are obtained by cutting experiments. Based on the characteristic parameters extraction of stress field and temperature field simulation under high speed milling, the stress field and temperature field in cutting process are expressed in some quantitative sense, and further the cutting parameters influence on filed parameters are analyzed. Finally, cutting parameters impact on surface affected layer is analyzed from the aspect of field characteristic parameter which provides the basic data for the study of cutting character of high speed milling on steel mold.

2. Filed Characteristic Parameter Definition

In order to study stress field and the temperature field distribution characteristics in cutting process in detail, and make quantitative and qualitative analysis on stress field and temperature field in cutting process, not only stay in representation analysis of simulation results, field characteristic parameters are adopted to describe filed distribution in this paper to quantify cutting parameters important impact on stress field and temperature field. The symbol expression and function description of these parameters can be seen in Table 1.

Table 1. The Characteristic Parameters Expression of Temperature Field and Stress Field Distribution

parameters	g (gradient)	d (deep)	mv (mean value)	max(maximum)
Function description	filed gradient	Field depth	mean value	Peak value

g - filed gradient parameter is used to describe gradient distribution characteristic of stress field and temperature field in cutting process, and mainly research gradient value in the orientation with most dramatic gradient changes under different cutting parameters conditions. Gradient value is achieved by simulation results analysis and calculation, which is as follows:

For a known binary function $f(x,y)$, the gradient is defined as:

$$grad\ f(x_0,y_0)=\nabla f(x_0,y_0)=f_x(x_0,y_0)i+f_y(x_0,y_0)j \tag{1}$$

Three-dimensional field obtained from finite element simulation could be the discrete result of a ternary function f(x,y,z), and function value of each point represents the corresponding stress or temperature value of that point. Take discrete finite element field as a continuous function, use the existed grid nodes to represent discrete points in the field, and define a gradient direction for each node, it can be reasoned out that adjacent point gradient are approximate, because the whole cutting is continuous at one moment.

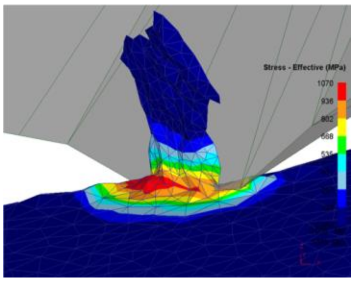


Figure 1. The Largest Gradient Direction

Figure 1 is the milling stress field distribution map, the stress field is "Circular" distribution in cutting simulation, and each color on work piece represents a stress value range, the specific data can be obtained by selecting the node values, the boundary of color changing is the position of inflection point, and these nodes value and inflection point value provide data to describe gradient distribution.

According to the definition of gradient, and the thinking processing method-"discrete continuous-discrete", the problem can be simplified further. Through the study of "bandwidth" in field distribution, bandwidth changing degree can be used to describe gradient changes condition approximately. It can be considered that each node value is relatively large on narrow band, and corresponding node value is relatively small in the region with wide bandwidth. Therefore, gradient changing condition can be judged and differentiated based on the observation of bandwidth first, and then select the narrowest path, and pick the nodes from that path, including inflection point value. Through the analysis of these values, the position with the most dramatic changes on work piece surface and along depth direction can be confirmed and the specific changing trend of physical field can be researched.

In order to make gradient comparison under different cutting simulating condition, a estimation method of gradient value ∣g∣ is offered in this paper after confirming the direction with the largest gradient value:

$$|g_i| = \frac{100L}{h_i} \bullet \sum_{j=1}^{n} \frac{|h_{j+1} - h_j|}{l_j} \tag{2}$$

In the formula, ∣gi∣ represents gradient value of the i th field, which is dimensionless; hj represents the band value with the number of j along the gradient direction, the specific stress field and temperature field is represented by S_j (stress value) and T_j (temperature value); L *is* the size of the maximum depth along field effecting direction, which is d (field influence depth defined above in this paper, unit: mm); h_i represents peak value of the field, which is max (unit of field peak is upon to specific field condition, and the stress field is Mpa, the temperature is ^{o}C).

d- field influence depth, represents the achieved depth below the work piece surface affected by stress field and temperature field, stress field and temperature field influence depth will alter under different cutting parameters; After finite element analysis, in treating process and by section view on work piece, field influence depth of any position can be researched. In simulation, filed depth is usually within 0.2mm, to express with other characteristic parameters under the same coordinate system, 10^{-4}mm is used as its unit to express the field influence depth-d.

mv-field mean value represents the average value of stress field and temperature field, and the field peak value-max, represents maximum value of temperature field and stress field. mv and max in on hand can be the corresponding reference of cutting heat and cutting force in cutting experiment; on the other hand, it can be the basis in the research on general changes of cutting parameters impact on the stress filed and temperature field, which is an important parameter in physical field changes. It also has important significance in the research on work piece machining process variables practical impact on work piece final surface formation.

3. Thermal Distribution Simulation of Hardened Steel High Speed Milling Process

3.1. Finite Element Model Establishment and Technology Parameters Setting

Thanks to DEFORM-3D, grid processing technology is simplified in the process of complex elastic-plastic deformation, the computational efficiency of which is higher than the general finite element software, therefore DEFORM software is used to simulate the process of mold three-dimensional milling process. In the process of simulating, the index-able milling cutter is selected, material of the tool is hard alloy WC, work piece material is hardened mold steel Cr12MoV. material parameters of AISI D3 (Cr12MoV is corresponding to America grades) in DEFORMD pre-treatment materials base is adopted in this paper, Figure 2 and Figure 3 is respectively the manufacturing schematic diagram and UG knife contact assembling map.

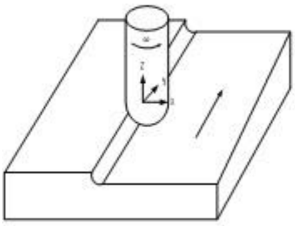


Figure 2. Manufacturing Schematic Diagram

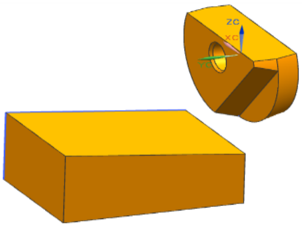


Figure 3. UG Knife Contact Assembling Map

The continuous chip fracture is judged based on dimensionless Cockcroft＆Latham fracture criterion, and Zorev friction model is used to describe the friction properties of work piece and cutting tool in the sliding and adhesive area; natural convection heat transfer is adopted among work piece (including chip) and milling cutter and the environment, heat transfer coefficient is 20 W/m 2• ℃. Continuous simulation of two knife tooth milling process is made using the boundary conditions established and technology parameters; Table 1 is technology parameter scheme of high speed milling simulation.

Table 1. High Speed Milling Experiment Technology Parameter Scheme

Experiment No.	speed	Feed per tooth fz(mm/z)	row spacing a_e (mm)	Cutting depth a_p （mm）
1-01	2000	0.08	0.3	0.2
1-02	3000	0.08	0.3	0.2
1-03	4000	0.08	0.3	0.2
1-04	5000	0.08	0.3	0.2
2-01	3500	0.1	0.3	0.4
2-02	3500	0.15	0.3	0.4
2-03	3500	0.2	0.3	0.4
2-04	3500	0.25	0.3	0.4
3-01	3500	0.08	0.2	0.3
3-02	3500	0.08	0.3	0.3
3-03	3500	0.08	0.4	0.3
3-04	3500	0.08	0.5	0.3
4-01	3500	0.08	0.4	0.2
4-02	3500	0.08	0.4	0.3
4-03	3500	0.08	0.4	0.4
4-04	3500	0.08	0.4	0.5

3.2. Stress Field Character Analysis based on Field Characteristic Parameters

Cutting parameters are important for stress field and temperature field distribution. Based on gradient values of stress field and temperature field distribution cloud map extracted from finite element simulation, and put which into formula (2)above in this paper, field characteristics value of corresponding technology parameters can be solved. In this section, the influence will be described using filed characteristic parameters.

Figure 4 is stress distribution cloud map of stress field in the cutting process, which shows that when cutting enter into steady area, the main cutting force maximum value change little, and the maximum stress is in the sheared region where is the nearest from knife tip. Stress field gradient-g changes significantly in different cutting edge region; the equivalent stress value of cutting edge away from knife tip is much smaller than the area near the knife tip.

It can be seen from Figure 5 that maximum stress is in the first deformation region, while in the second and the third deformation region, the stress of surface is less than those below the surface, which indicates that under the milling condition， the first deformation region has great influence on the second and third deformation region, which is likely to make the surface stress value is less than that in a certain depth below the surface, that is to say the maximum value of the second and third deformation region is not realized on the surface.

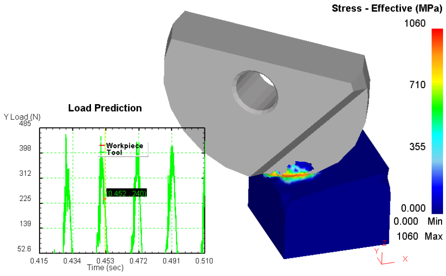


Figure 4. Cutting Simulation

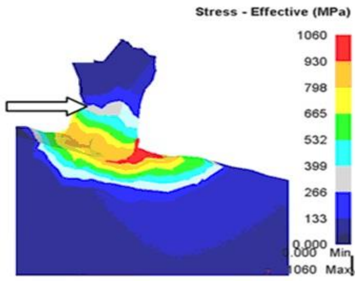
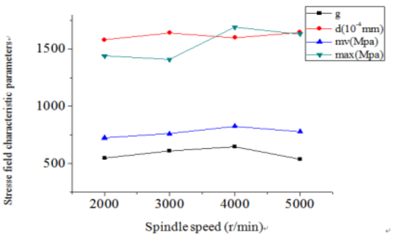
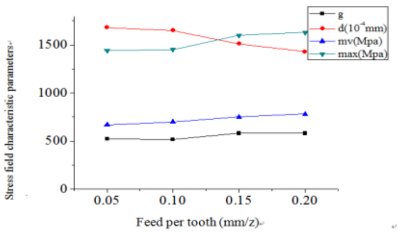


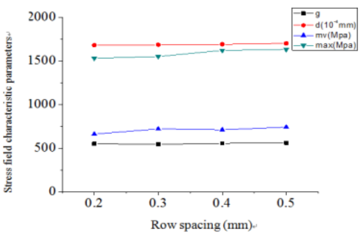
Figure 5. Equivalent Stress Distribution Simulation



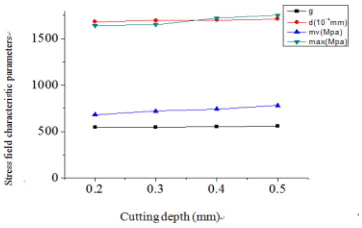
a) Spindle Speed Impact on Stress Filed Character Parameter



b) Feed per Tooth Impact on Stress Filed Character Parameter



c) Row Spacing Impact on Stress Filed Character Parameter



d) Cutting Depth Impact on Stress Filed Character Parameter

Figure 6. The Influence of Cutting Parameters on the Field Characteristic Parameters

It can be seen from figure 6 that: The curves to describe mean stress change are approximately parallel to the ones of maximum stress, the change of row spacing and cutting path have least impact on stress mean value and stress maximum value. Other cutting parameters impact on stress mean value and stress maximum value increase with the increasing of cutting parameters, and spindle speed has the greatest influence on stress filed character parameter, and it increases first and decreases later. Stress field depth value decreases with the increasing of feed per tooth, the reason of which is that with the increase of feed per tooth, the contact time of the tool and the work piece decreases.

3.3. Temperature Character Analysis based on Field Characteristic Parameters

According to high-speed cutting mechanism, a majority heat would be taken away by the chip in the cutting process. It can be seen that the peak temperature (max) of the chip is about 411oC (which can be seen in Figure 7), while the surface temperature of the work piece is within a relatively low range. The highest temperature regions have two places; one is the sheared region along the cutting edge near knife tip, and the other temperature peak in on cutting chips. The maximum temperature in the sheared region is about 260°C and 345°C.

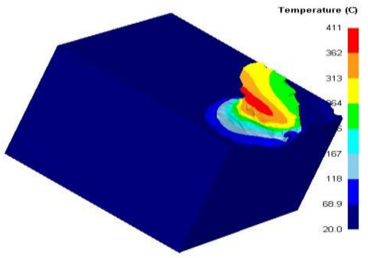
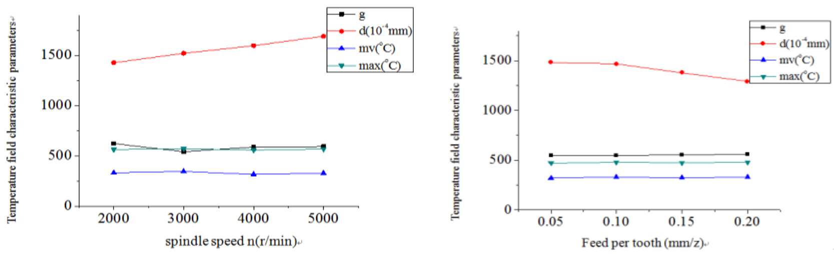
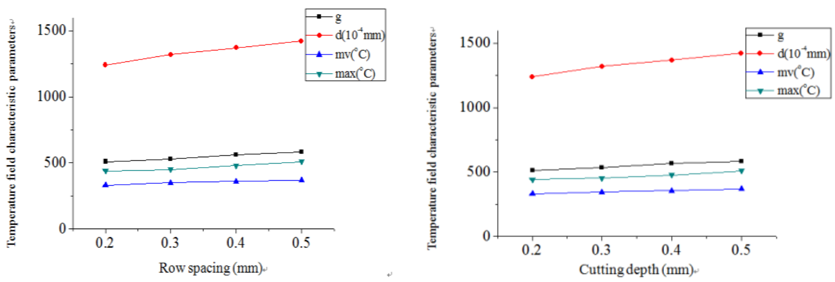


Figure 7. Simulation of Temperature Filed Distribution



a) Spindle Speed Impact on Temperature Filed Character Parameter

b) Feed per Tooth Impact on Temperature Filed Character Parameter



c) Row Spacing Impact on Temperature Filed Character Parameter

d) Cutting Depth Impact on Temperature Filed Character Parameter

Figure 8. Cutting Parameters Influence Trend on Temperature Field Characteristic Parameters

Figure 8 shows the influence of cutting parameters on temperature field characteristic parameters. From the figure, it can be seen, like the influence of feed per tooth on stress field characteristic parameters, with the increasing of feed per tooth, the filed influence depth will decrease accordingly. The results of spindle speed impact on temperature mean and peak value shows that field mean and peak value is highest when spindle speed is 3000r/min, that is to say temperature not always increasing accordingly to the increase of spindle speed. The influence of various parameters on the temperature field depth-d is much more significant than the impact on other field characteristic parameters. Changes of temperature gradient have a low point at 3000r/min and 0.1mm/Z, which is in obviously contrast with the highest value of mean and peak temperature value at 3000r/min.

4. Thermal Characteristics Analysis on Residual Stress of Hardened Steel in High Speed Cutting

4.1. Residual Stress Simulation of Hardened Steel in High Speed Cutting

Residual stress simulation process includes cutting stage, unloading stage, bounding stage and the cooling stage (which can be seen in Figure 9).

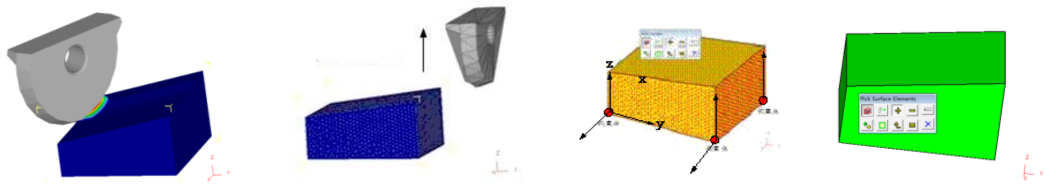


Figure 9. Simulation of Residual Stress

After the treatment of deform software, residual stress distribution map along the layer depth can be obtained which is shown in Figure 10, from which it can be seen that the residual stress distribution characteristic is in coincide with “the maximum stress value is not on surface”. Accordingly, the crack of the mold is generally not on the surface. Obtained stress field depth is minus using the method of stress filed average method, that is to say the stress is all compressive stress. The maximum stress region is in the depth around 0.02mm, and finally is at the position of 0.14 mm, and the absolute value of stress reduces to 40Mpa below basically.

From Figure 11 it can be seen that: Firstly, the curvy of residual stress changing with the alteration of feed per tooth single factor, has the trend of overall downward movement compared to the single-factor test of depth and spindle speed, that is to say the residual compressive stress value in certain depth is larger than the corresponding points in spindle speed single factor test. The reason maybe that in feed per tooth single factor test the cutting depth is 0.4mm, which is the as the twice as the cutting depth 0.2mm in spindle speed single-factor test. Secondly, the influencing trend of cutting depth impact on residual stress and the amount of feed per tooth impact on residual stress trend shows that residual stress trend map has obvious overall downwards trend when adjusting each parameter, each value of different parameters has rare crossover phenomenon, which proves cutting depth and feed per tooth are important parameters influencing residual stress.

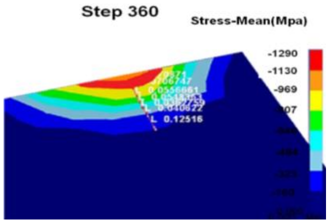
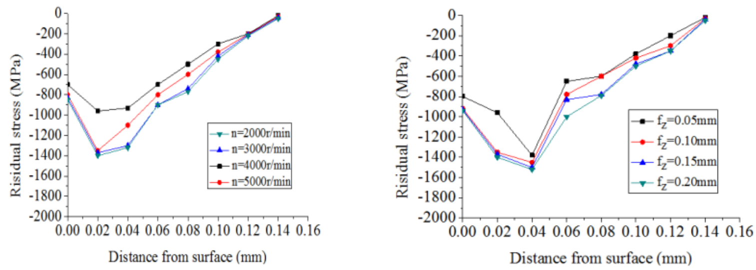
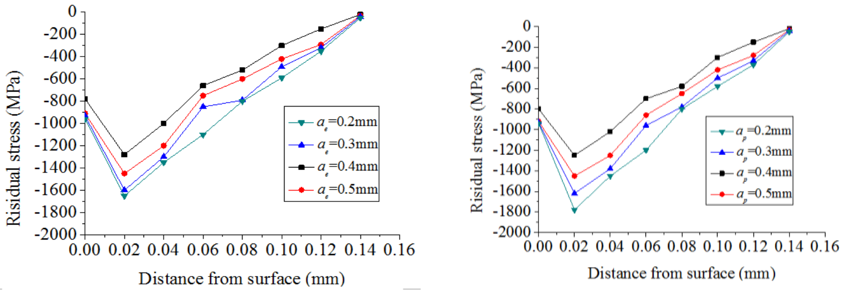


Figure 10. The Distribution of Residual Stress Along the Layer Depth Direction



a) Residual Stress Changes Trend Along Layer Depth of Spindle Speed b) Residual Stress Changes Trend Along Layer Depth of Feed Per Tooth



c) Residual stress changes trend along layer depth of row spacing d) Residual stress changes trend along layer depth of cutting depth

Figure 11. Residual Stress Changes Trend Along Cutting Depth Direction of Cutting Parameter

4.2. Residual Stress Distribution Analysis based on Field Characteristics Parameters

Combined with the changing rule of stress field and temperature field characteristic parameters and simulation results, thermal distribution mechanism of residual stress formation is analyzed:

(1)From Figure 11 (a) it can be seen that in a whole the residual compressive stress absolute value in the subsurface at the speed of 4000r/min and 5000r/min is larger than the value in other speed, and the simulation average and peak value decreases; while their residual compressive stress has high relative values, the reason of which may be that the temperature gradient value of the two speeds is higher than the temperature gradient value at the speed of 3000r/min. The effect of temperature gradient on residual stress is larger than the effect of stress gradient.

(2)Along layer depth direction, the maximum value of residual stress occurs when ap=0.5mm with any parameters; meanwhile from Fig. 11 (d) it can be seen that the cutting depth has the greatest impact on stress field max (in terms of growth trends and from the aspects of corresponding values), which shows stress field maximum value has great impact on residual stress, and stress field peak value and temperature gradient are stress field characteristic parameters which have the greatest impact on residual stress.

5. Thermal Characteristics Analysis of Work Hardening

5.1. Micro Hardness Testing and Test Results of High-Speed Milling of Hardened Steel

Did cutting experiments based on manufacturing parameters, cut work piece used in experiment into samples with the specification of 1mm*2mm*2mm using wire-electrode cutting method; Before testing samples are polished, the polished surface can be seen in Figure 12, the micro hardness tester (Figure 13) is used to test each sample micro hardness along layer depth direction; for each sample, the testing points position can be seen in Figure 14, the small diamond is the trace after the compression of the diamond indenter.

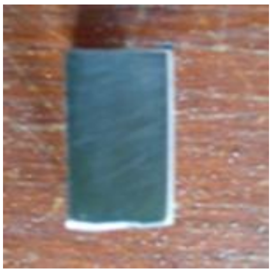


Figure 12. Surface After Polishing

Figure 13. Micro Hardness Tester

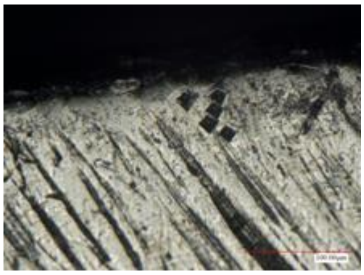
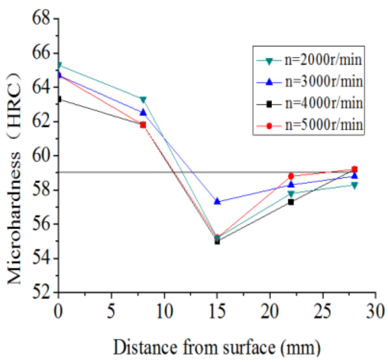


Figure 14. Micro Hardness Test Points Distribution

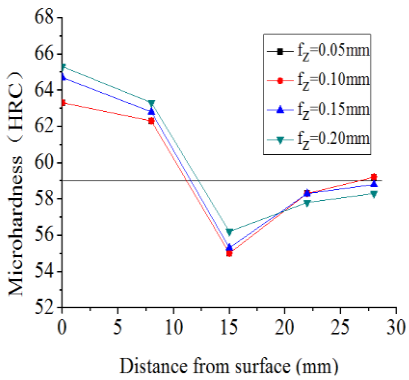
Select four testing points for all the testing samples along layer depth direction which can be seen in Figure 14, the first point distance is the distance that point be away from the surface, the distance between each test point is in turn 8μm, 7μm, 7μm and 6μm form top to bottom.

5.2. Work Hardening Distribution Analysis based on Field Characteristic Parameters

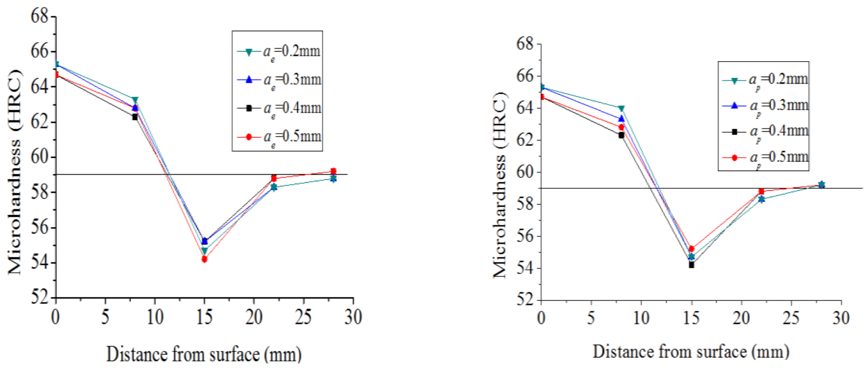
Trend map can be drawn using experimental results, which is shown in Figure 15. Take “depth value” at intersection point of each test point hardness values and HRC=59 line, as work hardening degree, and define this depth value as “white layer depth” approximately.



a) Testing Point Hardness Value of Spindle Speed Group



b) Testing Point Hardness Value of Feed Per Tooth



c) Testing Point Hardness Value of Row Spacing d) Testing Point Hardness Value of Cutting Depth

Figure 15. Testing Point Hardness Value of Each Group

From those tested trend diagram, it can be seen that work hardening existed on work piece machined surface which is caused by severe metallographic change of surface layer organization. Specifically, the grid work of each organization of work piece surface material has serious distortion under huge cutting force, and grain is stretched and broken. There is a intersection point with HRC=59 line when testing curvy is among 10 to 15, and it can be considered that the depth scope before intersection point is the white layer scope, the depth scope after intersection point and till back to HRC=59 line around can be considered as dark layer, the work hardening mentioned here can be taken as white layer depth alteration. From Figure 16 (a), it can be seen that the spindle speed have great influence on hardness value distribution of testing points, and in a whole the white layer depth becomes higher with the increase of spindle speed, and the depth of 4000 r/min was a little higher than the depth of the 5000 r/min.

With the increase of feed per tooth, work hardening degree increases. Feed per tooth has important impact on work hardening which is less than the influence degree of spindle speed. it is worth noting that when it's 0.2 mm/Z, not only white layer depth increases, the dark layer depth increases. Row spacing and cutting depth change did not cause much change of work hardening.

Temperature influencing depth increases with the increase of spindle speed, and a short incomplete low temperature tempering stage is experienced in work piece manufacturing process, which will make the decomposition of the marten site, and then hardness decline along the depth layer occur. From figure16, we can see how the cutting parameters affect temperature field characteristic parameters and the cutting temperature influence depth is less than 0.12 mm. Because the temperature slow down along the depth direction is first quick and then slow, temperature tempering softening effect can only continue to 25μm-30μm, continue increasing depth the effect is not obvious.

The influence of spindle speed and feed per tooth on stress field characteristic parameters is very significant, it can be seen that with the increase of spindle speed and feed per tooth, stress filed peak value significantly increased, and especially when the speed transfer from 3000 r/min to 4000 r/min, stress filed peak value increased nearly 300Mpa, and the phenomena of work hardening is the greatest. Thus, we can consider the stress filed peak value has significant impact on work hardening. In this way, the stress filed peak value can be used as a symbol of strain rate hardening, which is the main influencing factor in work hardening along layer depth. Temperature field influence hardness changes by the temperature mean through the detailed scope of the heat treatment temperature, while under different cutting condition, it showed little different impact on the change of hardness.

6. Conclusions

(1) The stress field and temperature field characteristic parameters are presented, and the field characteristic parameters changing trends with the alteration of cutting parameters is analyzed. Stress field mean and peak value changing trends under any parameters impacts are always parallel approximately; spindle speed has great impact on stress field gradient, and feed per tooth feed influence temperature filed gradient greatly.

(2) In high speed milling, the residual stress in the middle of work piece feed direction is mainly compressive stress along layer depth direction. Stress field peak value and temperature gradient are field characteristic parameters that have the greatest influence on residual stress. Residual stress distribution and stress distribution of machined surface are in coincide, that the maximum stress is not on the surface.

(3) Combined thermal simulation and machined surface micro hardness test, the conclusion can be obtained that the peak value of stress field can be used as a symbol of strain rate hardening, which is the main influencing factors impact work piece hardening occurrences along layer depth direction.

Acknowledgements

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References

[1] H. Schulz, E. Abele and N. He, "High speed machining theory and application", Beijing: Science Press **(2010)**.
[2] F. Y. Zhang, Ch. Zh Duan and M. J. Wang, "Machined surface affected layer development research", Machinery Design & Manufacture, vol. 10, **(2014)**, pp. 265-268.
[3] X. M. Huang, Zh. X. Zhou, J. Yang and M. Dai, "Action Mechanism of Plastic Deformation on the Grinding White Layer of Harden Bearing Steel", Journal of Hunan University (Naturnal Science), vol. 1, no. 37, **(2010)**, pp. 35-40.
[4] H. Hu, "Physical characteristics and function formation of machined surface", Mechanical & Electrical Engineering Technology, vol. 3, **(1993)**, pp. 8-14.
[5] D. Ubrello, G Ambrogio and L. Flice, "A Hybrid Finite Element Method - Artificial Neural Network Approach for Predicting Stresses and the Optimal Cutting Conditions During", Hard Turning of AISI 52100 Bearing Steal. Materials and de-sign, vol. 29, **(2008)**, pp. 873-883.
[6] X. P. Zhang, E. W. Gao and C. R. Liu, "Optimization of Process Parameter Residual Stresses for Hard Turned Surfaces", Journal of Materials Processing Technology, vol. 209, **(2009)**, pp. 4286-291.
[7] S. Han, S. N. Melkote and M. S. Haluska, "White layer formation due to phase transformation in orthogonal machining of AISI 1045 annealed steel", Materials Science and Engineering A, vol. 488, no. 1-2, **(2008)**, pp. 195-204.
[8] R. M'Saoubi, J. C. Outeiro and H. Chandrasekaran, "A review of surface integrity in machining and its impact on functional performance and life of machined products", Inter-national Journal of Sustainable Manufacturing, vol. 1, no. 1-2, **(2008)**, pp. 203-236.
[9] M. Stolorz, B. Behrens and A. Silipigni, "Influence of hard milling on the surface integrity of hot working steel", BHM, vol. 157, no. 11, **(2012)**, pp. 420-426.