Novel tool wear monitoring method in milling difficult-to-machine materials using cutting chip formation

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Abstract. The main problems in milling difficult-to-machine materials are the high cutting temperature and rapid tool wear. However it is impossible to investigate tool wear in machining. Tool wear and cutting chip formation are two of the most important representations for machining efficiency and quality. The purpose of this paper is to develop the model of tool wear with cutting chip formation (width of chip and radian of chip) on difficult-to-machine materials. Thereby tool wear is monitored by cutting chip formation. A milling experiment on the machining centre with three sets cutting parameters was performed to obtain chip formation and tool wear. The experimental results show that tool wear increases gradually along with cutting process. In contrast, width of chip and radian of chip decrease. The model is developed by fitting the experimental data and formula transformations. The most of monitored errors of tool wear by the chip formation are less than 10%. The smallest error is 0.2%. Overall errors by the radian of chip are less than the ones by the width of chip. It is new way to monitor and detect tool wear by cutting chip formation in milling difficult-to-machine materials.

1. Introduction

Difficult-to-machine materials have gained widespread applications in aerospace, marine and biomedical industries due to their following favorable properties: they are light weight, possess high strength, have excellent fatigue performance and offer high resistance to an aggressive environment [1]. However, the main problems in milling difficult-to-machine materials are the high cutting temperature and the rapid tools wear. Rapid tool wear serious affect the machining efficiency and surface quality. Thus, how to monitor and control tool wear is a pressing problem for milling difficult-to-machine materials.

Controlling tool wear was realized by selection and optimization of cutting parameters (spindle speed, feed rate, and depth of cut) [2]. However, it is impossible to obtain the real-time degradation process by selecting or optimization of cutting parameters. In order to obtain or monitor the degradation process of tool or insert, many work or researches have been done on it. To monitor tool wear, vibration signal is most commonly used to analyze status of tool wear because it is direct and easy to collect vibration signal. For example, average energy was used to monitoring tool wear for turning Ti-6Al-4V [3]. Ref. [4] monitored tool wear using classifier fusion based on acoustic emission signal. Tool wear was correlated with vibration in the milling process of hardened steel in ref. [5].

However, vibration signal can not accurately reflect the states of tool wear because there are many vibration sources. At this time, during the whole processing, it is impossible to measure tool wear by constantly interrupted machine. Milling chip contacted directly with tool is taken to study tool wear because it is a representation of tool wear. Chip morphology was modeled to monitor tool wear for ultra-precision raster milling in ref. [6]. Ref. [7] used multiple sensors in turning to monitor the tool wear and chip formation. For ultra-precision raster milling, chip morphology was studied well to monitor or predict tool wear. Ref. [8] proposed a new method to monitor tool wear for raster milling using cutting chip. This method was realized to monitor tool wear by developing cutting chip geometry model. The effect of cAN/TiAIN coating on tool wear and chip morphology in face milling of Ti6Al4V was studied in Ref. [9]. However, ref. [9] had not mentioned the relationship between tool wear and chip morphology. There are fewer studies on tool wear and chip formation for milling difficult-to-machine materials. Thus, this paper aims to develop the relationship between tool wear and chip morphology to monitor the tool wear.

In this paper, section 2 proposes a novel method based on the problems of developing the relationship between tool wear (obtained un-easily) and chip (obtained easily). Section 3 introduces the experiment for collecting data of tool wear and chip morphology. Section 4 analyses these data and discusses the results which are gotten with the proposed method in section 2. Section 5 gives a conclusion of this paper.

2. Proposed method

Following the introduction, the machining efficiency and process can be accessed timely by monitoring related characterizations such as tool wear, vibration, surface quality, chip and so on. And these characterizations are effected or controlled by same cutting parameters. Some characterizations are obtained easily. However, some characterizations are not obtained easily and even unavailable. It is necessary to develop the relationships or mapping models between characterizations obtained easily and characterizations obtained non-easily if characterizations obtained non-easily are very important for researches or applications. In other word, the characterizations with same variables can be replaced or represented each other. So, in this paper, tool wear (obtained by stopping the machine) will be represented by chips (obtained easily by collecting them after finishing the cutting). This idea is described in mathematic form as following.

Functions with same variables can be replaced each other. Group functions F have i functions f which have same variables **x**,

$$\mathbf{F}_{\mathrm{i}} = f_{\mathrm{i}}(\mathbf{x}) \quad \mathrm{i} = 1, 2, \ldots, \mathrm{n} \tag{1}$$

i^{th} function $\mathbf{F}_{\mathrm{i}}$ can be replaced by j^{th} function $\mathbf{F}_{\mathrm{j}}$. The i^{th} function $\mathbf{F}_{\mathrm{i}}$ becomes equation (2).

$$\mathbf{F}_{\mathrm{i}} = f_{\mathrm{i}}\left(f_{\mathrm{j}}^{-1}\left(\mathbf{F}_{\mathrm{j}}\right)\right) \tag{2}$$

Here, take linear equations as example. There are two functions $\mathbf{F}_1$ and $\mathbf{F}_2$: $\mathbf{F}_1 = a_1x + b_1$, $\mathbf{F}_2 = a_2x + b_2$. $\mathbf{F}_2$ is rewritten with $\mathbf{F}_1$ as equation (3).

$$\mathbf{F}_2 = a_2\left(\frac{\mathbf{F}_1 - b_1}{a_1}\right) + b_2 \tag{3}$$

The calculation results are precise if functions have exact expressions. However, if the function is developed by fitting from the experiments data, there are going to have errors or deviation. Figure 1 shows the schematic diagram of errors forming process. Function f_1 is fitted based on round black point. Function f_2 is fitted based on star shape point. Function f_1 is used to monitor or predict function f_2. Real value (experiment data) of f_1 at point x_1 is put in function f_1. The point x_2 is obtained in function f_1 (blue round point in the line of $\mathbf{F}_1$). After x_2 is put in the f_2, $f_2(x_2)$ is the monitored value (blue star point in the line of $\mathbf{F}_2$). The Δy_2 is the monitored error or deviation of function f_2 by the function f_1. In contrast, Δy_1 is the monitored error or deviation of function f_1 by the function f_2 (red round point and red star point).

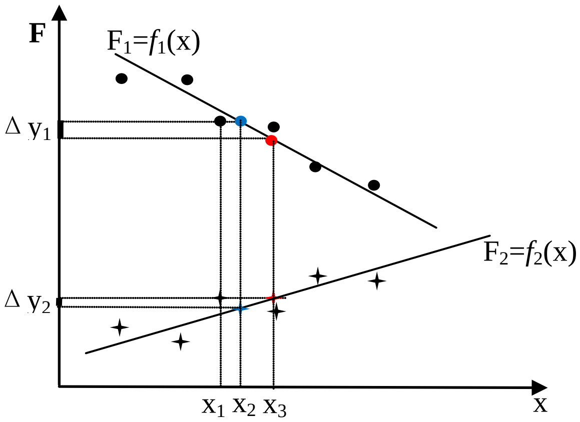


Figure 1. Schematic diagram of errors forming process.

3. Description of experiment

3.1. Work-piece material

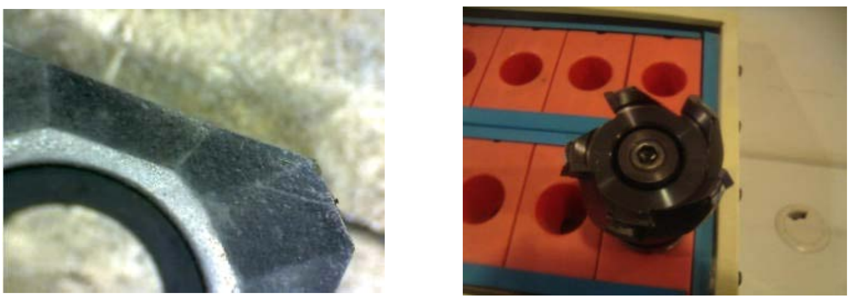
The tested material was an alpha-beta titanium alloy Ti-6AI-4V (TC4). Titanium alloy is an attractive material due to their unique high strength, which is classified as difficult-to-machine materials. The main problems in machining titanium alloy are the high cutting temperature and rapid tools wear. The chemical compositions of the titanium alloys (in wt.%) is given in table 1. The mechanical properties of tested material are 912MPa (tensile strengthσ_b) , 839 MPa (Yield Strength $\sigma_{0.2}$), 10% (elongation) and around 27 HRC (hardness). The work-piece used in the experiment was a block with the size 200 x 200 x 80 (mm).

Table 1. Chemical Compositions (in wt.%)

Element	Ti	AL	V	Fe	C	N	H	O	other
Proportion	remainder	6.4	3.7	0.24	0.085	0.023	0.011	0.17	<0.10

3.2. Cutting tool material

The tool (inserts) used for the machining experiments were cemented carbide CG10 SEKT1204AFFN-HL. The shape of the insert is square with four angles 45 degree cut (figure 2 (a)). Five inserts were fixed in the tool handle at the same time (figure 2 (b)). That means five measured values of tool wear can be obtained at the same time.



(a) (b)

Figure 2. Tool handle with five inserts.

3.3. Machining experiments

All the machining experiments were carried out on a vertical CNC milling machine XH714 which was controlled by FANUC controller (figure 3). The CNC milling has a continuously variable spindle speed. Throughout the whole experiments, the width of cutting was kept constant at 40 mm. and the spindle speeds (*n*) were set at 700, 1000 and 1300 rpm. The feed rates (*vf*) were set at 80, 100 and 120 mm/min. The depths of cut (*dp*) were set at 0.1, 0.3 and 0.5 mm. The machining experiments were carried out with cutting fluid. The cutting conditions used in this paper are shown in table 2.

Figure 3. Worktable.

Table 2. Design of experiments

	n rpm	*vf* mm/min	*dp* mm
1	700	100	0.3
2	1300	80	0.5
3	1300	100	0.1

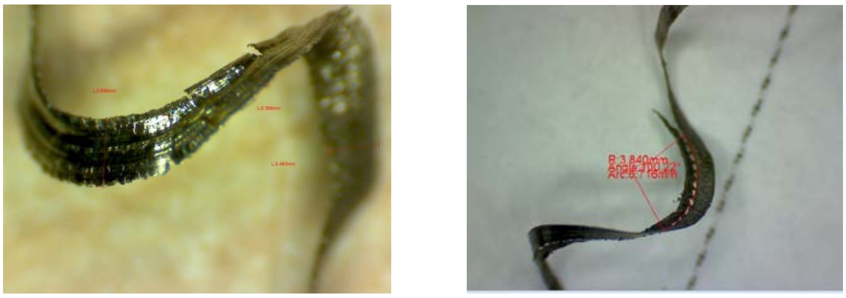
3.4. Tool wear and cutting chip measurement

The tool wear and chip formation were measured at the same time after a surface was milled (twice straight cutter path; width of cut is 40 mm; width of the block is 80 mm). The number of measurement of tool wear and chip formation is 10. It means that the processing is interrupted by 10 times. The time of each processing depended on the feed rate. The maximum wear lands were measured in the longest and the widest by the toolbox of software in microscope (figure 4). The width chip and radian of chip were chosen to be the parameters of chip because they can typically display the chip formation. Figure 5 shows the measurements of cutting chip formation. Cutting process was terminated after 10 processing was finished no matter the inserts were failed or not. Otherwise, cutting was forced to terminate when catastrophic fracture of the edge was observed (appeared a lots of sparks). The cutting process for second set parameters (*n*=1300 rpm, *vf*=80 mm/min, *dp*=0.5mm) is forced to stop at the 7th processing due to catastrophic fracture. Thus, in the section 4, there are only 7 groups' data for the second set parameters.

(a) Digital microscope

(b) Measurement of tool wear region

Figure 4. Equipment and measurement.



(a)Width of chip (b)Radian of chip

Figure 5. Cutting chip formation measurements.

4. Results and discussion

As discussed before, the relationship between tool wear and chip formation is developed. Figure 6, figure 8 and figure 10 show the tools wear values, width of chip and radian of chip for three sets parameters (table 2) to cutting times. It is easy to find that tool wear gradually increase along with cutting time. In contrast, width of chip and radian of chip are gradually decreased.

By method proposed in section 2, the monitoring values of tool wear by chip formation is shown in the table 3, table 4 and table 5. The errors are also listed in the three tables at the same time. So three tables list from left to right monitored values of tool wear by width of chip (W-by-W), monitored values of tool wear by radian of chip (W-by-R), monitored values of tool wear by average values of width of chip and radian of chip (W-by-WR), real tool wear (R-W), monitored errors by width of chip (E-by-W), monitored errors by radian of chip (E-by-R) and monitored errors by average value of width of chip and radian of chip (E-by-WR). Figure 7, figure 9 and figure 11 show the monitored errors by width of chip, radian of chip and average value of them.

Table 3 and figure 7 show that the monitored errors by radian of chip are less than the ones by width of chip for first set parameters (*n*=700rpm, *vf*=100mm/min, *dp*=0.3mm). The maximum monitored error by radian of chip is 18.95%; the minimum monitored error by radian of chip is 0.29%. The errors less than 10% are 70%. All the errors are less than 20%. However, the maximum monitored error by width of chip is 26.95%. The minimum monitored error by width of chip is 0.24%. The monitored errors by width of chip less than10% are 50%. It means that the monitored errors by radian of chip are less than the one by width of chip. All errors by average value of width of chip and radian of chip are less than 17%.

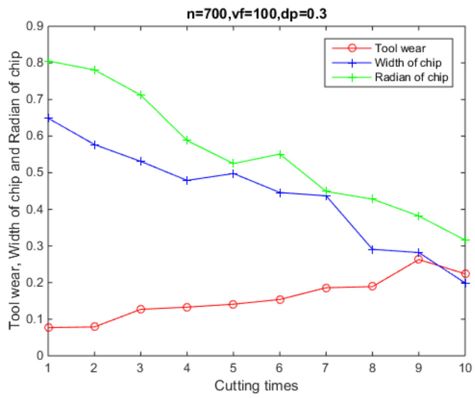


Figure 6. Tool wear, width of chip and radian of chip for the first set parameters.

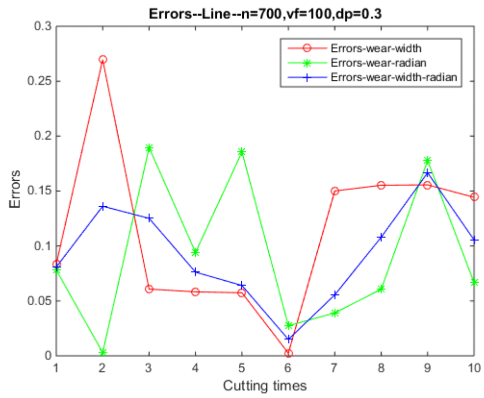


Figure 7. Errors of monitored tool wear by width of chip, radian of chip and average value of width and radian of chip for the first set parameters.

Table3. Monitored tool wears and errors by chip formation for the first set parameters

	W-by-W	W-by-R	W-by-WR	R-W	E-by-W	E-by-R	E-by-WR
1	0.0706	0.0701	0.0708	0.0770	8.35	7.81	8.08
2	0.1003	0.0792	0.0898	0.0790	26.95	0.29	13.62
3	0.1193	0.1029	0.1111	0.1270	6.08	18.95	12.52
4	0.1407	0.1455	0.1431	0.1330	5.83	9.41	7.62
5	0.1329	0.1672	0.1500	0.1410	5.74	18.55	6.41
6	0.1544	0.1582	0.1563	0.1540	0.24	2.75	1.49
7	0.1581	0.1933	0.1757	0.1860	15.01	3.90	5.55
8	0.2184	0.2005	0.2094	0.1890	15.53	6.07	10.80
9	0.2221	0.2163	0.2192	0.2630	15.56	17.77	16.67
10	0.2563	0.2389	0.2476	0.2240	14.43	6.67	10.55

Table 4 and figure 9 show that the monitored errors by radian of chip are less than the ones by width of chip for second set parameters (*n*=1300rpm, *vf*=80mm/min, *dp*=0.5mm). The maximum monitored error by radian of chip is 39.59%; the minimum monitored error by radian of chip is 3.36%. However, the monitored errors by width of chip less than 6% are 71% even though the maximum error is 46.43%. All of errors by average of width of chip and radian of chip are less than 25%.

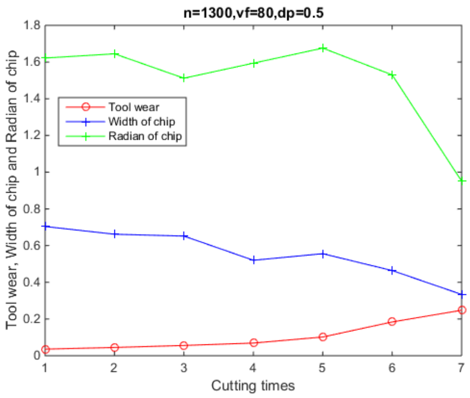


Figure 8. Tool wear, width of chip and radian of chip for the second set parameters.

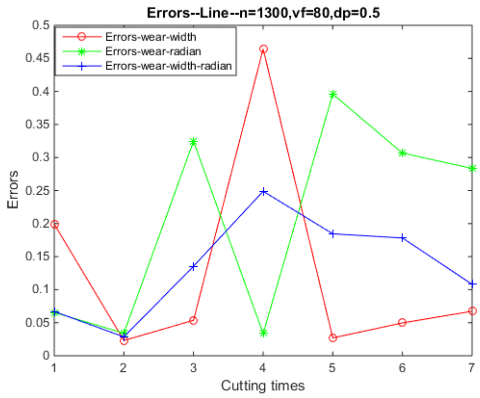


Figure 9. Errors of monitored tool wear by width of chip, radian of chip and average value of width and radian of chip for the second set parameters.

Table 4. Monitored tool wears and errors by chip formation for the second set parameters

	W-by-W	W-by-R	W-by-WR	R-W	E-by-W	E-by-R	E-by-WR
1	0.0881	0.1172	0.1026	0.1100	19.92	6.54	6.69
2	0.1094	0.1082	0.1088	0.1120	2.30	3.40	2.85
3	0.1145	0.1603	0.1374	0.1210	5.37	32.45	13.54
4	0.1816	0.1282	0.1549	0.1240	46.43	3.36	24.89
5	0.1633	0.0961	0.1297	0.1590	2.70	39.59	18.45
6	0.2100	0.1532	0.1816	0.2210	4.96	30.67	17.82
7	0.2761	0.3799	0.3280	0.2960	6.73	28.35	10.81

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Table 5 and figure 11 show that the monitored errors by radian of chip are less than the ones by width of chip for the third set parameters (*n*=1300rpm, *vf*=100mm/min, *dp*=0.1mm). The maximum monitored error by radian of chip is 26.33%; the minimum monitored error by radian of chip is 3.55%. The monitored errors less than 15% are 70%. However, the monitored errors by width of chip are about 40% which are not useful for the real engineering. The results of first set parameter show the same phenomenon. All of errors by average value of width of chip and radian of chip are less than 34%.

The overall errors monitored by radian of chip are less than the ones by width of chip for first set parameters and third set parameters. For the second set parameters, the overall errors monitored by radian of chip are equal to the ones by width of chip. The overall errors monitored by average value of width of chip and radian of chip are smaller than the ones by the radian of chip or width of chip. So width of chip is not suitable for monitoring tool wear. Radian of chip or average value of radian and width of chip can be chosen to monitor tool wear.

In addition, width of chip varies from big to small following that the depth of cut narrows. With the fixed parameters, width of chip varies from big to small along with the tool wear getting more serious. Width of chips is proportional with the radian of chips.

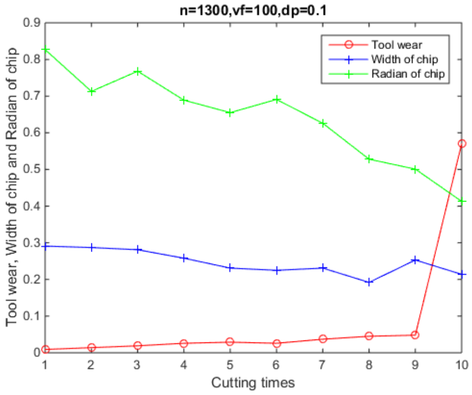

Figure 10. Tool wear, width of chip and radian of chip for the third set parameters.

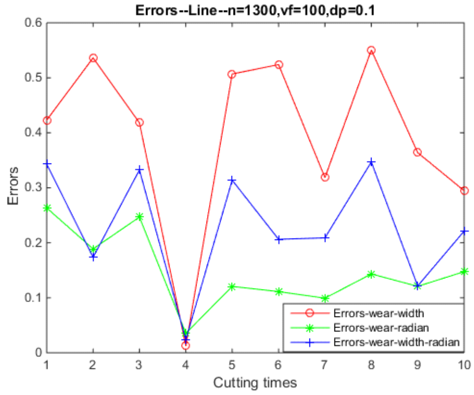

Figure 11. Errors of monitored tool wear by width of chip, radian of chip and average value of width and radian of chip for the third set parameters.

Table 5. Monitored tool wears and errors by chip formation for the third set parameters

	W-by-W	W-by-R	W-by-WR	R-W	E-by-W	E-by-R	E-by-WR
1	0.0035	0.0044	0.0039	0.0060	42.3	26.33	34.32
2	0.0046	0.0119	0.0083	0.0100	53.62	18.89	17.37
3	0.0064	0.0083	0.0073	0.0110	41.81	24.68	33.24
4	0.0132	0.0135	0.0133	0.0130	1.24	3.55	2.40
5	0.0211	0.0157	0.0184	0.0140	50.69	12.07	31.38
6	0.0229	0.0133	0.0181	0.0150	52.40	11.13	20.64
7	0.0211	0.0176	0.0193	0.0160	31.86	9.93	20.89
8	0.0326	0.0240	0.0283	0.0210	55.05	14.33	34.69
9	0.0146	0.0258	0.0202	0.0230	36.39	12.08	12.15
10	0.0261	0.0315	0.0288	0.0370	29.48	14.74	22.11

5. Conclusions

The research explored the method for monitoring tool wear by cutting chip formation. From the study, specific conclusions are as follows: tool wear gradually increase along with cutting time. In contrast, width of chip and radian of chip are gradually decreased along with the cutting time. For a fixed cutting parameters, width of chip decrease along with that the tool wear is getting more serious. It is possible and useful to monitor tool wear in milling difficult-to-machine materials by cutting chip formation. The monitored errors by radian chip and average value of width of chip and radian of chip are less than the ones by the width of chip.

The method proposed in this paper can be used to monitor or predict the related two representations for milling the difficult-to-machine materials. The following work is going to focus on developing the models of cutting parameters and each representation (vibration, surface quality, chips formation and tool wear). Thereby the balance of quality and efficiency for milling difficult-to-machine materials is found by multi-disciplinary optimization.

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References

[1] https://www.researchgate.net/post/Why_is_difficult_to_machining_titanium_and_titanium_alloys
[2] Zhang P P and Guo Y 2015 Mapping time-variant modeling of tool wears and cutting parameters on difficult-to-machine materials, *Proceedings of the 10th world congress on Engneering Asset Management*, 28-30 september 2015 (Tampere, Finland)
[3] Srinivasa Pai P and D'Mello G 2015 Vibration signal analysis for monitoring tool wear in high speed turning of Ti-6Al-4V, *Indian Journal of Engineering & Materials Science* 22 pp 652-660
[4] Kannatey-Asibu E, Yum J and Kim T H 2017 Monitoring tool wear using classifier fusion, *Mechanical Systems and Signal Processing* 85 pp 651-661
[5] Mendes de Aguiar M, Eduqrdo Diniz A and Pederiva R 2013 Correlating surface roughness, tool wear and tool vibration in the milling process of hardened steel using long slender tools, *International Journal of Machine Tools & Manufacture* 68 pp 1-10
[6] Zhang G Q, To S and Xiao G B 2014 The relation between chip morphology and tool wear in ultra-precision raster milling, *International Journal of Machine Tools & Manufacture* 80-81 pp 11-17
[7] Bhuiyan M S H, Choudhury I A and Dahari M 2014 Monitoring the tool wear, surface roughness and chip formation occurrences using multiple sensors in turning, *Journal of Manufacturing Systems* 33 pp 476-487
[8] Zhang G Q, To S and Xiao G B 2014 Novel tool wear monitoring method in ultra-precision raster milling using cutting chips, *Precision Engineering* 38 pp 555-560
[9] Çalışkan H and Küçükköse M 2015 The effect of cAN/TiAIN coating on tool wear, cutting force, surface finish and chip morphology in face milling of Ti6Al4V superalloy, *International Journal of Refractory Metals and hard Materials* 50 pp 304-312