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Fatigue Behavior And Microstructure Examination Of Aisi D2 Trim Dies

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FATIGUE BEHAVIOR AND MICROSTRUCTURE EXAMINATION OF AISI D2 TRIM DIES

by

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1. Introduction

As the continuous study of Project No ASP-360: Trim Die Chipping Measurement, a further research of tool life (in the project, AISI D2) in the sheet metal forming is developed in the laboratory conditions under a better controllable environment and testing conditions.

From the previous study of our research group we know that the grain orientation has a major influence on chipping damage of the in-line trim die for the same tool steel under the comparable working process. However many uncertain factors may exist in the stamping production environment so that a laboratory testing method needs to be established in this project to simulate the die trimming process as fatigue testing, that can be precisely controlled for investigating the orientation effect when other testing conditions are the same, and more parameters can be inspected.

The initial laboratory testing method can also serve as a platform for evaluate more tooling steels (such as Caldie, Carmo) and more tool manufacturing processes (heat-treatment, coating, etc.) for future research development.

2. Literature Review

2.1 Tool Steel Review

Tools used in sheet metal forming industry are facing their high challenge to withstand a high applied stress, especially at the cutting edges in trimming operation, and sometimes at raised temperature; they usually require distinct hardness, toughness, chipping and abrasive resistance, and also with a high demand for relatively prolonged fatigue life for industry productions[1-3]. Therefore, it is commonly mandatory that tool steels be heat-treated with varieties of quenching conditions, such as water- hardening, oil- hardening, and air-hardening[4, 5].

To satisfy different applications of sheet forming and manufacturing process requirements for various properties of tool steels[3, 6], the AISI (American Iron and Steel Institute) and SAE (Society of Automotive Engineers) classify tool steel with as a grade scale and maybe its combination with a given number based on hardening methods and alloys, as seen in Table 1.[7]

Table 1 AISI-SAE Tool steels grades

Essential property	**AISI-SAE grade**	**Significant characteristics**
Water-hardening	W	
Cold-working	O	Oil-hardening
	A	Air-hardening; medium alloy
	D	High carbon; high chromium
Shock resisting	S	

High speed	T	Tungsten base
	M	Molybdenum base
Hot-working	H	H1–H19: chromium base H20–H39: tungsten base H40–H59: molybdenum base
Plastic mold	P	
Special purpose	L	Low alloy
	F	Carbon tungsten

There are some common tool steels generally available in the market and used in various industries[8], shown as Table 2.

Table 2 Common tool steels specifications and applications

Tool Steel Grade	Heat-treatment (F)	Quench	Rockwell Hardness	Applications
W-1	1450-1600	Water	56c	Knives Scissors and Shears, etc.
O-1	1450-1600	Oil	62c-64c	Shear Blades Trimming Dies Drills, etc.
A-2	1700-1900	Air	59c-62c	Same as O1 and

				W1, with deeper hardenability
D-2	1600-1650	Air or Oil	60c-62c	High wear qualities, chosen as long tool life.

Therefore, as tool and die material for high strain steels under car body stamping process to simulate the life long on-line production, AISI D2 is our primary choice among tool steel grades.

2.2 About Fatigue Test and Fatigue Life

Fatigue life, N_f, defined by ASTM (American Society for Testing and Materials), is the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs[9]. Generally, two types of figure have been developed historically: high-cycle fatigue (HCF) and low-cycle fatigue (LCF). A high cycle fatigue test indicates to the fatigue life in the range of 103-108 cycles, often tested at 20-50Hz frequencies in a hydraulic test machine; while a low-cycle fatigue test is under the fatigue life is less than 103 cycles and amongst 0.01-3 Hz frequencies. [10-12]

In HCF, the material performance is typically obtainable by S-N curve, also known as Wöhler curve (Wöhler, 1867)[13]. S refers to the amplitude of cyclic stress, while N as cycles to failure in logarithmic scales. S-N curves are derived from testing on material samples by regular sinusoidal stress to evaluate the number of cycles to failure, and shown in Figure 1.

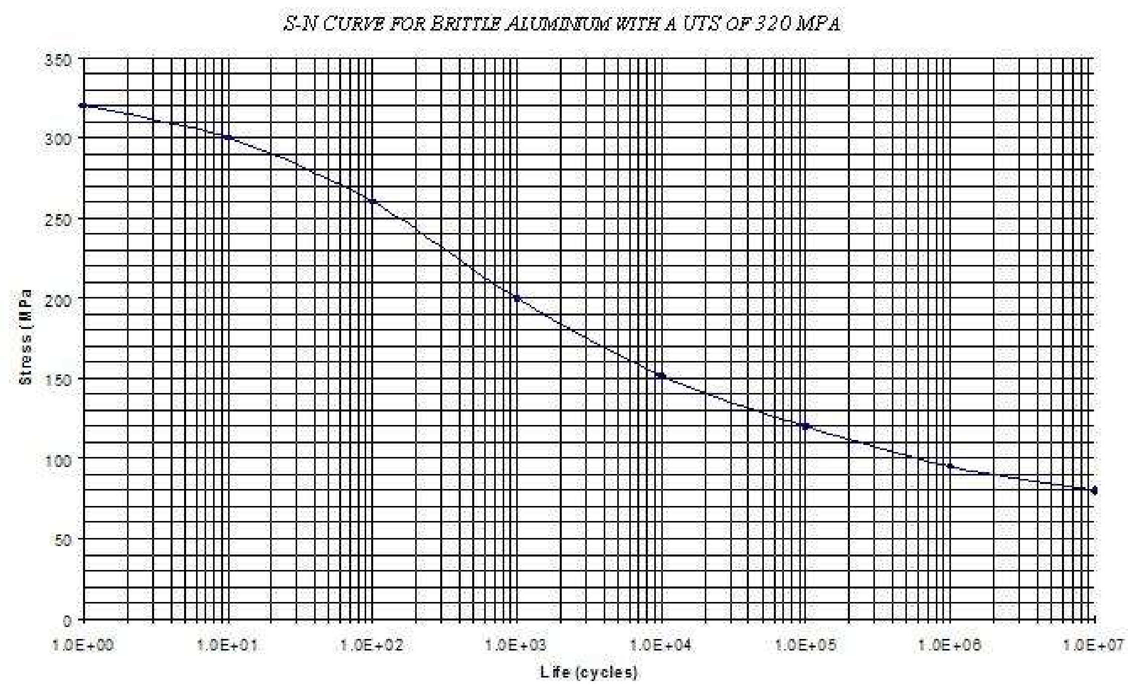


Figure 1 S-N curve for brittle aluminum

In LCF, fatigue life is usually anticipated by Coffin[14]-Manson[15] (Coffin, 1954 and Manson, 1954) equation:

$$\frac{\Delta\epsilon_p}{2} = \epsilon_f'(2N)^c$$

Where,

$\frac{\Delta\epsilon_p}{2}$ is the plastic strain amplitude;

ϵ_f' is an empirical constant known as the fatigue ductility coefficient, the failure strain for a single reversal;

$2N$ is the number of reversals to failure (N cycles);

c is an empirical constant known as the fatigue ductility exponent.

Nowadays, sheet metals' (high strength steel, aluminum, etc.) strength properties keep growing to fulfill industries' requirements, along with tool and die qualities as even more advanced for fatigue life pertained to different manufacturing process. Several refining methods have been introduced by previous works: intermetallic coating (such as TiN) on tool steel surface or near cutting edge would significantly develop strength and hardness for fatigue damage, since such improvement caused by coating can reduce residual tensile stress or add compressive residual stress on the surface layer[16]; fine finish heat-treatments as quenched and tempered could also improve the fatigue factors, and the designated heat-treating cycles could lead to preferred hardness[17]; high-performance powder metallurgical tools, as compared to traditional rolled tool steels under a fatigue loading, can offer tool components with a superior lifetime[18].Besides, the usage of a high stiffness structure could be very appealing, as the plastic strain generosities are noticeably decreased[19].

2.3 Microstructure Observation

Appeared as fatigue life and mechanical properties functioning of tool steels, insight of microstructure observation and analysis to damage crack development and tool steels grain structures themselves could reveal more evidences related to tool geometry shapes, thermal effects, and varieties of manufacturing process.

First, some common design mistakes could directly downgrade fatigue performance based on microscope inspection, such as lack of radius and hardness evenness alongside the unqualified tool, and inappropriate usage and a complete deficiency of strength dismissing led to premature fracture[20]. Then, heat-treatments for tool steels (cold work[21, 22] and hot work[23, 24]) could considerably alter microstructure information like compositions (austenite, etc.) transferred, primary or secondary carbides refined. Finally, grain evidence, such as grain size and grain orientation, misrepresent because of certain machining procedures also affect to fatigue behavior of tool steel, and it would be revealed in this paper.

3. Testing Design and Experiment Conditions

3.1 Testing Design Concept and Marching Work

For simulating the in-line trimming process to combine the trimming testing and also the chipping testing, a trimming simulator concept is designed as Figure 2[25].

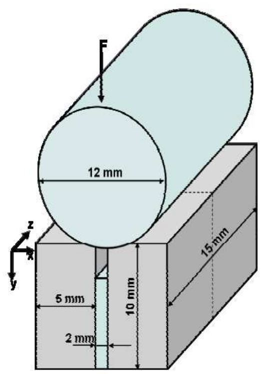


Figure 2 Trimming simulator concept design

In this simulator, we choose tungsten carbide as the contact rod, and machine the tooling steel as two cubes. A high-cycle sinusoidal wave loading applies to contact rod and transfers to the cutting edges of the steel cubes, the fatigue damage will happened at the cutting edges. To verify the tungsten carbide rod is sufficiently stronger than the tooling steel, the Knoop micro-hardness test is operated at the contact surface (can not be on the curved surface and edge) for both materials and the results are given in Figure 3 Hardness comparisons between AISI D2 and tungsten carbide under 1kgf

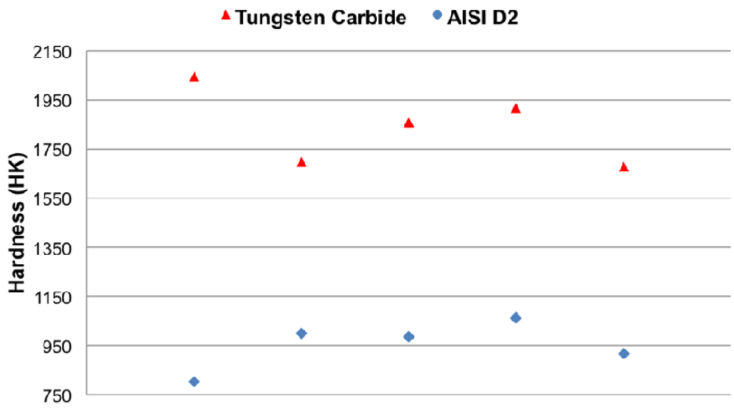


Figure 3 Hardness comparisons between AISI D2 and tungsten carbide under 1kgf

To adjust the simulator for the Intron servo-hydraulic fatigue testing 8801 machine working condition and dimensions, an assembly engineering drawing is plotted as shown in Figure 4.

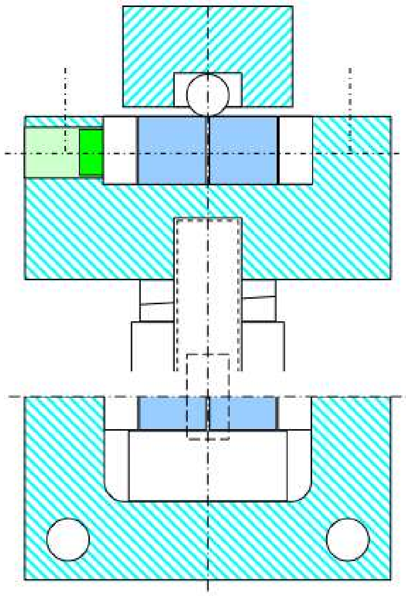


Figure 4 Assembly Drawing of Trimming Simulator

After the machining work, the trimming simulator is fabricated. The testing system setup and the simulator are shown in

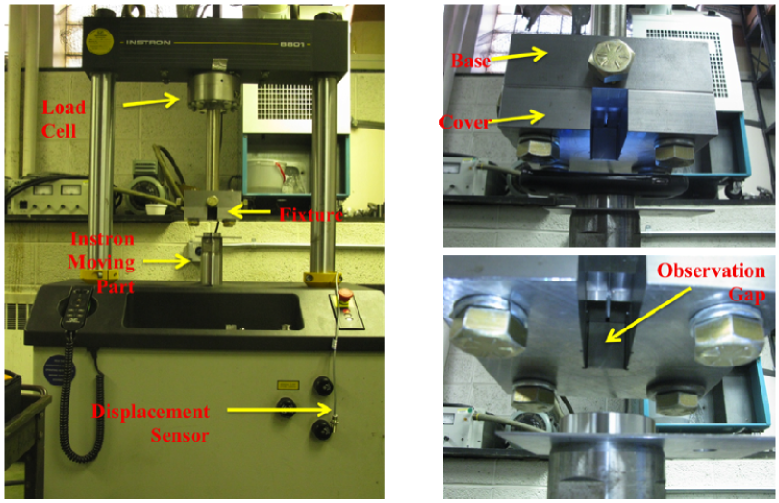


Figure 5 A and B, respectively.

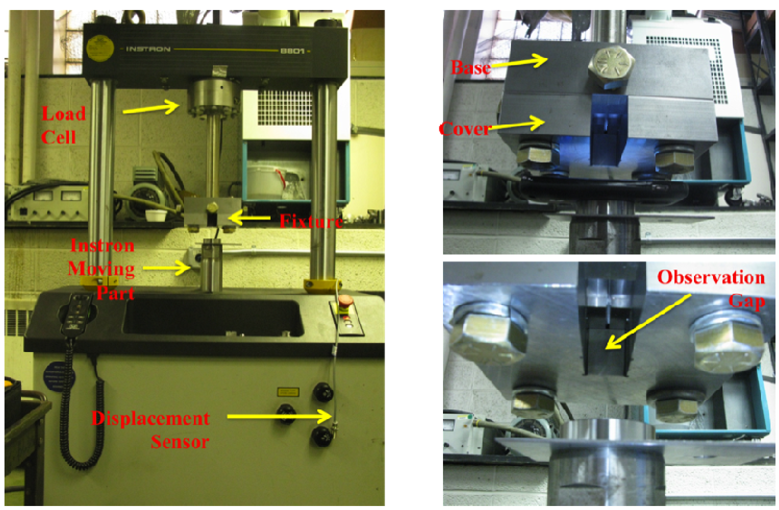


Figure 5 (A) Intron 8801 machine (B) The trimming simulator

3.2 Tooling Steel Material Properties Overview

In this research the tooling steel we used for the trimming die chipping is AISI D2, which is widely used as tools for forming, drawing and dies for varieties of molding due to its high wear resistance, high compressive strength and low distortion.

The optical microstructure observation shows the grain orientation and size information in Figure 5. Clearly, we can see the grain orientation in three dimensions (rolling direction RD, transverse direction TD, and thickness direction ThD) is consistent with the rolling orientation shown in Figure 7(A). Considering the three plane normal directions and three shear directions there are total six orientations for the cutting edges (XY, XZ, YX, YZ, ZX, and ZY) in Figure 7(B).

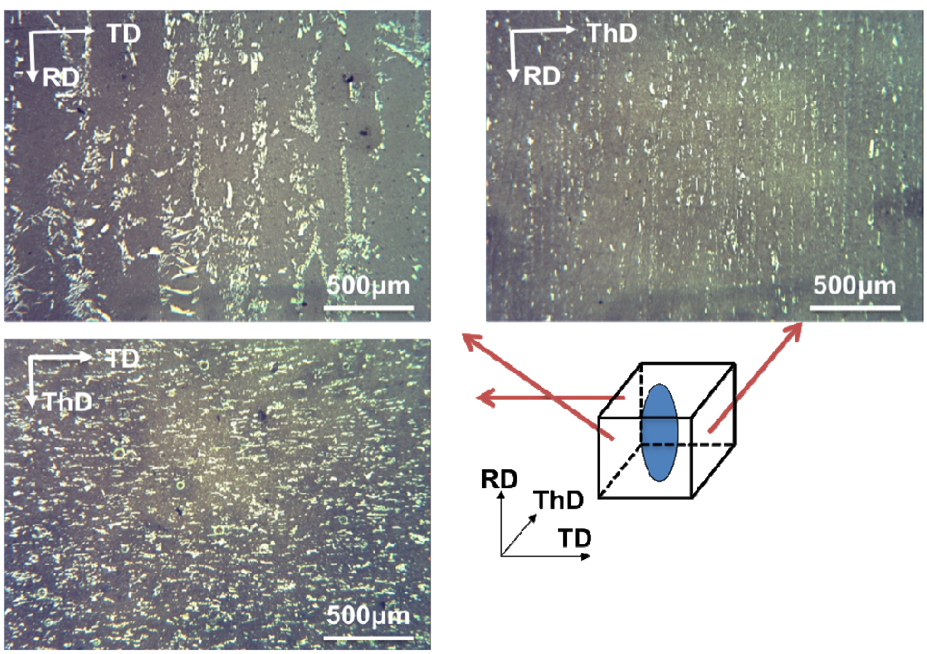


Figure 6 Microstructure of AISI D2 after heat-treatment

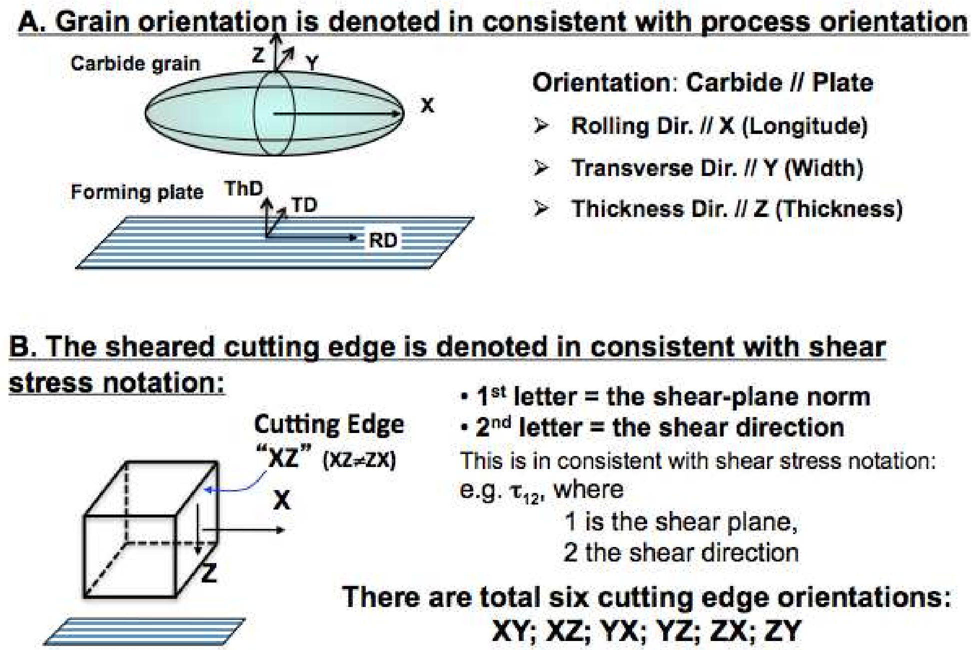


Figure 7 Cutting edge orientation notations

3.3 Testing Conditions and Procedures

3.1.1 Material Description

AISI D2 tooling steel machined as 1-inch cube. Totally it has 12 cutting edges with 6 orientations since two edges are identical.

3.1.2 Testing System

Instron 8801 servo-hydraulic system with ±100 kN load capacity and ±3" full stroke travel distance. Instron digital controller 8800, capable of three control modes: load control, displacement control and strain control; and under various load functions including build-in constant speed and constant strain rate functions.

Computer data acquisition system consisting of computer with A/D card and software, power supply, and signal conditioner (to amplify mV dc signal to Volt dc, for thermocouples and extensometer). Instron has a build-in signal conditioner that outputs the load and stroke singles with a linear conversion of full-scale load and stroke values into ±10 dc Volts. The analogue to digital data acquisition card has a use-specified sampling rate up to 100 kHz (for all specified channels used).

3.1.3 Testing Conditions and Procedures

Applying different sine wave loading amplitudes under different frequencies on six orientations (XZ, ZX, XY, YX, ZY, YZ). For example, Figure 8 shows one certain testing circumstance (load=80kN and frequency=10Hz).

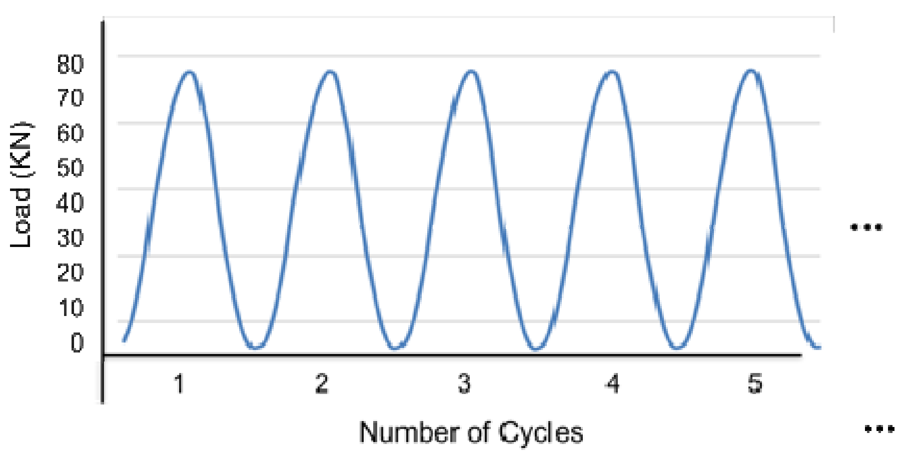


Figure 8 Testing conditions under load=80kN and frequency=10Hz

Also, during the testing, it is interrupted at various numbers of cycles (e.g. 5k, 10k, 50k, 100k and 500k), for measuring damage and its evolution.

3.4 Damage Observation and Measurement Methods

Using stereomicroscope (typically, 5-50 times magnifications) observes damage areas of D2 dies, There are two types of damage happen in the fatigue compression test: Contact deformation and chipping damage. In most case, contact deformation is very common and rare for chipping damage in Figure 9.

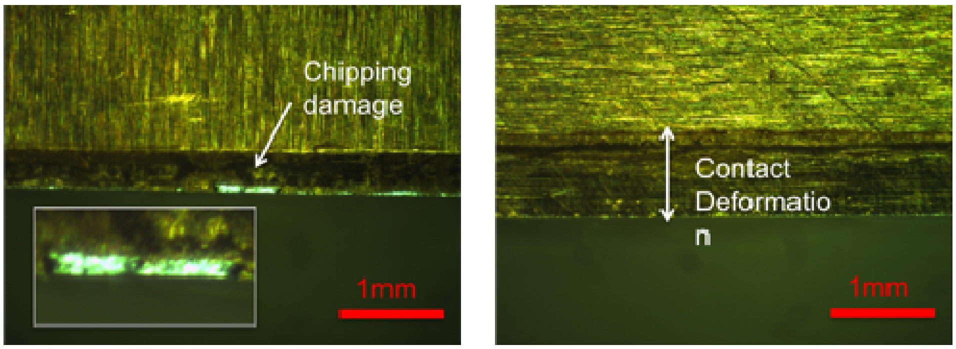


Figure 9 D2 damage observations for chipping damage and contact deformation

Then, the damage measurement method is: 1) Gather all the partial images for an edge into one picture using Photoshop; 2) Use mouse to trace the edge of damaged region with Photoshop's Edge Tracing Function; 3) Fill-in the traced damaged area and save to a binary image containing the missing area only; 4) Input the binary image into Matlab to read the coordinate of pixels for the missing metal and calculate the damage missing top area. 5) Converting the pixel dimension to real physical dimension, based on the length scaling factor as known edge length (25.4mm) and the number of pixels. For instance, XY damage measurement under 80kN/50Hz for 500k Cycles shows in Figure 10.

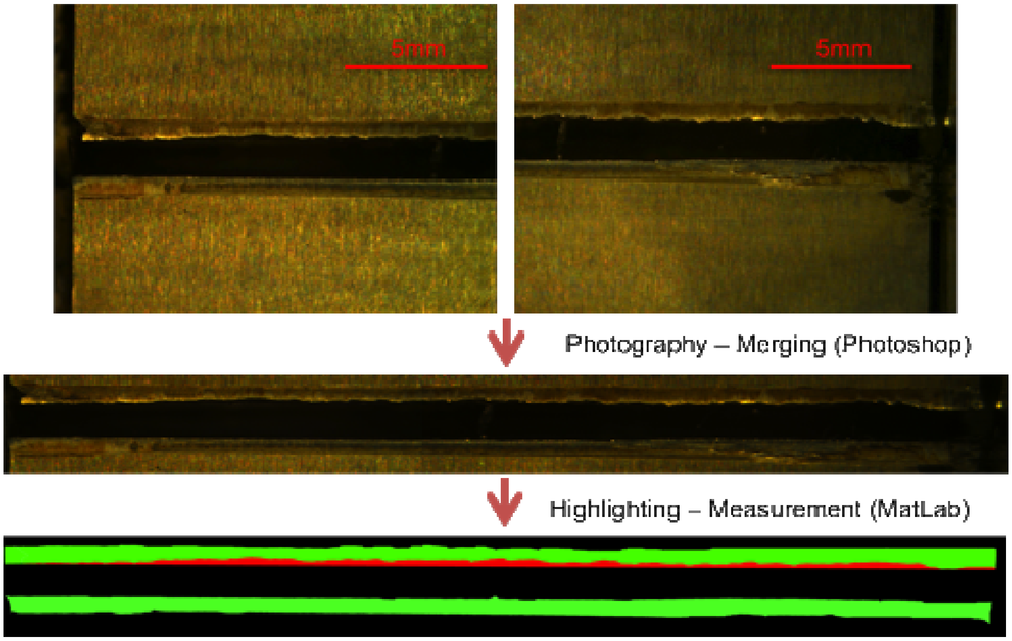


Figure 10 Image measurement method illustration

4. Results and Analysis

4.1 Testing Results Summary and Analysis

As one case to demonstrate damage measurement and testing data process, damage evolution for XY orientation under 1.57kN/mm and 10Hz demonstrates in Figure 11 and damage comparison among YX and XY and XZ under 1.57kN/mm and 10Hz for 500k cycles presents in Figure 12.

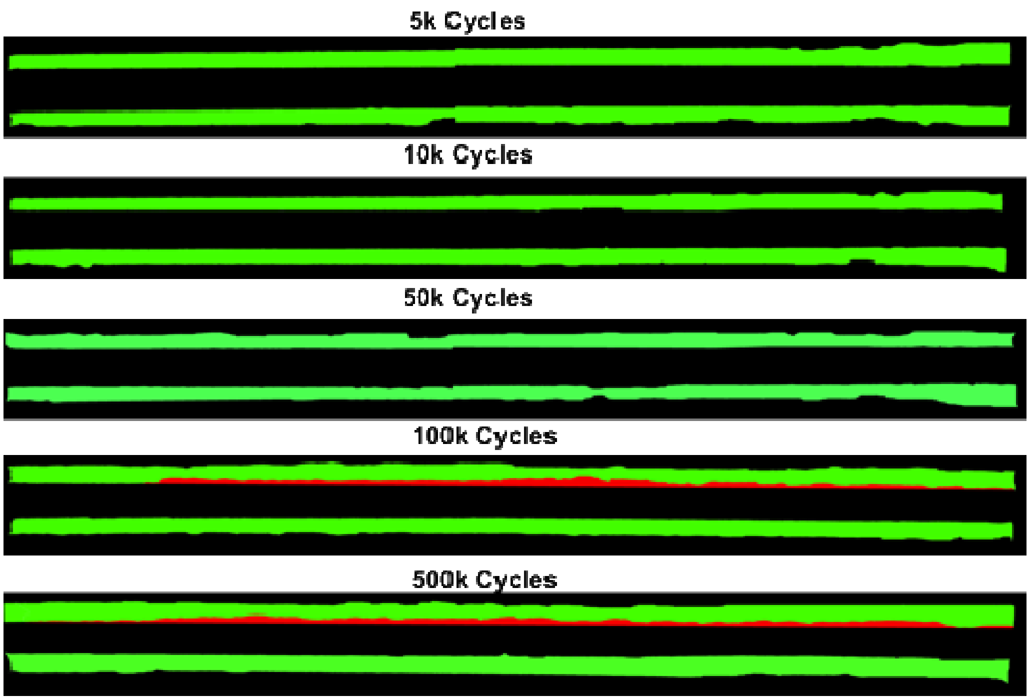


Figure 11 Visual damage developments for 1.57kN/mm and 10Hz

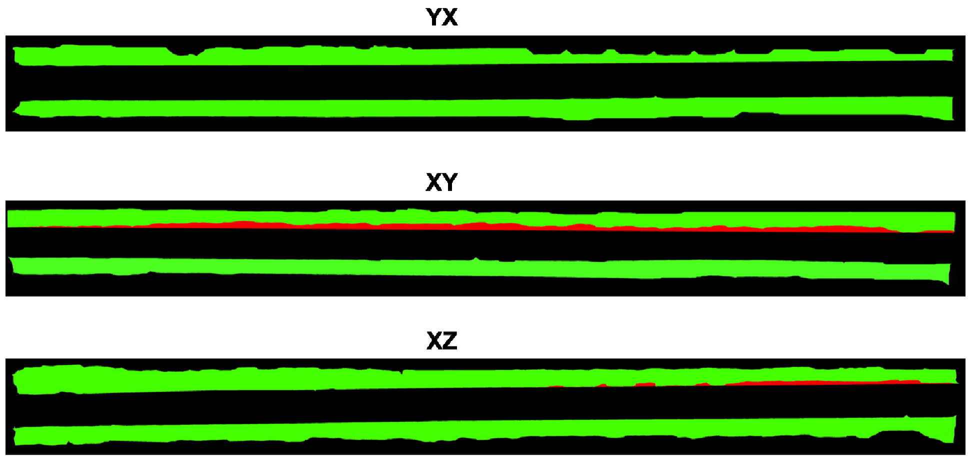


Figure 12 Comparison of orientations under 1.57kN/mm and 10Hz for 500k cycles

For enhance and consistent data process, input data and output data are converted to average value based on cutting edge length:

1) 80kN Force / edge length=80kN/(25.4mm(one cutting edge) x 2)=1.57kN/mm;
2) 50kN Force / edge length=50kN/(25.4mm(one cutting edge) x 2)=0.98kN/mm;
3) Damage Area/edge length=(total damage area (two blocks)) mm^2/(25.4mmx2)= (damage values in chart) mm^2/mm

Power fitting all the data under 1.57kN/mm and 10Hz testing conditions in Figure 13 to constrain testing data fluctuation and measurement error.

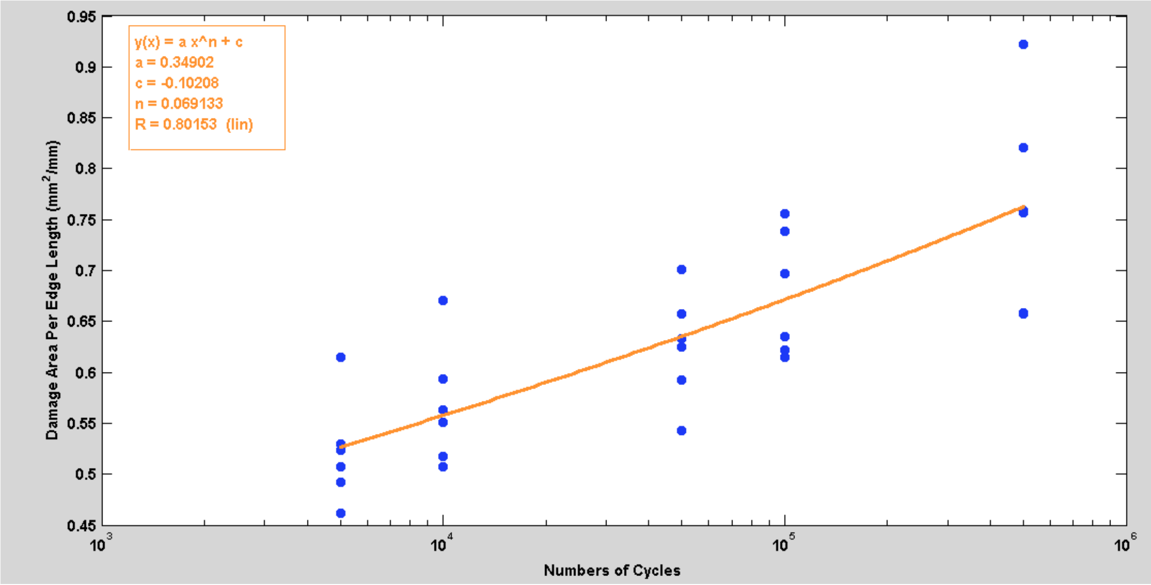


Figure 13 Power fitting curves for all damaged data under 1.57kN/mm and 10 Hz

As result of power fitting equation,

$y(x) = ax^n + c$

Parameters are ***a***=0.35, ***c***=-0.10, n=0.069.

With n=0.069 applied to individual orientations power fit curves in Figure 14,

$y(x) = ax^{0.069} + c$

When x=1 at first cycle, put individual a and c values in each of six orientations, y value is the first cycle damage.

Also as n=0.069, take derivation y over x, the cyclic data rate,

$dy/dx = a69/1000x^{0.931}$

is the damage per cycle with ranking. Therefore, we have fitting parameters in Table 3.

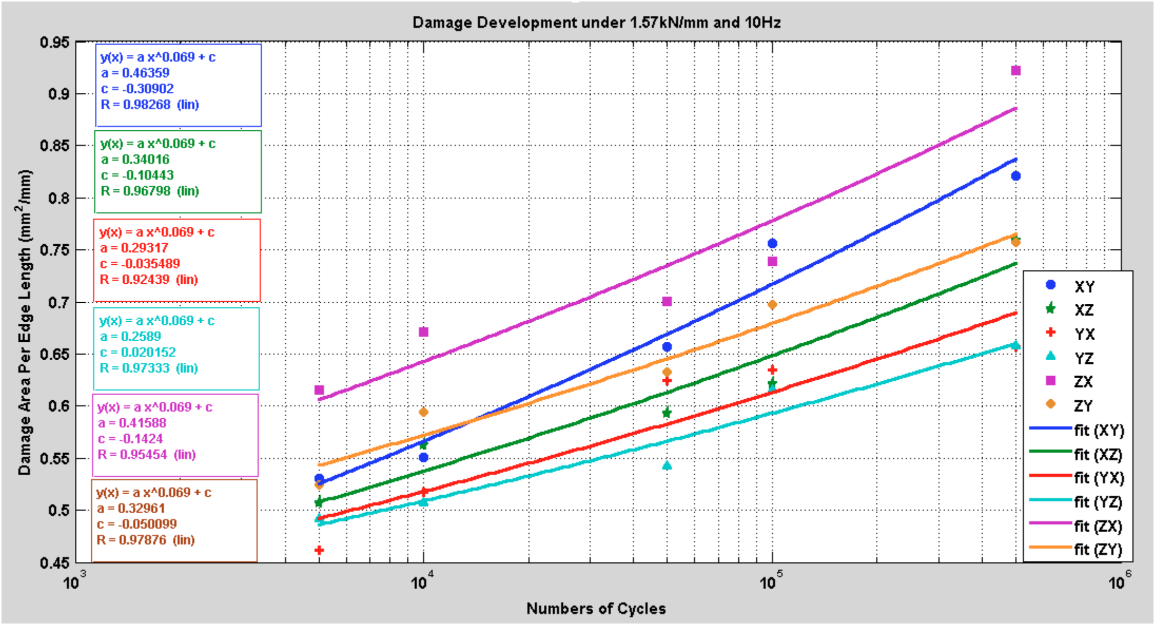


Figure 14 Power fitting curves of damage development under 1.57kN/mm and 10 Hz

Table 3 Analysis results of power fitting plot under 1.57kN/mm and 10 Hz

Orientations	XY	XZ	YX	YZ	ZX	ZY
a Value	0.464	0.34	0.293	0.259	0.416	0.33
c Value	-0.309	-0.104	-0.035	0.02	-0.142	-0.05
First Cycle Damage (mm^2/mm)	0.155	0.236	0.258	0.279	0.274	0.280
Cyclic Damage Rate (mm/cycle)	0.320	0.235	0.202	0.179	0.287	0.228

As ranking first cycle damage rate and cyclic damage rate at selected number of cycles the results are shown in Figure 15,

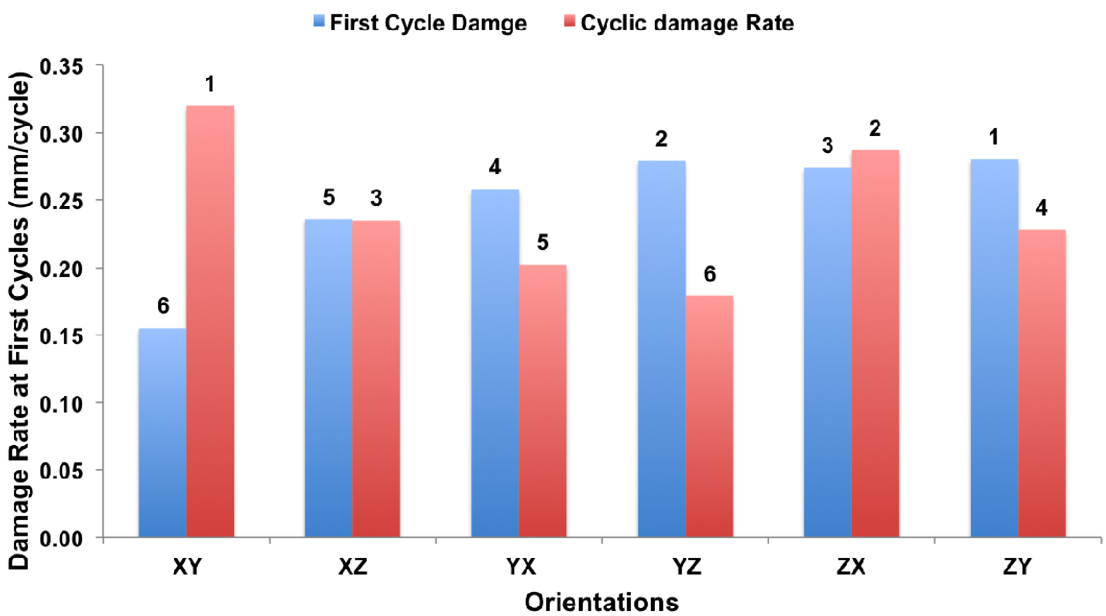


Figure 15 Rankings of damage development parameters under 1.57kN/mm and 10 Hz

In addition, final damage area at 5,000 and 50,000 cycles ranking under 0.98kN/mm and 10 Hz testing condition are shown in Figure 16.

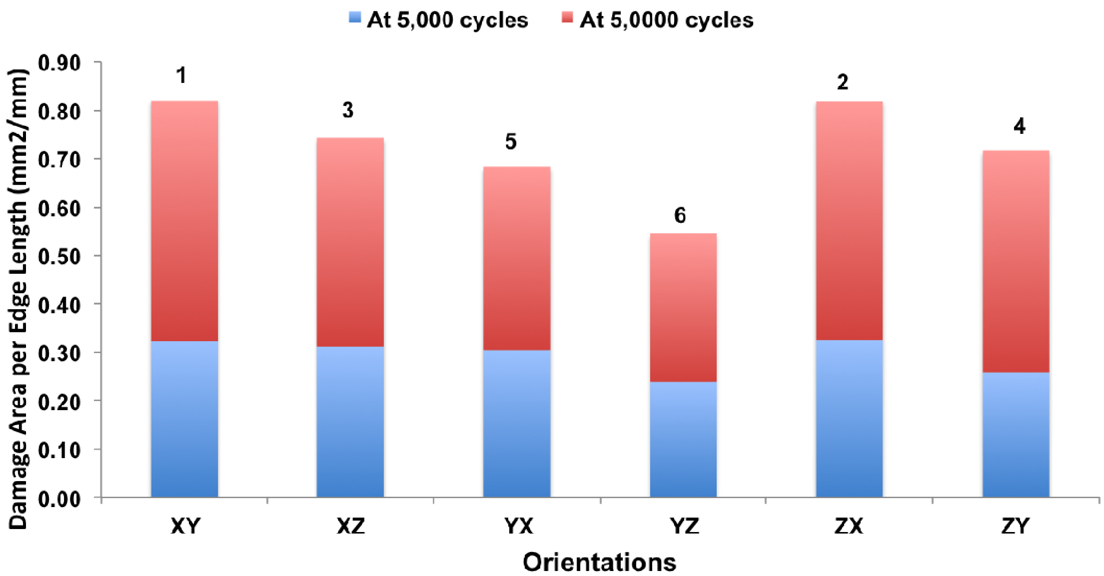


Figure 16 Final damage area under 0.98kN/mm and 10Hz

Therefore, AISI D2 tool steel as cutting edge, the damage area amount evaluation ranking is: XY and XZ > ZX and ZY > YX and YZ. Applying the result to AISI D2 tool steel rolling process, the best quality edge for chipping resistance is transverse direction, the middle one is thickness direction, and the worst edge is longitudinal direction, which should be avoid during rolled tool steel machining process on cutting edge.

4.2 Microscope Examination for Cracking Damage

Microstructure Examination for ZY under 50kN/50Hz along different sections of the whole cutting edge, the crack developments show in Figure 17.

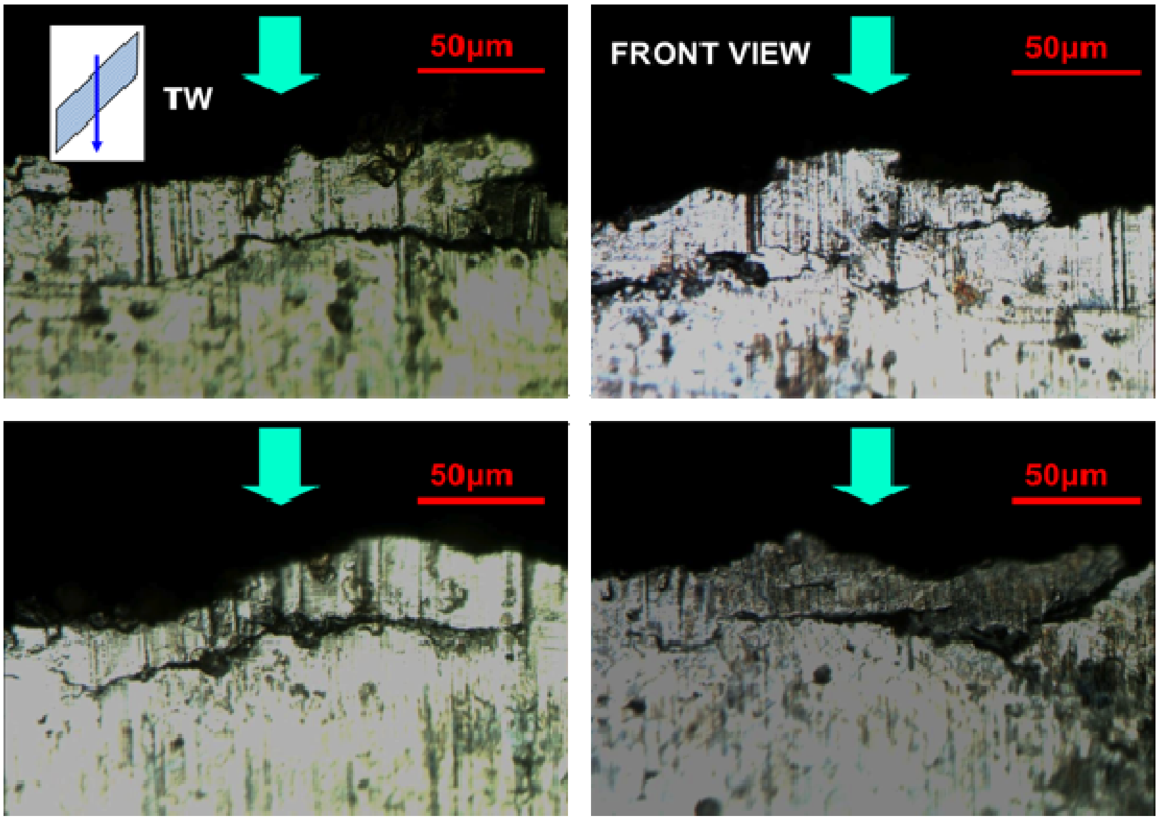


Figure 17 Microstructure examination for ZY under 50kN/50Hz

The chipping appearance of ZX with ZY and their comparison are shown in Figure 18, and more damage morphologies from SEM micrographs are shown in Figure 19. From the pictures, chip thickness and length are in consistent with the carbide dimensions, suggesting that chipping is developed along the carbide-matrix interface.

Therefore, the two sets of data of six orientations show obvious and significant orientation effect, and the ranking of damage severity for different orientations is obtained, and the results are verified by more data. Under current testing condition the major damage form is edge deformation, which, for the brittle material, involves interior micro-damage. Microstructure examination of interior damage is under way; chip dimension is consistent to the carbide dimension: Chip thickness is similar for ZY and ZX, and chip segment length is long for ZY and short for ZX, which are the carbide dimensions in cutting edge, suggesting chipping is associated with the carbide peel-off from the matrix, shown in Figure 18.

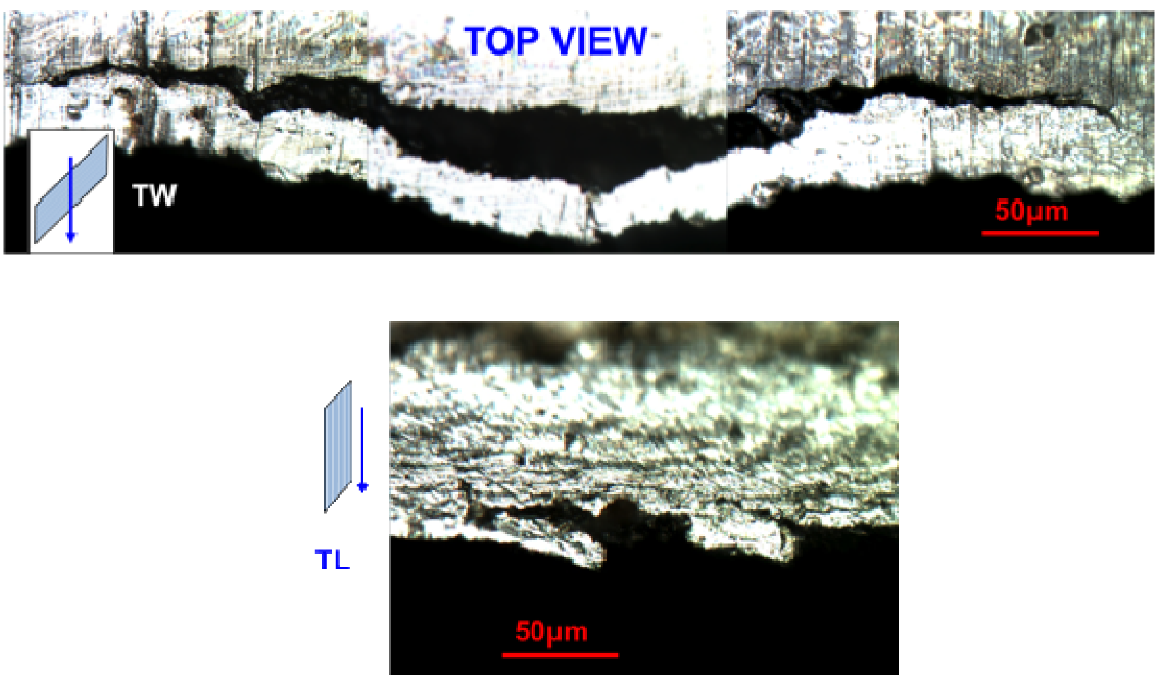


Figure 18 Chip appearances: ZY vs. ZX under 50kN and 10Hz

Figure 19 and Figure 20 show, in ZY orientation, large chipping damage happens, and damage surface has the “layer by layer” chipping phenomenon, which is consistent with grain boundaries. And Figure 20 shows cracking development in ZY along the carbide boundary between two grains. The development has the trend to affect other segments that will start to fracture.

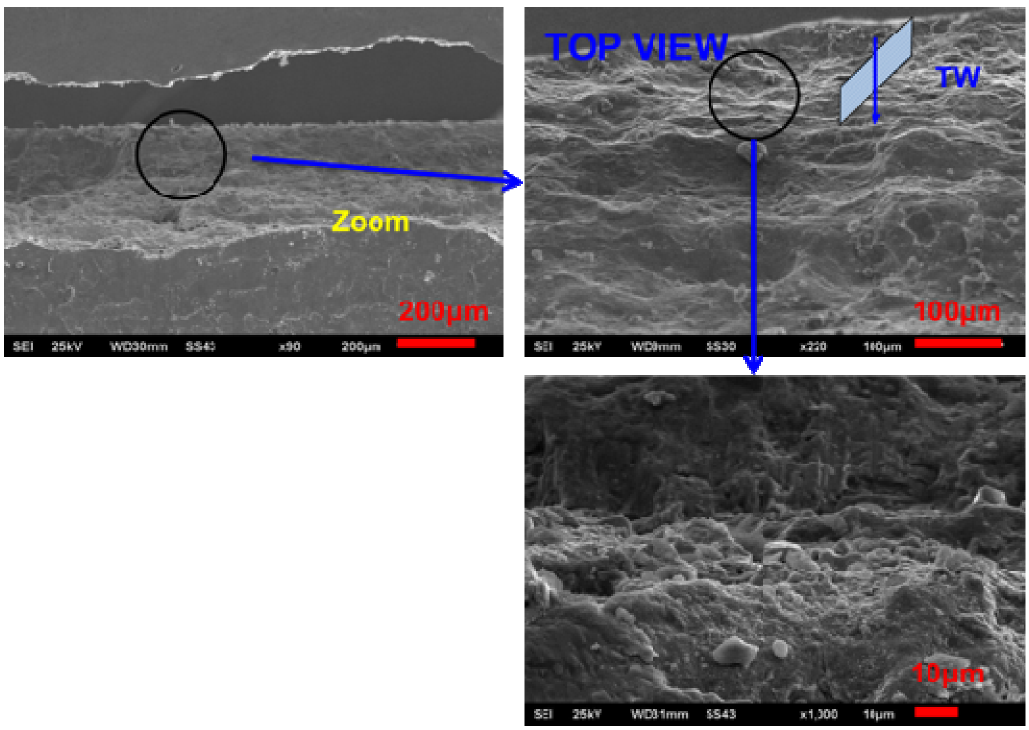


Figure 19 Orientation ZY damage surface observation under 50kN and 10Hz

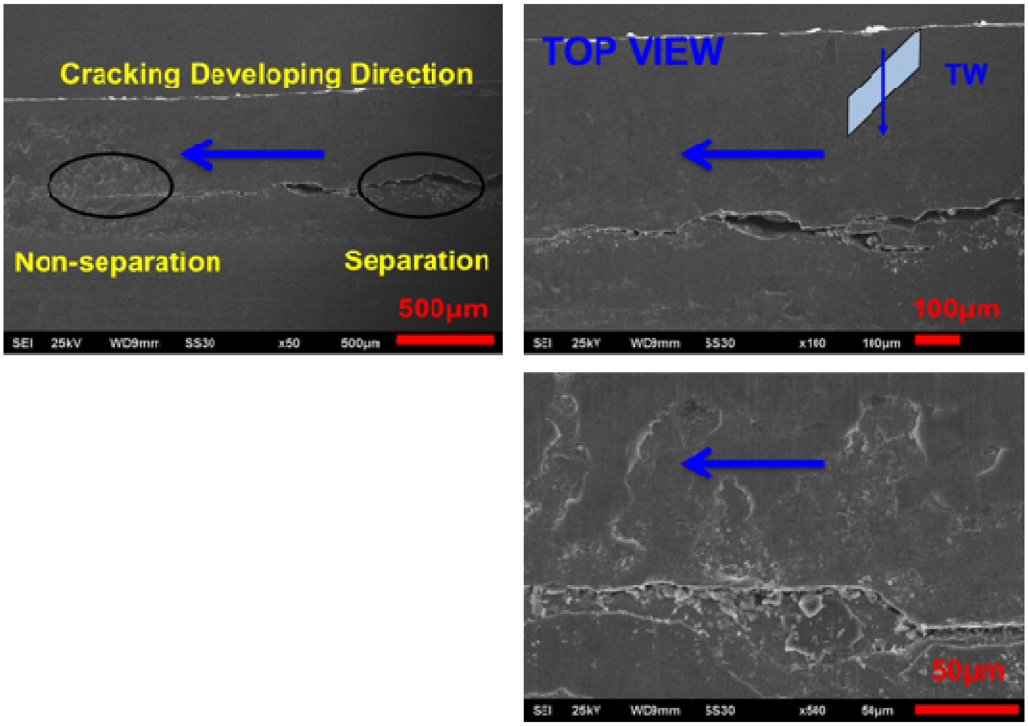


Figure 20 Orientation ZY cracking developments 50kN and 10Hz

5. Conclusion

Based on the testing results analysis and crack microstructure observation, two major factors determine the chipping damage of AISI D2 tool steel cutting edge are: 1) intergranular fracture – the crack develops along with grain boundary, so called “layer by layer”; 2) transgranular fracture: the crack splinter and penetrates inside primary carbide and is controlled by the carbide strength.

The dominant damage of ZX and ZY orientations is former one. Grain Z direction has the thinnest dimension among all, and the main adhesive force of this direction is not sturdy enough to hold each “layers” when it’s as chipping edge resistance. Therefore, after long term of fatigue chipping process, sever damage happens alongside the grain boundary.

XY and XZ’s damage progress origin is the second one. Grain X direction has the longest shape compared with Y and Z’s. While X as shear plane normal direction, the long axis of grain is less stable than the short axis, which is Y orientation. However, since the strength of primary carbide in microstructure, initial damage of X direction is relatively low. The fractures will happen inside until the loading intensity reach the given level and phase, and then severely cumulate due to the unsteady formation and unpredictable bearings.

Direction Y at YX and YZ has a moderate damage, since it avoids both of two leading damage development causes. As damage factor 1 of intergranular fracture, it relies less on grain boundary adhesive influence for cracking in Z direction; while by way of factor 2 of transgranular fracture, Y direction (that has short axis of primary carbide) is less sensitive to the crack propagation within the primary carbide, as compared with that in X direction (that has long axis of the primary carbide). Therefore, in tool trails and die crafting procedures for stamping or other related manufacturing process, tool steels, exclusively, as rolled and machined products, should apply the load in the transverse direction (Y direction in this paper) to the plane normal at cutting edge. This approach can extend tool and die fatigue life to higher range.

6. Discussion and Future Work

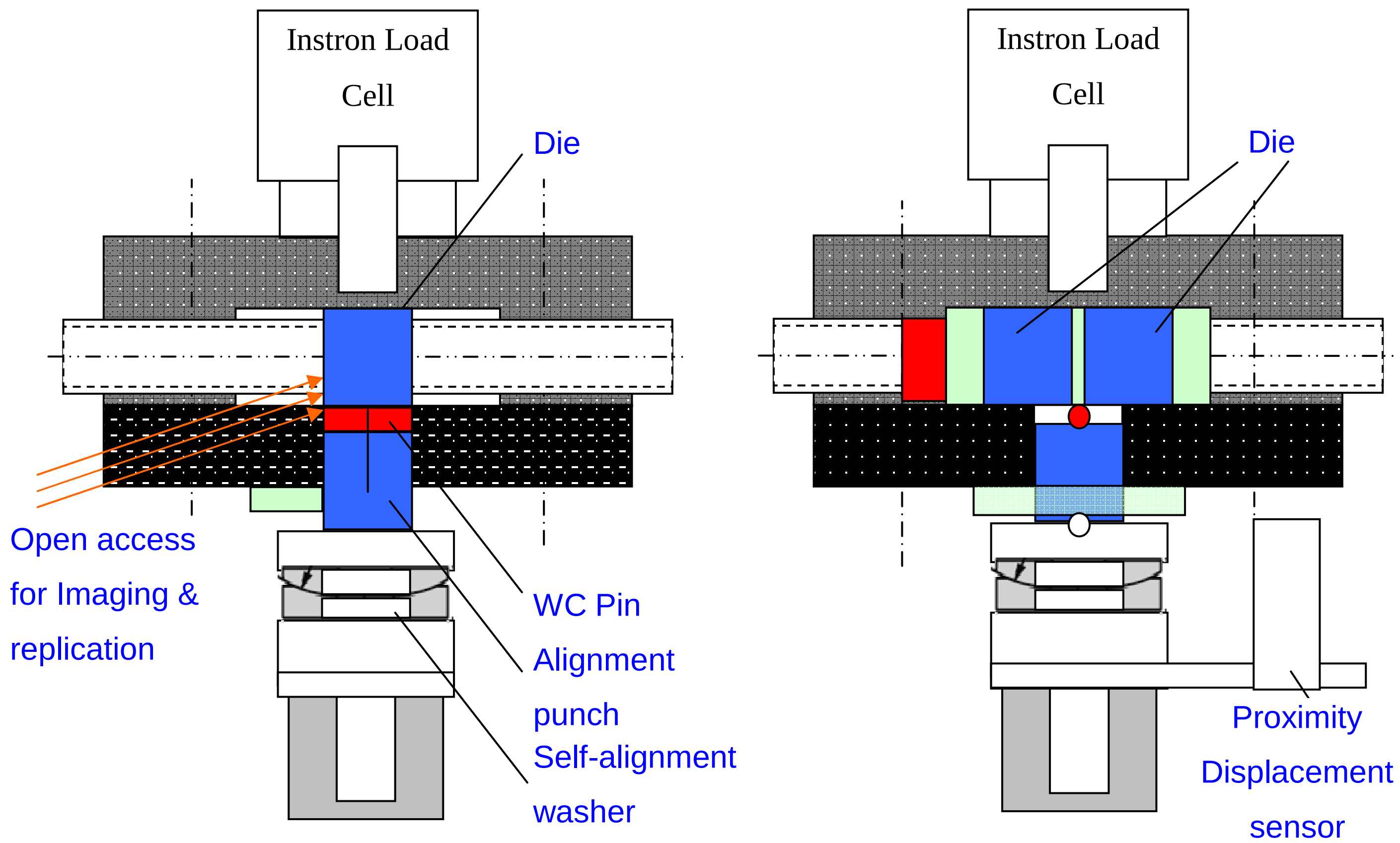
In this paper, we categorize six orientations (XY, XZ, YX, YZ, ZX, ZY) to three inclusive groups based on plane strain normal directions (XY and XZ; YX and YZ; ZX and ZY), which the major differentiation for tool steel as trim cutting edge. Also, as the second letter represents the shear direction, may also have impact matter to damage ranking under the same normal direction, for example, the alteration between XY and XZ cutting edges could be study for microstructure mechanism and SEM cracking growth.

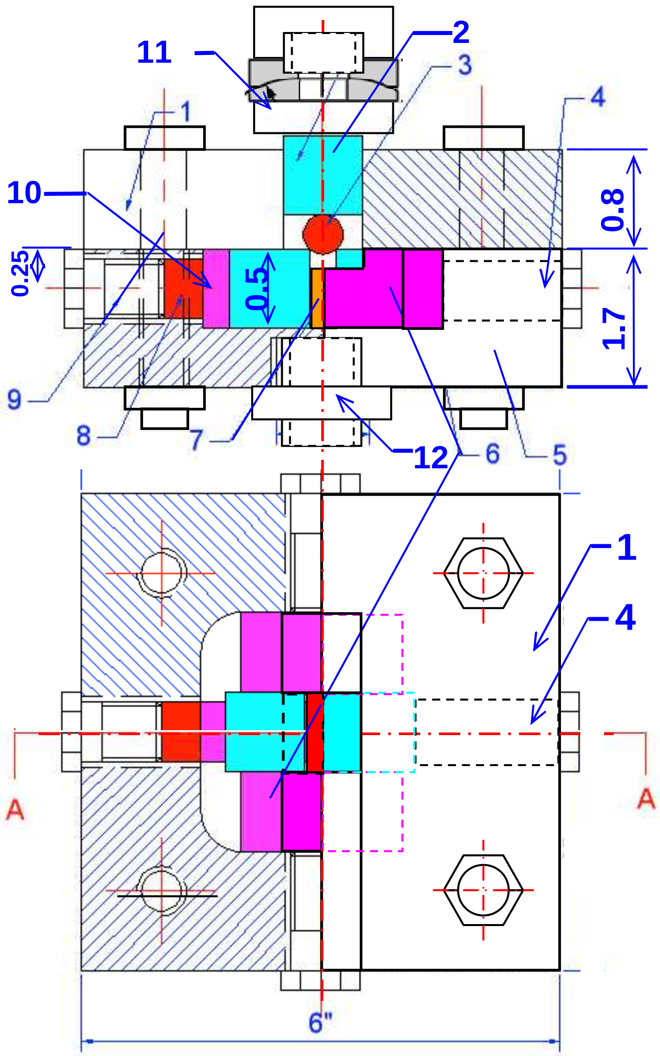
Since this paper is in early-stage development of testing design and experimental conditions, not sizeable data cannot be streamline collected and processed during fatigue testing and damage image analysis. Therefore, testing results may include inevitable machine and human errors throughout the result values gathering and measurement. More convenient image acquisition and automatic analysis and calculation using image process software could be introduced to generate considerable data and eliminate certain errors.

In the introduction chapter, it mentioned this paper build the tooling testing platform as die set, and operate this set to exam more tool steels qualities or other tool materials applied in the automotive industry, especially for auto body stamping process. As the second stage of research and testing development for this project, a up-to-date tool steel, Caldie cold rolled tool manufactured by Uddeholms with higher chipping resistance than AISI D2, is undergoing experiment for future study.

APPENDIX

Engineering Drawing of Trim Die Fatigue Tester





Pt	Name	Qt	Material	Note
1	Cover	1	AISI 4140, 27-32 RC	6"x6"x 1.25", mild steel acceptable
2	Punch Cube	1	AISI 4140, 27-32 RC	1" cube (Tol. +0/-0.0002") with central groove and cone hole
3	Contact Pin	1	WC, dia.1/8", 1/4", 1/2"	www.mcmaster.com Pt#8788A128,162, 251
4	Set screw & nut	4	3/4"-16xL2.5" + locking nut	www.mcmaster.com Pt # 92620A875 & 93827A267
5	Base	1	AISI 4140, 27-32 RC	6"x6"x1.75", mild steel acceptable
6	Side block	2	Mild steel	LxWxT=2"x1"x1" with 1"x1"x1/4" groove on top
7	Central shim		Metal foils	
8	Side Loadcell	1	(3/4" dia, 0.5" tall)	www.omega.com Pt#. LCM302-5KN
9	Bolt & nut	4	3⁄4"-20xL3.75"	www.mcmaster.com Pt # 91257A757 & 93827A249
10	Backing block	2	Mild steel	LxWxT=1"x1"x0.5"
11	Instron ram subassym	2	Mild steel, M30x1.5mm,	One with thread, one without thread to match McMaster Pt 98148A182
12	Loadcell adapter	1	Mild steel, M30x1.5mm	Match Instron existing loadcell
13	Trim die Cube	3	TBD	For each die material to have three Cube

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ABSTRACT

FATIGUE BEHAVIOR AND MICROSTRUCTURE EXAMINATION OF AISI D2 TRIM DIES

by

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Major: Mechanical Engineering

Degree: Master of Science

AISI D2 steels are widely used as tools for forming, drawing and trimming dies due to its high wear resistance, high compressive strength and low distortion, and its performance as a trim die material for cutting ultra-high strength steels (at 1GPa or above) is investigated in this study.

To simulate the production trimming process under a laboratory accelerated fatigue condition, a trim die simulator and testing technique have been developed. In this test 1" cubic die samples were used that offers total 12 cutting edges of 6 different material grain orientations in shearing, and with adjustable die clearance. A non-contact metal removal volume measurement was developed to quantify the degree of fatigue damage during cyclic loading, and the metallurgical replica method was used at different number of cycles from the interrupted testing for obtaining micro-damage information. The damage rate at the cutting edge was obtained as a function of trimming process variables, including the die material grain orientations, the loading frequency, and the

amplitude of fatigue loading. The microstructure, micro-damage and fractured surfaces were examined with optical microscopy and scanning electron microscopy.

The results show that there exist two types of distinct damage processes: the continuous contact deformation process that occurs at a low fatigue load, and the discontinuous cutting edge chipping process at a high fatigue loading with significantly higher material removal rate. The chipping involves crack initiation and propagation within the carbide phase surrounding the pro-eutectic grains, leading to grain broken and fall apart. An empirical trim die damage rate model in Paris law form is obtained from experimental data regression, and can be used for tool life prediction. The grain orientation relative to the cutting direction is found to have remarkable effect on trimming damage rate.

AUTOBIOGRAPHICAL STATEMENT

One of my biggest childish dreams is driving a car maybe have my own car one day, at that time automobiles still weren't extensively spread in my county, and only very few of families and people could own them. Instead, I had enormous toy cars in my childhood: electric cars, assembly models, cars from cartoon, you name it, and they helped me to develop more serious interest and understanding for vehicles.

Fortunately, automotive industry in my own county is booming when I was about to enroll college, along with it is the establishment of automotive engineering at many universities. I have no any hesitation to choose this major. During the four-year study in my college, Shenyang Institute of Technology, I learned comprehensive knowledge about automotive engineering and automotive industry, also known Detroit, is the motor city of the world. This city is like Mekka to me, as I decided to devote not only my major but also my career to automotive industry.

After my graduation for my bachelor's degree, I applied and had the offer from Wayne State University, one of the best colleges in Detroit Area, to continue my master's education in mechanical engineering. It is my pleasure that Dr. Xin Wu recruited me to his research group, and then I worked on Trim Die Stamping Project from USCAR –Auto/Steel Partnership–Stamping Tooling Team, to sponsor my Master's thesis. During the project, I learned and utilized sheet metal metallurgy and stamping manufacturing process for auto car body production. Also I had opportunities to communicate with engineers from Big Three, suppliers and toolmakers. Besides, another good thing during my Master's degree pursuit is, I was instructional assistant for ME3450 Manufacturing Process I course for two semesters. I trained undergraduate students for the material testing experiments to have the communication and organization skills, or it is just a purely enjoyable experience for myself.