CHIP FORMATION CHARACTERISTICS IN HIGH SPEED MACHINING UTILIZING HIGH SPEED MICROVIDEOGRAPHY

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ABSTRACT: The present article aims to investigate the chip separation process in order to derive the chip formation characteristics during cutting of AL7075 aluminum alloy. Aluminum machining concerns the scientific community due to chip formation problems that affect tool life and product quality. Studying the cutting action contributes to understanding and addressing those problems effectively. For these purposes an experimental setup, utilizing high speed imaging system will be introduced. The proposed setup is based on a milling machine and remains unaffected by external devices that may impact to the cutting system. The chip characteristics are measured by a high speed camera placed under the cutting tool during machining. The camera is connected to a computer for recording and controlling the experimental procedure in real-time.

KEY WORDS: Chip formation, high speed machining, high speed camera, AL7075.

1 INTRODUCTION

Nowadays there is a growing concern over the deployment of materials combining low-weight and high mechanical strength properties. AL7075 is a zinc based aluminum alloy that is widespread in automotive and aerospace industry due to its high strength to density ratio. Additionally, the T6 temper is widely used in mold tool manufacturing due its ability to be highly polished. A common problem in aluminum machining is the tendency of built-up edge formation especially at high temperatures. Adhesive interactions become more intense for higher friction values between the tool-chip interfaces, as well as for inappropriate cutting conditions. Such phenomena lead to undesirable stress concentrations and affect the tool integrity. Thus it is important to investigate the chip separation process in order to derive the chip formation characteristics.

In order to investigate the cutting action closely to the deformation zone, researchers have followed two directions. At the first direction, researchers developed experimental models involving special quick stop devices (Astakhov, 1999), (Astakhov et al., 1997), (Astakhov, 2006), (Chern, 2005), (Gente et al., 2001), (Jaspers and Dautzenberg, 2002), (Nabhani, 2001). These models are based in “freezing” the cutting action by retracting instantly the tool from the workpiece. In this method the retraction speed of the tool is critical. At the beginning of the retraction process the tool remains in contact with the workpiece until the retraction acceleration has resulted in an equal speed of the tool-workpiece system. Therefore, from the start of the tool retraction until the end of the tool-chip contact the cutting conditions varying continuously. During this period the deformation zones are affected, resulting in different chip morphology. The successful implementation of the aforementioned method is highly depended on the sufficient fast retraction of the tool, which is difficult to be achieved especially in high cutting speeds.

Following the second direction, researchers proposed experimental setups, utilizing high speed imaging systems. Sutter (2005) used a high-speed camera for taking photographs of chips during the cutting process of middle hard steel (French Standards XC18). The tool-chip contact length and the shear angle were measured over a wide range of cutting speeds, different rake angles and depths of cut. Another research of Sutter & Ranc (2007) studied the temperature fields in a chip during high-speed orthogonal cutting of C15 and 42CrMo4 steels, based on recording photographs of the chip formation in real time. Pujana et al. (2008) used square grid marked workpieces of 42CrMo4 steel in order to measure the chip geometry, shear angle, strain, strain rate and vibration amplitude.

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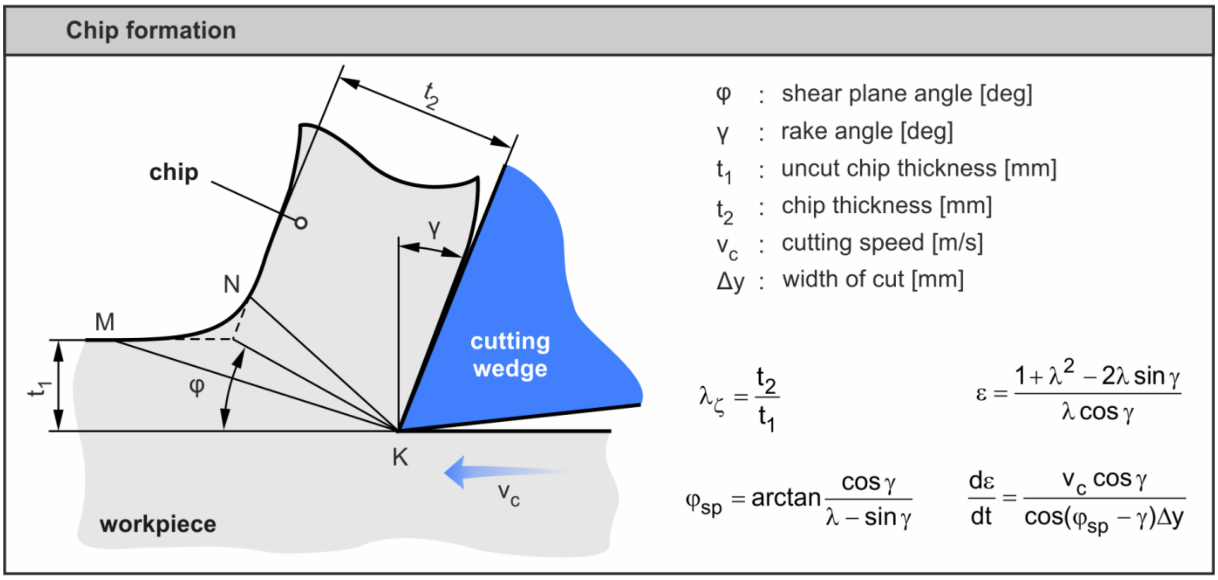

Figure 1. Nomenclature of chip formation model

The dynamics of chip formation during orthogonal cutting was also investigated by Cotterell and Byrne (2008b). The authors proposed an experimental setup for machining Ti-6Al-4V in different cutting speeds at a recording rate of 24,000 frames/sec. Another research (Cotterell and Byrne, 2008a) of the same authors characterized the segmented chip formation of Ti-6Al-4V and introduced a thermal model of the process. Temperature and plastic strain maps of two AISI4140 steels with different machinability indexes were obtained by (Arriola et al., 2011). The hardware used was a high-speed dual-spectrum (visible and infrared) camera as well as a thermal camera for the measurement of the surface temperature. List et al. (2012) developed a numerical model for cutting temperature prediction in high speed machining based on chip formation characteristics. A high-speed camera was used to take photographs during chip formation aiming to observe chip morphologies in order to evaluate their numerical model.

Ivester et al. (2007) measured the chip segmentation in AISI1045 steel with use of high speed digital camera and compared the results to Finite Element Modeling simulations (FEM). FEM simulations were also used by Mabrouki et al. (2008) in order to study the dry cutting of aluminium alloy A2024-T351. The chip fragmentation phenomenon was observed with video acquisition and compared with the aforementioned FEM results. Lee et al. (2006) developed a particle image velocimetry technique to measure parameters of the deformation field such as strain rate and strain as well as their distribution in the primary deformation zone. The workpiece materials used were lead, OFHC copper and titanium whereas sapphire and HSS tools of different angles were used to impose different levels of strain. Utilizing a high-speed imaging system Deng et al. (2012) analyzed large strain extrusion machining with different chip compression ratios. The results showed that the proposed method can produce very high strains by changing the CCR, thereby enabling the production of nanostructured materials.

The present paper introduces an experimental method based on high-speed image acquisition for the determination of the chip formation characteristics. These characteristics are very useful for tool designers, as well as for tool stress analyses. The method proposed is contact free, thus the cutting action is not affected by external quick-stop devices that may impact to the cutting system by introducing errors. Finally, an extended experimental investigation was conducted over a wide variety of cutting conditions.

2 DETERMINATION OF CHIP FORMATION CHARACTERISTICS

Chip formation characteristics are very important in tool engineering analyses. For this purpose, several pre and post-processing algorithms based on the finite elements method have been proposed by researchers (Antoniadis et al., 2002), (Belis et al., 2013). These algorithms use the chip compression ratio (CCR) in order to determine the tool-chip contact length (Astakhov, 2006). Subsequently, the tool-chip contact length is used in order to distribute the cutting forces on the tool's rake face.

The present research adopts the orthogonal model presented by Merchant (*figure 1*). This model is suitable for approximating machining operations where the tool's edge is considered as single-point. The parameters investigated in this work include the chip compression ratio λ and the shear plane angle φ. The chip compression ratio, as defined by researchers (Groover, 2007), (Merchant, 1945) is the ratio of the chip thickness t_2 to the uncut chip thickness t_1. The shear strain ε is an alternative measure of plastic deformation encountered in metal cutting, which can be used instead of the chip compression rate. This paper favored the use of chip compression ratio due to better behavior in extreme deformation values (Astakhov, 2006), (Astakhov & Outeiro, 2008). The shear plane angle φ is defined as the angle in which the shear stress exceeds the shear strength of the workpiece material, thus the shear deformation takes place preferably at this angle. Another useful parameter in machining operations modelling include the shear strain rate which is function of vc, φ, γ and Δy (Davim et al., 2007), (Davim, 2007), (Shaw, 2005), (Stephenson & Agapiou, 2006).

The chip compression ratio is highly affected by the cutting speed which has the strongest influence on the energy distribution on the tool. Other parameters that have a strong influence on chip compression ratio are the tool rake angle γ, the cutting feed f, the cutting wedge angle β, the tool's material and its tribological characteristics and the cutting system lubrication. Degner et al. (2009) studied the parameters effect on CCR. The authors observed that increasing the feed rate and cutting speed values result in shear angle increase and CCR decrease. Additionally, increase of tool's rake angle result in slight increase of CCR. Astakhov and Shvets (2004) observed that the cutting speed greatly affects CCR in a non-linear manner while later found out that the non-linear behavior due to built-up edge formation at the tool. Researchers made numerous attempts to establish a CCR prediction model. However, none of these attempts managed to match the experimental results (Astakhov, 2006). Therefore, the only accurate method for the determination of CCR is the experimental investigation.

3 EXPERIMENTAL INVESTIGATION

3.1 Experimental setup

The basis of the proposed experimental setup consists of a high speed camera (HSC). The aforementioned international scientific community has proposed a number of similar devices based on turning machines. At the present work a variation of the above method has been implemented, in a 5-axis vertical machining center DMU 50 of DMG. The first step of the method proposed involves the conversion of milling to turning kinematics. This requires mounting the workpiece on the machine's spindle, holding the cutting tool in the table and develop the corresponding protocol for controlling the new kinematic.

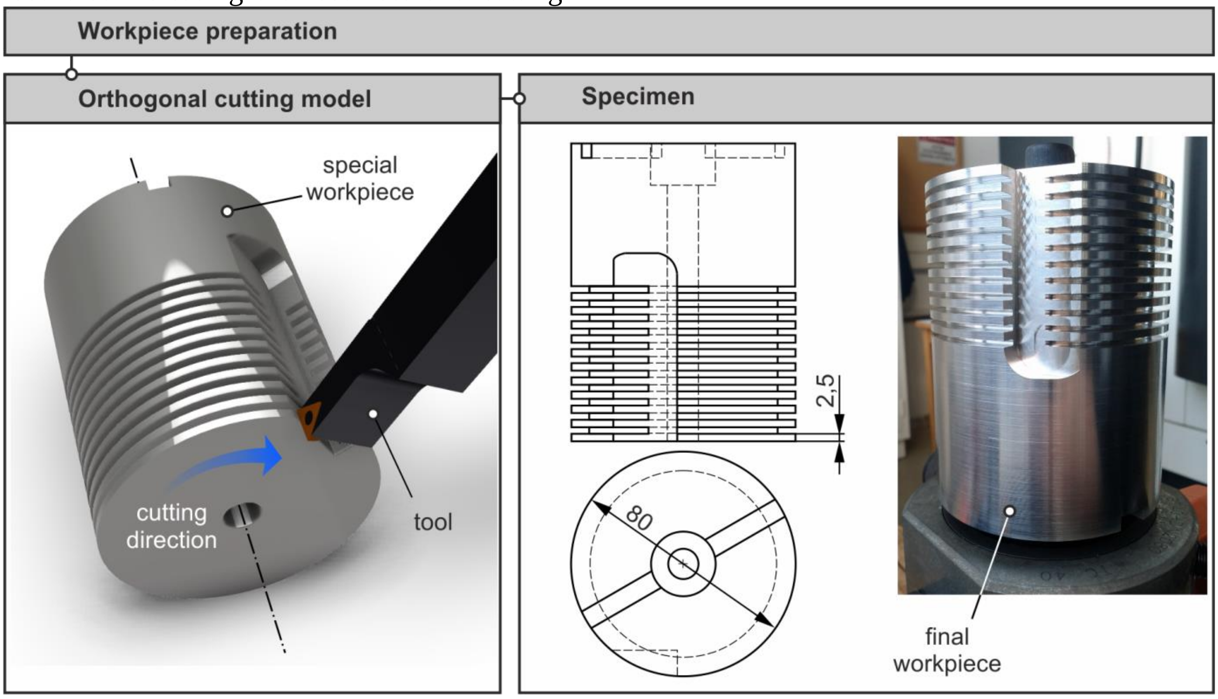

Figure 2. Special workpiece (AL7075) preparation

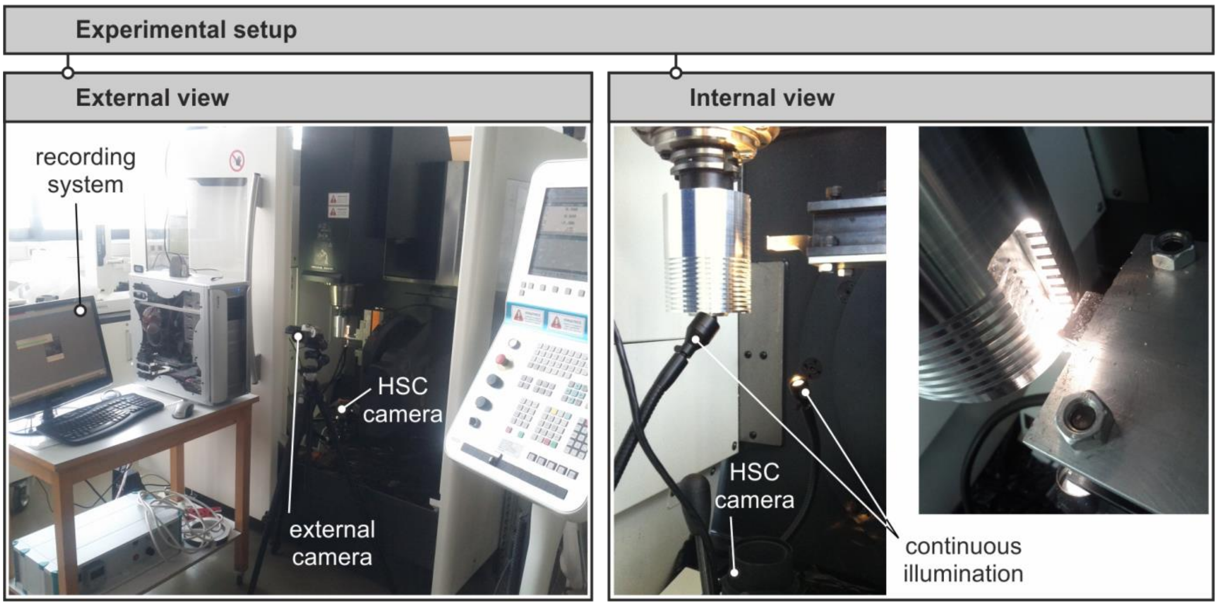

Figure 3. Experimental setup

In order to mount the workpiece at the spindle a special configuration was created. For this purpose a tool holder SK40 complying with DIN69871, suitable for mounting face mills, was incorporated. The workpiece was machined with a face mill on both sides and a throughout hole was drilled. In order to find the center of the workpiece a Heidenhain TS640 3D probe was used. Also, in order to prevent drill deflection and ensure coaxiality of the hole, a special peck-drilling cycle was programmed. Additionally, a special configuration that includes a slot and a circular pocket was machined in order to fit the tool holder.

The tool was fixed on the machine's table with the aid of a vice and a custom-made fixture. In order to reduce the vibrations of the system a metal plate was attached on the aforementioned fixture, ensuring adequate support of the cutting tool in all directions. In the next step, the cylindrical face of the workpiece was machined in order to eliminate any eccentricity. Moreover, eleven discs were machined perpendicular to the axis of rotation with use of a grooving tool. The diameter of the workpiece was 80mm and the width of each disc was 2.5mm. Finally, a longitudinal slot was machined in order to assemble the tool with the workpiece. The configuration is also associated with getting the proper cutting depth before machining starts. This procedure is to ensure orthogonal cutting conditions; otherwise in case of gradual insertion of the tool, the velocity vector would change respectively, resulting in classical turning operation. The right part of *figure 2* illustrates the initial design and the workpiece machined, whereas the left part depicts the orthogonal cutting model proposed for a milling machine.

Figure 3 depicts the experimental setup based on the machining center. An internal view of the system is illustrated in the right part of *figure 3*. The high-speed camera (HSC) is placed in parallel with the workpiece rotation axis. Both the camera and the source of continuous illumination are placed under the cutting tool in order to record the machining operation. An internal view of the system is illustrated in the left part of *figure 3.* The camera was connected to a computer which recorded the machining operation, while an external camera was used for macroscopic recording of experimental procedure. Image processing parameters as well as the camera parameters were controlled by the computer through appropriate camera software.

The camera used was a MotionBLITZ EoSens mini2 digital camera of Microtron with CMOS 1696x1710pixels sensor, able to record up to 200.000 fps. The total recording time is 3sec at full resolution, while the shutter speed can be set in the range of 2μs-1sec. The camera was also equipped with suitable macro lens of SIGMA Company with a minimum focal length of 300mm. The cold light source used was SCHOTT KL2500 LCD, with maximum light flux of 1300lm.

Table 1. Cutting conditions

Exp.	v_c [m/min]	a_p [mm]	γ [deg]	Exp.	v_c [m/min]	a_p [mm]	γ [deg]	Exp.	v_c [m/min]	a_p [mm]	γ [deg]
1	100	0,2	6	21	100	0,2	3	41	100	0,2	0
2	100	0,3	6	22	100	0,3	3	42	100	0,3	0
3	100	0,4	6	23	100	0,4	3	43	100	0,4	0
4	100	0,5	6	24	100	0,5	3	44	100	0,5	0
5	80	0,2	6	25	80	0,2	3	45	80	0,2	0
6	80	0,3	6	26	80	0,3	3	46	80	0,3	0
7	80	0,4	6	27	80	0,4	3	47	80	0,4	0
8	80	0,5	6	28	80	0,5	3	48	80	0,5	0
9	60	0,2	6	29	60	0,2	3	49	60	0,2	0
10	60	0,3	6	30	60	0,3	3	50	60	0,3	0
11	60	0,4	6	31	60	0,4	3	51	60	0,4	0
12	60	0,5	6	32	60	0,5	3	52	60	0,5	0
13	40	0,2	6	33	40	0,2	3	53	40	0,2	0
14	40	0,3	6	34	40	0,3	3	54	40	0,3	0
15	40	0,4	6	35	40	0,4	3	55	40	0,4	0
16	40	0,5	6	36	40	0,5	3	56	40	0,5	0
17	20	0,2	6	37	20	0,2	3	57	20	0,2	0
18	20	0,3	6	38	20	0,3	3	58	20	0,3	0
19	20	0,4	6	39	20	0,4	3	59	20	0,4	0
20	20	0,5	6	40	20	0,5	3	60	20	0,5	0

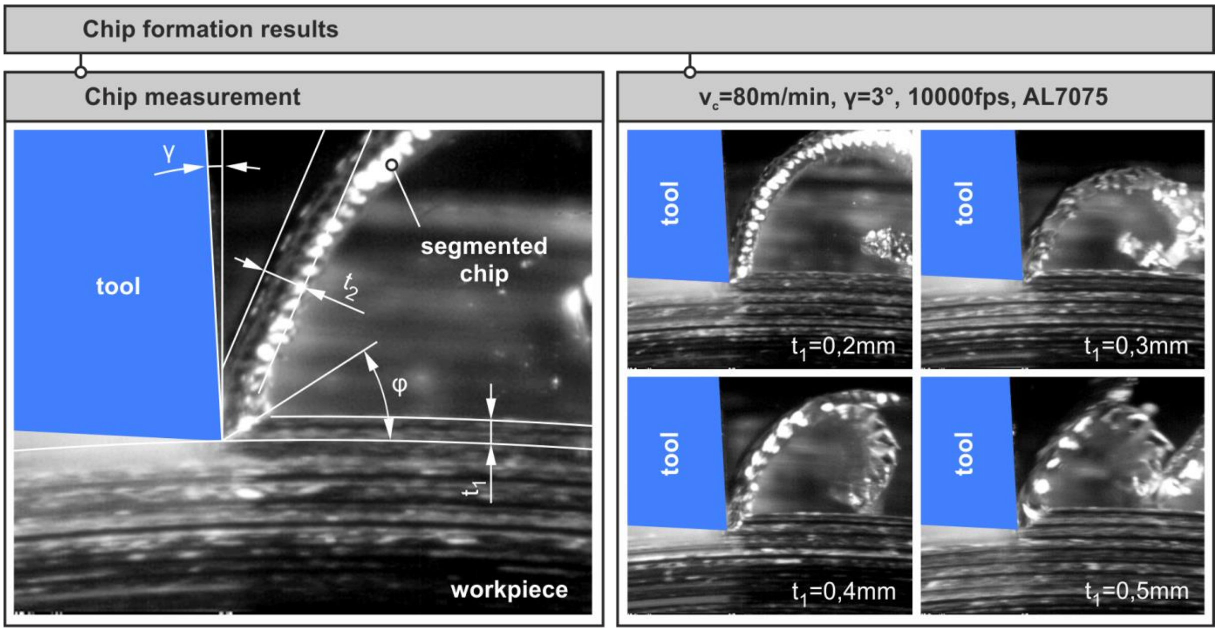

Figure 4. Chip formation results

3.2 Experimental procedure

The experimental study of chip compression ratio consists of 60 dry cutting experiments. The cutting conditions tested cover a wide range of cutting speeds, depths of cut and three different rake angles. The rake angles studied were 0°, 3° and 6°, for cutting depths of 0.2, 0.3, 0.4, 0.5 mm and for cutting speeds of 100, 80, 60, 40 and 20m/min. In more detail, the cutting conditions of each experiment are illustrated in *Table 1*.

During the experiments, the recording speed of the camera was adjusted to 10.000fps, the shutter speed to 62ms and the image resolution was limited to 272x228pixels. Control and management of recording area was determined via special MotionBLITZ software.

4 RESULTS

Each experimental result consists of a sequence of thousands photographs from which a certain number was selected for further processing. The direct result from observation of each experiment, relates to the formulation and the type of chips produced. The calculation of the remaining parameters requires measurements on the images. These measurements were made with the help of image processing software and according to these results the chip compression ratio was calculated. *Figure 4* introduces some examples of measurement on different cutting conditions.

The left part of *Figure 4* illustrates an example of chip measurement where t_1 is the uncut chip thickness, t_2 is the deformed chip thickness and φ is the shear angle. Moreover, to confirm the proper positioning of the tool, the rake angle γ was also measured. The right part of *Figure 4* presents four examples of chip formation with constant cutting speed of 80m/min and rake angle of 3° whereas the depths of cut were 0.2, 0.3, 0.4 and 0.5mm respectively.

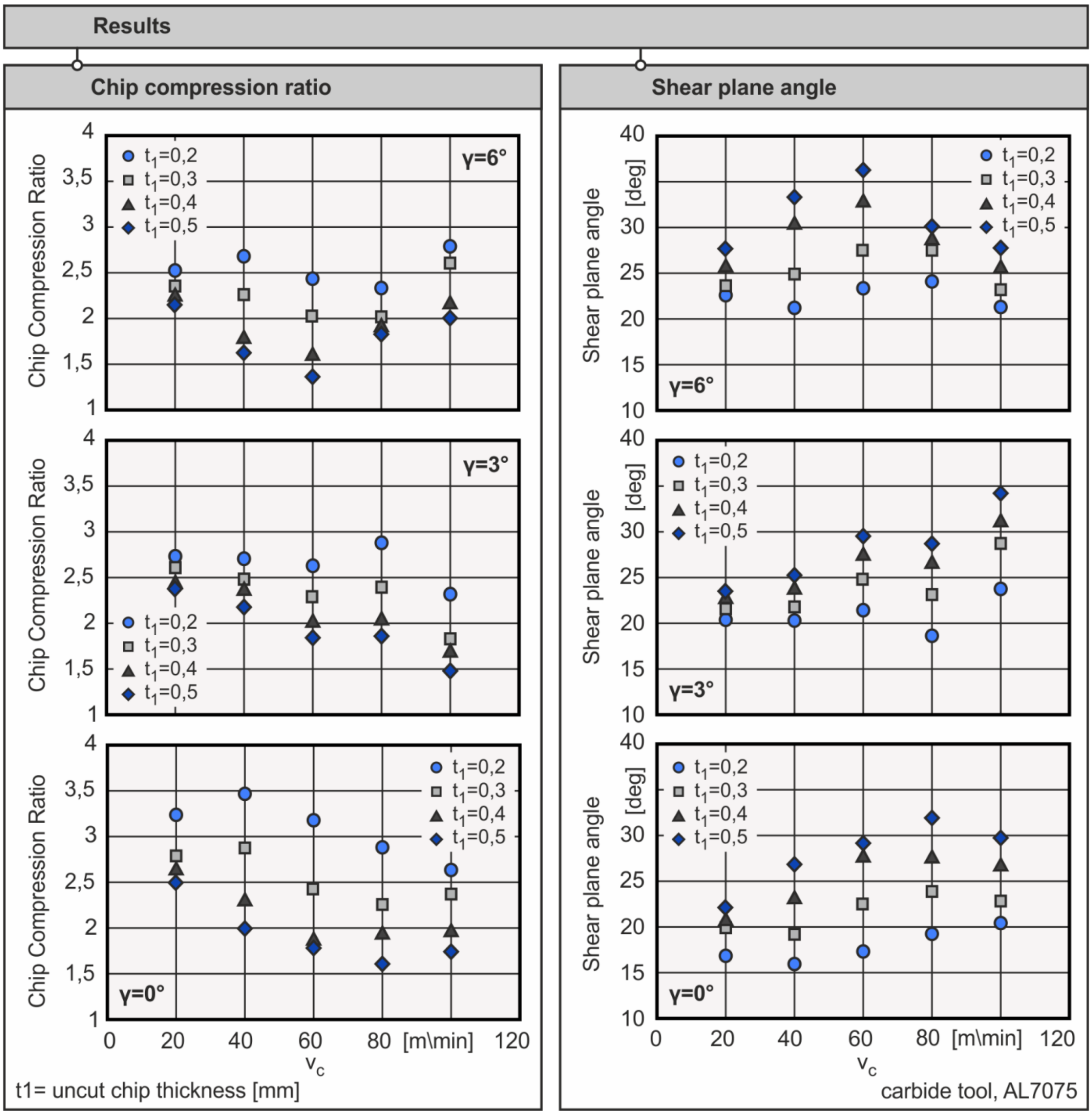

Figure 5. Results of chip formation characteristics

In these experiments the chip thickness as well as the shear angle was slightly increased. Also the observed chip formation during cutting was continuous but with different fracture frequency.

Often in manufacturing processes calculation of the strain rate in order to determine material properties and evaluate machining operations is required. This calculation is based on shear plane angle measurement which is presented in the right part of *figure 5*. Additionally, the results of chip compression ratio are presented in the left column of *figure 5* as a function of the cutting speed and the conclusions drawn can be summarized in the following:

- smaller values of uncut chip thickness, result in smaller chip compression ratio for all the cutting speeds tested,
- both chip compression ratio and shear plane angle show non-linear behavior with respect to cutting speed,
- smaller values of uncut chip thickness, result in higher shear plane angle,
- both chip compression ratio and shear angle are slightly affected by tool rake angle increase.

The variation observed in values may be due to temperature increase which in turn increases the plastic deformation.

5 CONCLUDING REMARKS

The present work studied the chip formation characteristics during high-speed machining of aluminum alloy AL7075. The novelty of the research lies in the incorporation of a high-speed imaging system that was integrated into a 5-axis machining center. The proposed method is contact free resulting in elimination of external devices errors that may affect the cutting system. Commercial image processing software was used for measuring chip formation characteristics from the recorded image sequence. The research emphasizes on the chip compression ratio determination which is very important parameter for tool engineering analyses.

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