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Investigations Regarding Process Stability Aspects in Thread Tapping Al-Si Alloys

Andreas Steininger*, Anton Siller, Friedrich Bleicher

Technical University of Vienna, Karlsplatz 13, 1040, Vienna, Austria

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Abstract

The large number of drills and taps in automotive powertrain components make these processes to a considerable machining step. Due to the fact that hypereutectic Al-Si alloys tend to adhere on the tool surface, the machinability of these alloys is challenging. Especially the adhesion of Al has a negative influence on the chip transportation and leads to an increase of stochastic inclinations of clogging the chip flute. A variety of physical vapour deposition (PVD) coatings like TiCN, CrN, TiB_2 on carbide metal taps have been tested in machining experiments. Also two types of DLC coatings have been compared in the tests. In order to improve the chip transportation, the tribological effects were determined by investigating the affinity of build-up edge and aluminium adhesion in the rake flank. Results are discussed in terms of materials, which are fit for purpose of automotive powertrain machining steps.

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Keywords: Tapping; Adhesion; Aluminium alloy; chips; tool coatings

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1. Introduction

In industrial machining operations tapping is still regularly applied. Although the performance of thread forming tools has risen and the field of application has grown, tapping remains a very common procedure. Especially due to modern computer numerical controls (CNC), tapping in a manufacturing procedure is elementary to implement. Based on the large number of internal threads, e.g. in the automotive industry, the process stability and productivity of tapping should not be underestimated.

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* Corresponding author. Tel.: +43-1-58801-31114; fax: +43-1-58801931114.
E-mail address: steininger@ift.at

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Nomenclature

A	Area of uncut chip cross sectional
α	Included angle of thread
α_s	coefficient of thermal expansion and thermal conductivity of coating
α_u	coefficient of thermal expansion and thermal conductivity of substrate
BUE	Build up edge
BUL	Build up layer
D	Major Diameter
d_1	Minor diameter
d_2	Pitch diameter
E_S	Young's modulus of coating
f	Feed per rotation
F_{cz}	Cutting force per flute
F_z	Thrust force
γ_f	angle of helical flute
γ_p	rake angle
h`	Radial depth of cut
h	Uncut chip thickness
H	Height of fundamental triangle
κ_r	Chamfer angle
$k_{c1.1}$	Specific cutting force
M_z	Cutting torque
P	Pitch
σ_i	Intrinsic strain
σ_T	Thermal strain
T_B	Temperature of coating during coating process
T_M	Temperature of coating during machining process
z	Number of flutes
Z_g	Number of threads

A tool failure is fairly connected to expensive re-working or rejected work pieces. Particularly Aluminum- Silicon alloys with the adhesion tendency of the Aluminum to the tool surface proved to be problematic. Warrigton, Kapoor and DeVor [1] reported that the occurring build up edges (BUE) and build up layers (BUL) are deteriorating the chip formation and make it more difficult to clear the chips through the flutes. Consequently this will lead to a higher probability of clogging the pitches and the flutes In Fig 1a a typical adhesion of Al to the rake face surface with energy dispersive X-ray (EDX) spectroscopy can be seen. List et.al [2] investigated in an orthogonal cutting test the tool wear mechanisms of cemented carbide tools as a function (Fig.1b) of the tribological conditions, the temperature and the cutting speed. Also here the BUE/BUL formation was the dominant effect.

According to these investigations the tool/work piece adhesive interaction is an important issue to get a stable machining process [3],[4],[5]. Also implementations of automatic monitoring and classification systems to predict the wear of tapping tools have been investigated [6].

In this work conventional tapping tests in flooded conditions with 2.600 rpm and a feed rate of 1mm/rev have been performed with tungsten carbide tools and different coatings like TiCN, SCiL-TiCN, TiB_2, and DLC in hypereutectic Al-Si alloy.

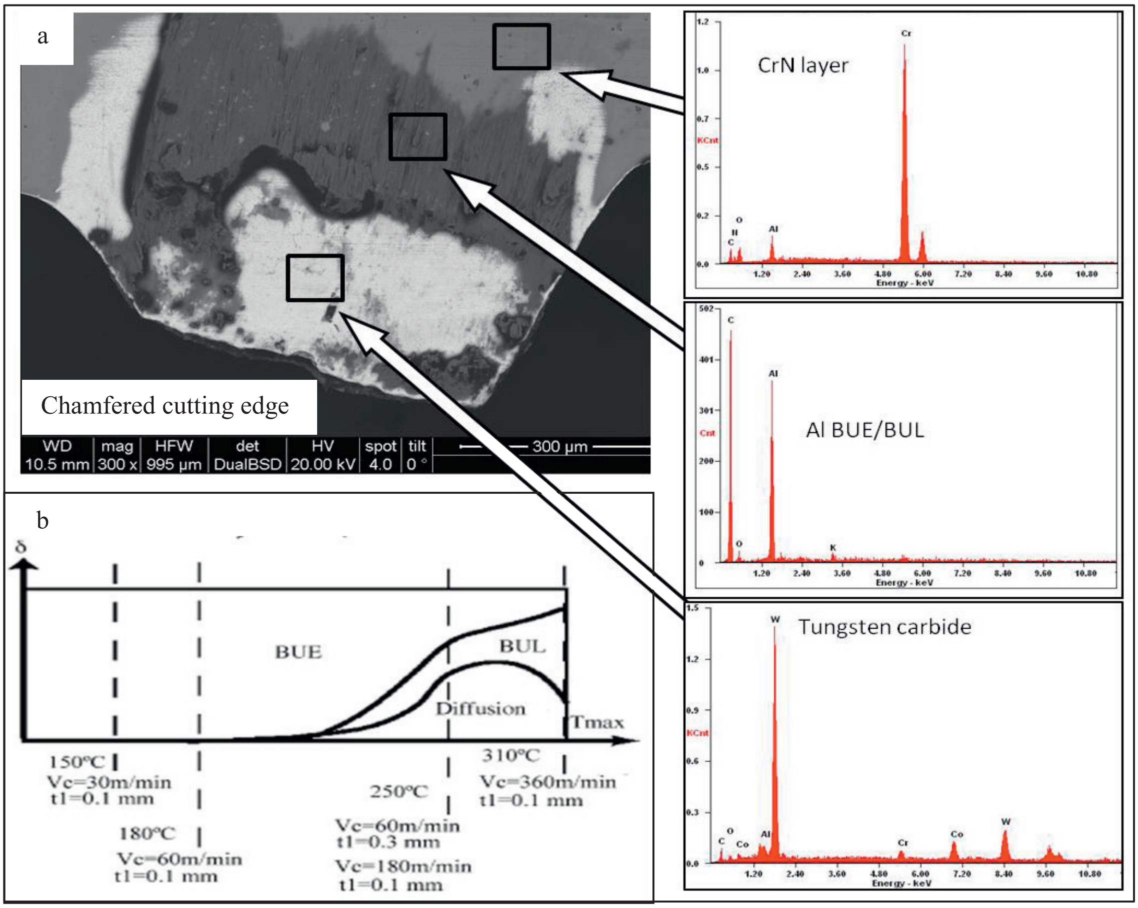

Fig. 1. (a) Adhesion of Aluminum the tool rake face and the EDX spectroscopy; (b) Tool wear mechanism as a function of cutting and tribological conditions in dry machining of aluminum alloys [2].

2. Experimental Details

2.1. Description of workpiece and cutting tools for tapping

The work piece material tested was a hypoeutectic AlSi9Cu3 aluminum-silicon alloy usually used for power train components. Uncoated as well as coated tungsten carbide tapping tools have been employed for the investigation. The variety of the coatings comprises TiCN, CrN, SCiL-TiCN, TiB_2 and DLC. In course of this work the experimental setup was performed as follows: with the different tools 1.100 taps were performed and at the start of the machining procedure as well as at the end of it measurement procedures were done. The quantity tests have been performed with rectangular blocks of 34 cm x 42 cm x 2.5 cm, the measurements with smaller blocks of 7 cm x 15 cm x 2.5 cm, respectively. The cutting tools employed for tapping were spiral taps with the size of M6 x 1 with an angle between the pitches of 60 °. All tested tools consisted of three helical flutes (γ_f =15°) and an inner bore for the coolant supply. For the prior drilling also tungsten carbide tools with 4.9 mm diameter and two 90 ° flutes were used.

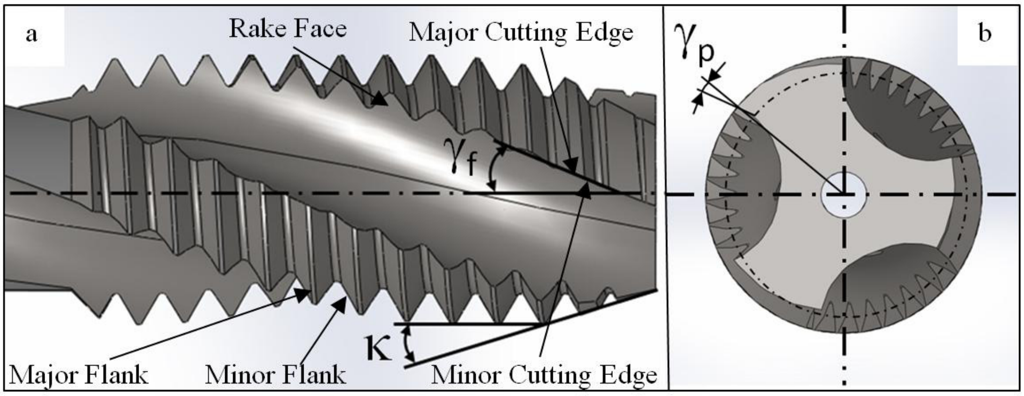

Fig. 2. (a) Tapping tool with the chamfer length; (b) Cross section of the first major cutting edge with rake angle.

Additionally all tapping tools were delivered with a chamfer length among 1.5 to 2 pitches. So all the cutting load is concentrated to these six (see fig. 2, A to F) tapping teeth simultaneously during the machining process. According to the analytical cutting force/moment calculation from Victor und Kienzle, see equation (1 and 3), this force is determined by the area of uncut chip cross sectional, see equation (2). According to these equations, analytical calculations in Tab. 1 have been performed to get an estimation of the expected cutting forces and moments.

$$\mathrm{F}_{cz} \approx \frac{1}{z}\cdot A\cdot k_c \rightarrow \quad k_c = g(f,\gamma_p,v_c,h) = k_{c1.1}\cdot\left(\frac{h}{h_0}\right)^{-m}\cdot f_\gamma\cdot f_{v_c}\cdot f_R \tag{1}$$

$$A = \frac{\pi}{4}\cdot(d-D_1)^2\cdot\tan\left(\frac{\alpha}{2}\right)+\frac{\pi}{16}\cdot(d-D_1)\cdot P \tag{2}$$

$$M_z = z\cdot F_{cz}\cdot\frac{D_2}{2} \tag{3}$$

Table 1. Analytical calculation of tapping force for M6 thread in AlSi9Cu3.

Tapping force calculation	H	P	z_g	z	κ_r	D	d_1	h	h`	A	$k_{c1.1}$	F_{cz}	M_z
Units	[mm]	[mm]	[-]	[-]	[°]	[mm]	[mm]	[mm]	[mm]	[mm²]	[N/mm²]	[N]	[Nm]
Values	0,866025	1	1,50	3	20	6	4,92	0,11	0,12	0,295	602	95,45	0,70

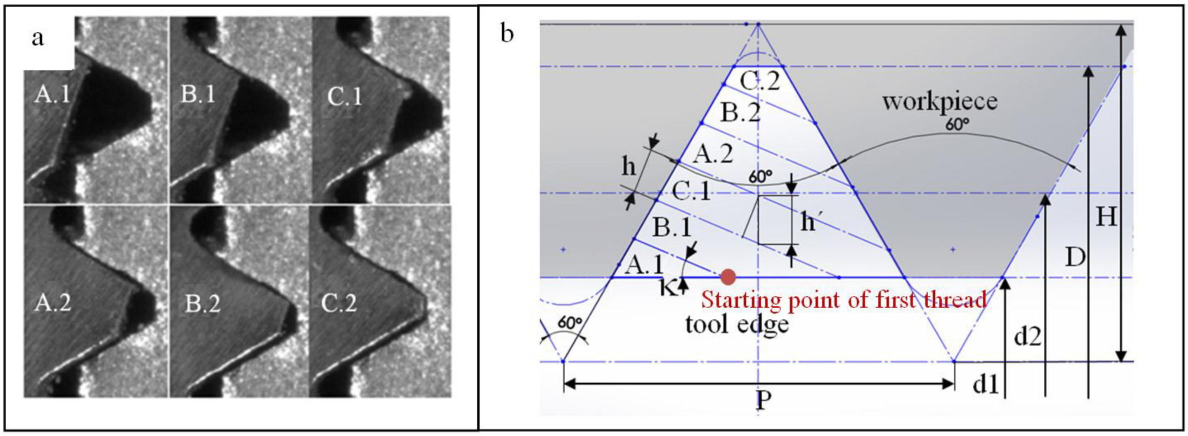

Fig. 3. (a) Cross section of the cutting area for each chamfer thread edge during tapping[7]; (b) 2D Modell of the chamfer thread edge with theoretical uncut chip geometry.

In fig. 3a the chamfer form E [8] of the inspected tools is shown at the cross section of the cutting area. Fig.3b shows that with this chamfer length (1.5 to 2 rotations) approximately six major cutting edges are performing the chip removal. The subareas, namely A.1 and A.2, B.1 and B.2, C.1 and C. respectively, of the three flutes represent the summed cutting cross section. Due to the fact that in the DIN 2197 the position of the starting point of the first thread (and the width of the chamfer length) is not exactly defined, a tool manufacturer can set this point at one's own discretion. As a result, the distributions of the subareas of the uncut chip cross sectional along the number of flutes are varying and also the number of major cutting edges is varying. In fig.4, a comparison between the uncut chip cross sectional subareas is shown for the different number of major cutting edges. It is evident that the material removal energy is correlated to the subarea of the uncut chip cross sectional and the length of the cutting edge. This also affects the chip formation, which is influencing the process stability of tapping enormously [3-5]. Also the tool wear of the cutting edges is connected to this fact.

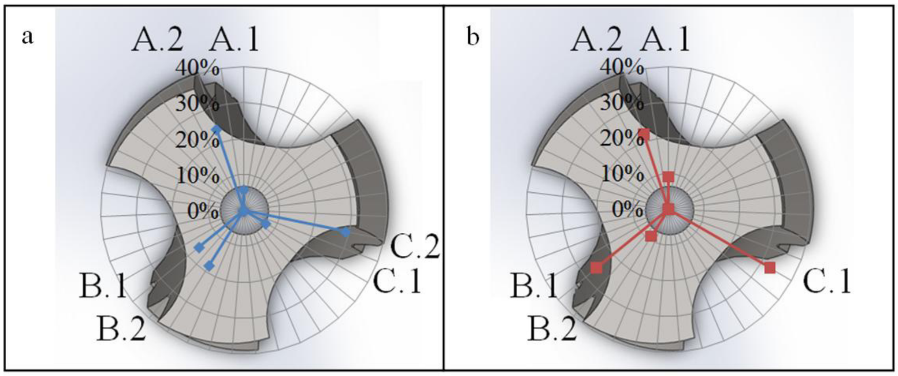

Fig. 4. (a) Distribution of the uncut chip cross sectional subarea for six major cutting edges (A.1-C2); (b) Distribution of the uncut chip cross sectional subarea for five major cutting edges (A.2-C.1)

2.2. Experimental Setup

All the experiments have been performed on a vertical milling machine (Hermle C20) with a constant feed rate of 1 mm/rev and a cutting speed of 49 m/min. Instead of using a synchronized tapping tool holder, a rigid hydraulic clamping chuck was used in order to avoid the damping of the effect of the feed force. This feed force (F_z) and the forward/backward torque M_z were measured by a piezoelectric dynamometer with four 3-component force sensors (Type: Kistler 9129AA: X,Y,Z ±10kN) as it can be seen at Fig. 5 with the so called measurement work piece. All tapping operations have been supported by internal coolant, therefore a rate of 2.33 L/min was chosen. This specific coolant is an oil in water emulsion with 6% lubricant phase based on the commercially available product "OMV mixcut".

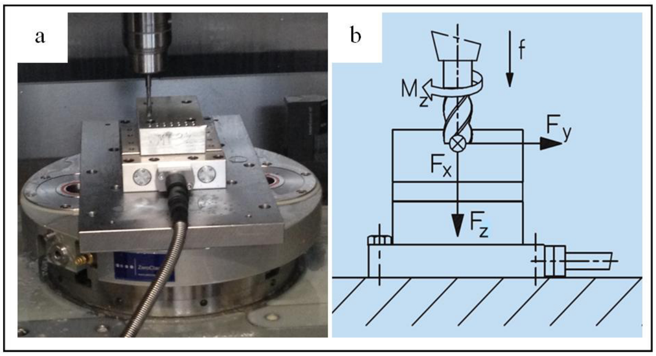

Fig. 5. (a) Experimental setup with dynamometer, work piece and tool; (b) Direction of cutting forces.

2.3. Tapping tests

The process of the tests realized as follows: First 14 measurements with each tapping tool have been logged. Afterwards every tool had to perform the quantity of 1.100 taps. It has to be stressed that no tool failure occurred during the quantity tests. Accordingly the measurement tests have been repeated and the resulting data were analyzed. The graph of the resulting torque and the feed force is shown in fig. 6. This typical profile of the torque can be classified in three stages for the forward operation (between t_0 and t_3). The first stage (between t_0 and t_1) represents the initial cuts of the three edges. Followed by the machine operating with constant feed and cutting speed, so in this section the feed force and the torque is regarded as constant (between t_1 and t_2). Subsequently, the tool is approaching the deepest point of 16 mm and for that circumstance the machine has to decelerate the spindle and the feed axis synchronously to stop and change the direction of rotation and feed. This process is documented by a marginal increase of the torque within a high feed force deflection. After stopping and changing the rotational direction the momentum declines to a negative value. Following the shift of the feed force the acceleration of the spindle and the axis is detected.

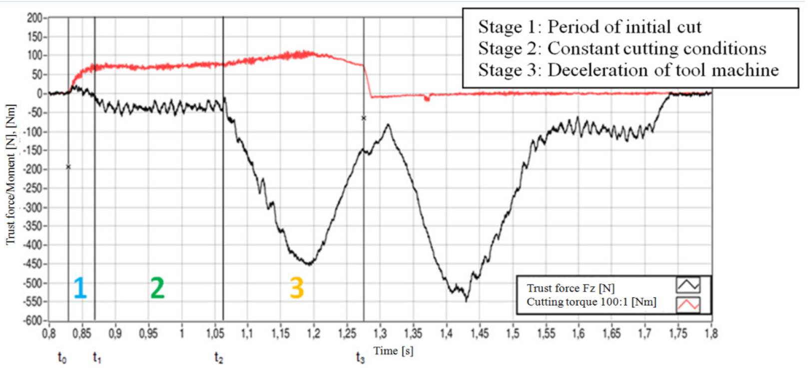

Fig. 6. Graph of tapping torque and feed force.

The forward chip formation mechanism is the considered part for the analysis. The arithmetic mean and the root mean square deviation have been calculated for the moment of the cutting moment and as well as for the feed force during the three stages. In Figure 7 the calculated values are shown exemplarily for the uncoated tungsten carbide tapping tool. The curve depicted in blue represents the average values at sharpened conditions and after the quantity of 1.100 taps, the values of the curve shown in red are increasing. This increase is caused by the tribological wear on the rake face of the tools.

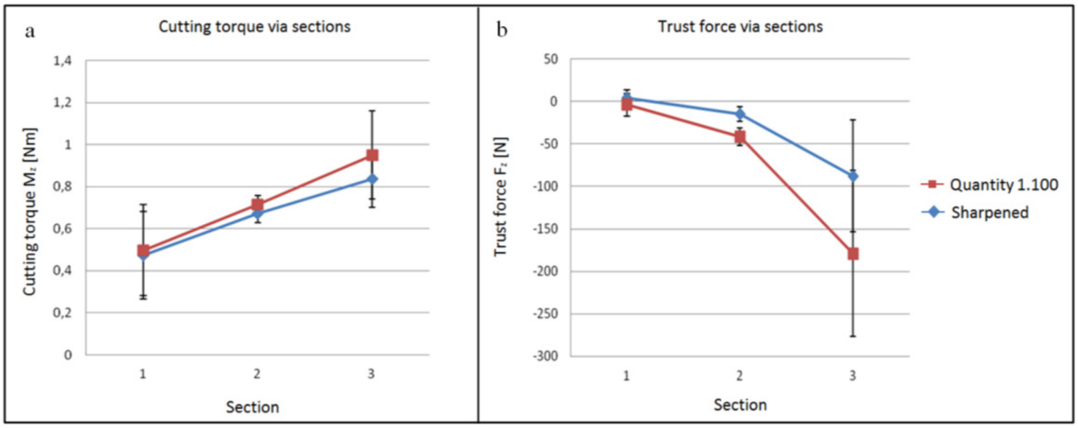

Fig. 7. (a) Cutting torque trend via tapping depth; (b) Feed force trend via tapping depth.

3. Results

The performance of the different tools is defined by the combination of the tapping force measurements, the documented tool wear, and the morphology of the chips occurred during the process, respectively. All these factors are related and influence the cutting performance. Hence these parameters affect the process stability. The main goal for the process is to achieve a smooth chip formation and subsequently a tool with little, but due to the adhesion tendency of Aluminum, nearly unavoidable tribological wear. Improving the chip transportation through the flutes leads to a rise of the process stability. As depicted in fig.6 the measured moments showed the lowest levels of cutting load. According to these results, the DLC coated tools showed the most promising morphology of the chips. Tools employing DLC coatings showed the highest performance.

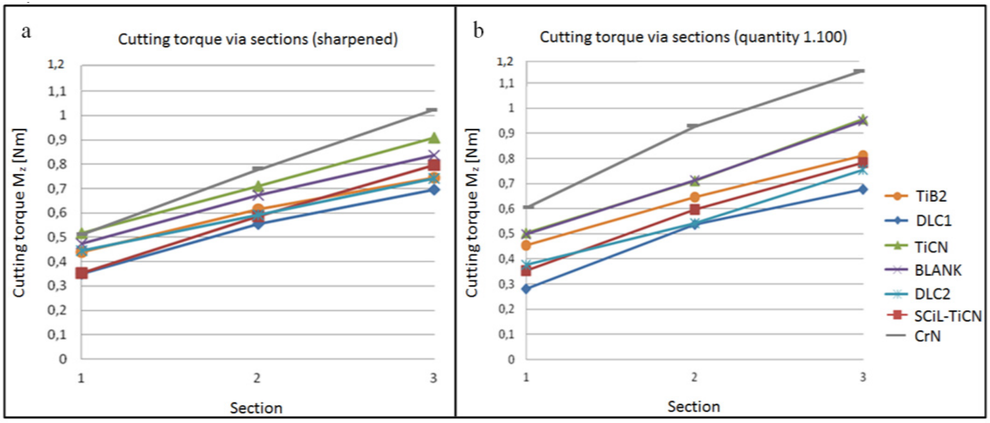

Fig. 8. (a) Arithmetic average of cutting torque via tapping depth in sharp condition; (b) and after quantity of 1.100 taps.

As shown in fig. 7 the chip generated by the DLC tool has a very smooth surface and straight edges. Also the Aluminium adhesion (BUE and BUL), analysed by applying scanning electron microscopy (SEM), showed the lowest tendency to the DLC coating. Nevertheless the DLC coatings also exhibit undesirable effects. The so called "eggshell effect" [9] can be observed in the area of the cutting edge and the rake face. In this area the main cutting forces are applied so the adherence is negatively affected by the difference in the hardness between the coating and the base material, the inherent compressive stress (σ_i) and the thermal strain (σ_T) caused by different thermal expansion coefficient, see equation (4) [10].

$$\sigma = \sigma_T + \sigma_i \rightarrow \sigma_T = E_S(\alpha_S - \alpha_U)\cdot(T_B - T_M) \tag{4}$$

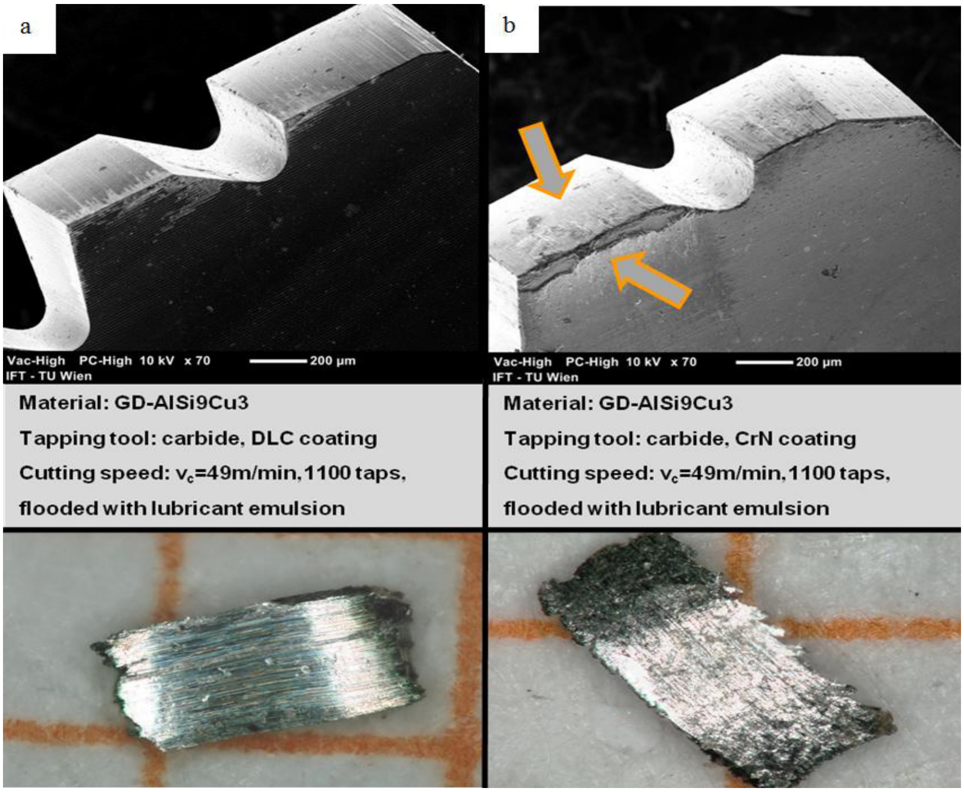

Fig. 9. (a) SEM and picture of DLC coated tool; (b) SEM and picture of CrN coated tool.

Conclusion

In this study several tapping tools coated/non coated have been tested with hypoeutectic aluminum silicon alloy. The main conclusions are as, follows:

The cutting performance is related to the adhesions wear as it is described by in several studies [1], [2], [4], thus it influences the process stability. This wear mechanism occurs in general when machining Aluminum alloys and it can be seen in fig. (1b) it is dependent on the cutting speed and the temperature respectively. Due to the low cutting speed in the tapping process the dominant mechanism is the BUE.

The highest performance was achieved when employing tools with DLC coatings. This was shown by measuring the tapping torque and by analysis of the tendency of BUE/BUL and the chip morphology. Regarding to these facts it can be assumed that a minimum of the cutting torque is connected to a reduced tendency of BUE and BUL. Also the morphology of the chips, produced by the DLC coated tools, showed smoother surfaces, straighter edges and reduced fringes. By creating smoother chips, the probability of clogging the pitches and the flutes should decrease. Despite the tribological advantage of the DLC coatings there are still issues like the bonding to the substrate which need to be further addressed.

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