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Innovative Tool Coatings for Increasing Tool Life in Milling Nickel-Coated Nickel-Silver Alloy

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Abstract

In the automotive market, there is a strong interest for the production of sidewinder keys made of Nickel-coated Nickel-Silver alloy. The Nickel coating improves wear resistance and brightness of the key, nevertheless it reduces the machinability and the tool life when milling the key groove is short. In this work, several innovative tool coatings were applied on conventional mills to enhance the machinability of Nickel-coated Nickel-Silver alloy. Tool life and burr formation obtained with the tested tools were investigated and discussed. Some of the coatings proved to be very promising for this application thank to their excellent tool life. Specifically, the PCD tool was the most interesting since the tool life was significantly longer than conventional carbide tool.

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Keywords: Tool coating; Tool life; Milling; Nickel-coated Nickel-Silver alloy

1. Introduction

Nowadays, the automotive market is one of the main sectors leading the product innovation of the key producers. The car key has evolved over the last few years driving the industrial interest towards innovative materials for key production with high corrosion resistance and good mechanical properties. Moreover, key producers apply different surface coatings in order to increase their wear resistance and the aesthetic appearance. However, this reduces the

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machinability of the material, thus increasing the production costs. For this reason, experimental studies for identifying innovative tool coatings to increase tool life in key-code cutting process are required.

A sidewinder key is a particular type of car key that is composed of a rectangular blade with a wavy groove of constant depth at each side. In the case of car keys, the groove on the top face of the blade is equal to that on the back, making the key reversible. Groove shape is changed from one car key to another in order to univocally characterize it. The groove is obtained with a particular machine tool named “key cutting machine”, however the mechanical process is a conventional milling process using a specific end mill, mostly in slotting configuration. In Figure 1, the key cutting machine used in this work is shown. In Figure 2, the CAD-CAM example of milling process is illustrated together with an example of a finished Nickel-Silver sidewinder key.

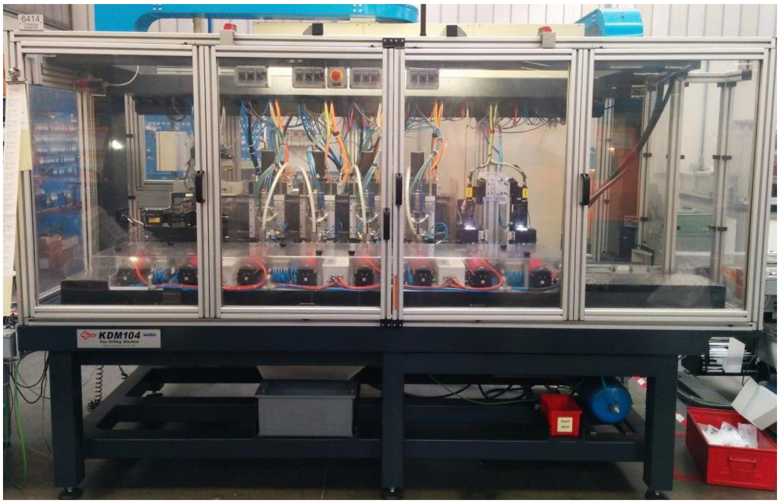

Fig. 1. CNC milling machine for key cutting.

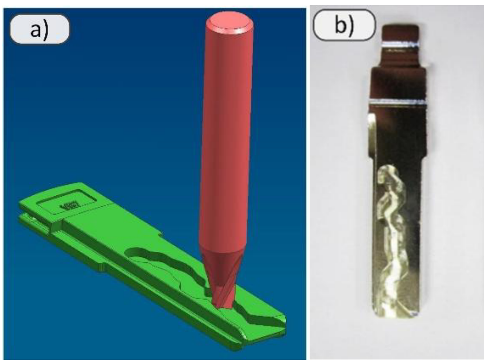

Fig. 2. a) CAD-CAM example of code cutting operation; b) Example of a finished sidewinder key.

Sidewinder keys are made of special alloys, since they have to resist to abrasion and corrosion, such as high alloy steels or other non-ferrous alloys. Among copper-based alloys, Nickel-Silver alloys are frequently adopted for this application. In detail, they are Copper-Nickel-Zinc alloys, with small percentages of other elements such as Lead, Tin and Manganese [1, 2]. It has to be recalled that the name Nickel-Silver was originally adopted because of the silver-white color of such alloys, which do nevertheless contain only traces of Silver or no Silver at all.

These materials may be wrought, cast, rolled, stamped, forged, drawn, extruded and machined. They are extensively used because of their good mechanical properties and resistance to corrosion for parts such as keys, tableware (commonly silver-plated), marine fittings, and plumbing fixtures. Because of their high electrical resistance, they are also used in heating coils.

The Nickel-Silver alloy considered in this work was CuNi12Zn25Pb1 (CW404J) with 60-63% of Copper, 11-13% of Nickel, 0.5-1.5% Lead and remainder Zinc, with hardness in the range 155-185 HV30, tensile strength in the range 530-610 MPa.

Machinability of difficult-to-cut materials is of great interest for industry as reported in [3]. Several studies can be found in literature, analyzing the machinability of a wide range of materials such as Inconel [4, 5], Cobalt based superalloys [6], biocompatible materials [7] and fiber glass composite materials [8].

In particular, machinability of copper-based alloys was deeply investigated in literature, as can be seen in the review [9]. However, it should be noticed that Copper-based alloys are composed of several subclasses with radically different chemical, physical and mechanical properties. Accordingly, the machinability of such materials may vary significantly [10]. For instance, the machinability of brass is strongly dependent on its chemical composition [11, 12], and in particular on the presence of Lead.

Similarly, Nickel-Silver alloys exhibit different behaviors depending on their chemical composition. In the current case, the machinability of the investigated material was about 60-70% with respect to free-cutting brass [10, 13].

Relatively high normal clearance and normal rake angles are generally recommended when machining Copper-based alloys, due to their low modulus of elasticity. Tools designed for machining Copper-based work materials do typically address to the ISO application group N. As recalled in [10], both cemented carbides and PCD tools are good candidates for efficient machining of Copper-based alloys. Conventional coatings (such as TiCN and TiAlN) as well as other coatings (such as AlCrN) – typically used for cutting materials in ISO group N – could be suitable for enhancing the tool performance when machining Copper-based alloys. However, no clear recommendations regarding tool materials and coatings for the specific work material considered here were found in technical literature.

Similarly, no precise information regarding cutting parameters for end-milling of Nickel-Silver alloys in slotting configuration was found. For the sake of reference, the recommended cutting speed for similar materials and cutting conditions should be in the range 80-240 m/min, the feed per tooth should be in the range 0.02-0.05 mm and the axial depth of cut should not exceed half of cutter diameter [13, 14].

For the industrial case study investigated in this work, a Nickel-based coating was applied to raw material – before key cutting – in order to further increase the wear resistance of sidewinder keys. However, the coating has a negative effect on tool life and cutting process performance.

In this work, the application of innovative tool materials and tool coatings was investigated in order to increase tool life when machining Nickel-coated Nickel-Silver alloy.

2. Experimental procedures

In order to compare the performances of different tool coatings on tool life, experimental tests were carried out, as described in the following.

Machining test were directly performed in industry during the normal production of sidewinder keys with a key cutting machine.

Special end-mill cutters were realized with the following geometrical specifications: tool tip diameter 3.10 mm, axial length of cut of about 1.2 mm (with small chamfers at the beginning and at the end), 3 helicoidal teeth with moderate positive axial rake angle γ_a, slightly positive normal rake angle γ_n and high normal clearance angle α_n, in accordance with the technical recommendations reported in literature for Copper-based alloys.

In order to maximize coating performance, two different carbide grades (named A and B) were selected as core materials. Specifically, cemented carbide A was equivalent to K30 ISO grade with grain size of about 0.6 μm, 10% of Cobalt content, 14.5g/cm^3 density, hardness 1610 HV30 and transverse rupture strength of about 3600 N/mm^2. Cemented carbide B was equivalent to K40-K50 ISO grade with grain size of about 0.5 μm, 12% of Cobalt content, 14.1g/cm^3 density, hardness 1680 HV30 and transverse rupture strength of about 3800 N/mm^2.

Seven different tool coatings were chosen, in accordance with the rough indications found in technical literature and the suggestions deriving from coating producers or machining experts.

A PCD tool was also included in the Design of Experiments because it was considered promising for this application. In this case, only one active tooth was present, with zero axial rake angle.

The characteristics of the investigated tools are listed in Table 1. An example of cutting tools with different coatings are shown in Figure 3.

Tool wear tests were carried out by assuming constant cutting parameters, as follows: cutting speed v_c equal to 115 m/min, feed per tooth f_z equal to 0.02mm, depth of cut a_p equal to the depth of the groove (1.2mm).

Different cutting parameters were adopted in the case of PCD tool, in order to achieve a satisfactory part quality and tool performance with such a different tool geometry: cutting speed v_c equal to 170 m/min, feed per tooth f_z equal to 0.04 mm.

Table 1. Tool characteristics.

Tool code	Tool core material	Coating						
		Material	Thickness [μm]	Deposition technique	Structure	Microhardness [HV 0.05]	Friction coeff. against steel []	Color
T1	A	AlCrN	0.5 - 4	PACVD	Mono-layer	3200	0.35	Blue-grey
T2	A	AlCrN-based	0.5 - 4	PACVD	Multi-layer	3200	0.35	Bright grey
T3	B	TiSi-based	1 - 1.5	PVD - HDP	Mono-layer	4300	0.25	Brown
T4	B	TiCN	1- 3	PVD	Multi-layer	3500	0.5	Blue-grey
T5	B	ZrN	1 - 4	PVD	Mono-layer	2100	0.4	Light yellow
T6	B	AlCrN	0.5 - 4	PACVD	Mono-layer	3200	0.35	Blue-grey
T7	B	TiAlN	0.5 - 4	PACVD	Nano-Based	3300	0.30 - 0.35	Violet-grey
T8	-	PCD	-	-	-	8000	-	Black

Fig. 3. Example of cutting tool coatings.

With these assumptions, the linear feed speed for cemented carbide and PCD tool were approximately the same.

Although tool trajectories were significantly varied from one part to another (since each key has to be unique), the total trajectory length was approximately constant. Moreover, the total number of keys produced by a tool during its life was generally large. Thus, the effect of tool trajectory on tool life was not considered significant.

Cutting tests were executed in dry conditions. Tool life criteria were assumed in order to assure the desired product quality, rather than focusing on tool integrity only. For increasing tool wear, undesired burrs of increasing height were detected on the workpiece at groove edges. In some cases, machined groove width was also decreasing for increasing tool wear. Accordingly, the tool was considered worn when burr height exceeded 0.02 mm or groove width was below the lower tolerance specification limit. For each tool, 10 tool wear test replicates were performed.

3. Data analysis and discussion

Some examples of machined grooves and worn cutting edges inspected at the end of the tool wear tests are illustrated in Figure 4.

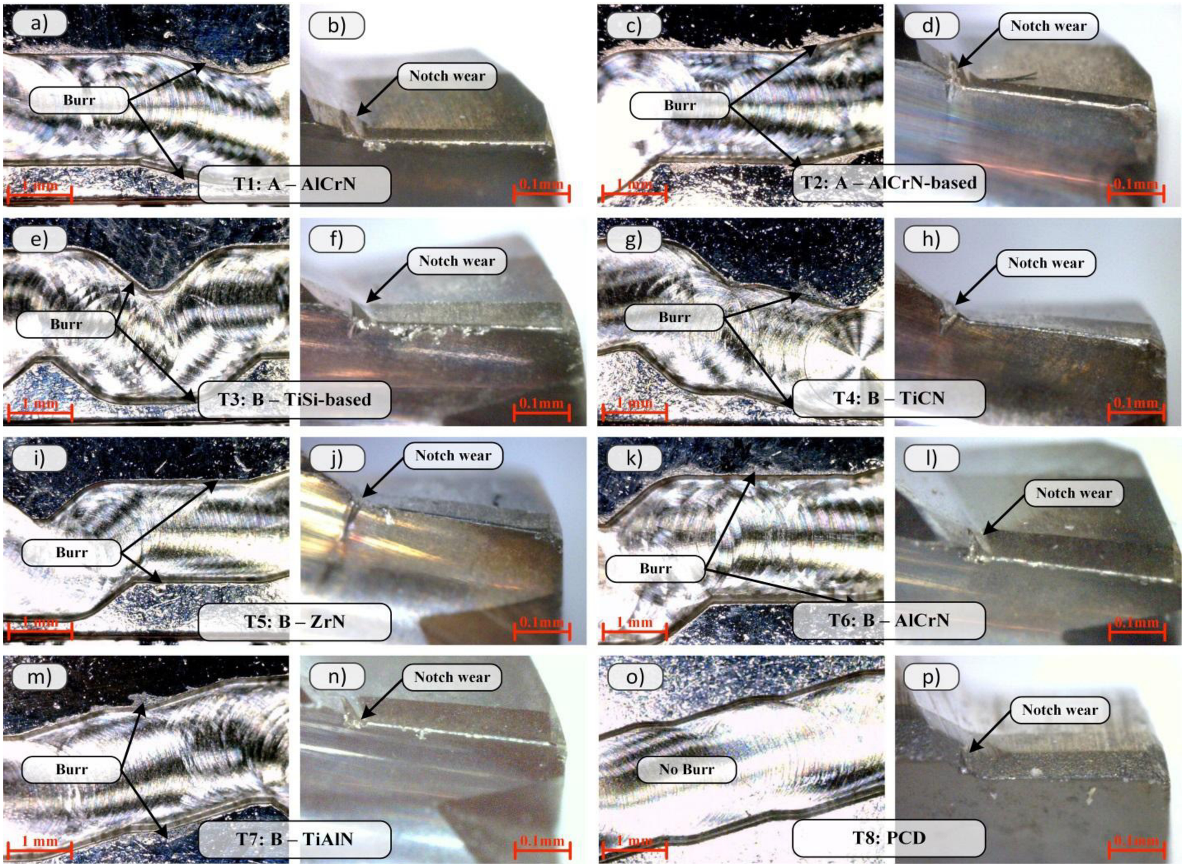

Fig. 4. Examples of observed burrs and tool wear effects with the considered tools.

In most cases excessive burr formation at groove edges was the main cause of tool wear test termination. Only in a few cases (when T3, T4 or T5 tools were adopted) the grove width was below the lower tolerance specification limit.

Notch wear at the end of the engaged cutting edge was dominant among other tool wear effects. This was likely due to the Nickel coating present on workpiece surface. Tool wear land width was generally small.

After data collection in the shop floor, tool life values were determined in accordance with the tool wear criteria defined above. The boxplot in logarithmic scale of the tool life against the different tool coatings is shown in Figure 5.

It should be pointed out that before this research work the average tool life when using conventional uncoated carbide tools for this application was about 270 min.

Experimental data demonstrated that PCD tool (T8) had the longest tool life, since it was significantly higher than all other tools.

Tool coatings based on AlCrN (T1, T2, T6) were affected by significantly shorter tool life. Besides, there was no statistical difference between average tool life values obtained with AlCrN-based coatings.

An intermediate performance among AlCrN-based coatings and PCD was exhibited by TiSi-based, TiCN, ZrN, TiAlN coatings (T3, T4, T5 and T7 respectively). Again, no significant difference between average tool life values obtained with the latter coatings was observed. However, by analyzing the lower confidence limits for each of these four coatings, TiSi-based and TiCN (T3 and T4) seem more promising than ZrN, TiAlN coatings (T5 and T7), when the reliability is of major concern, in the perspective of unmanned production.

It can also be observed that tools with core material B performed on average better than those with core material A, probably due to a better adhesion of the coating to core material. However, no general conclusion can be drawn here, because of the lack of combinations involving core material A and the coatings which were applied to core material B only.

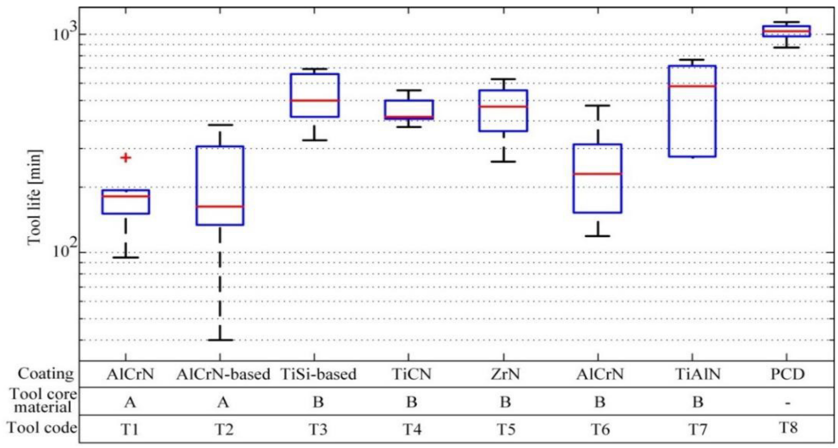

Fig. 5. Box plots, whiskers plots and outliers of tool life obtained with different cutting tool coatings.

It is worth noting that PCD cutter was more expensive than cemented carbide cutters. Nevertheless, since tool life of PCD cutter was approximately double than cemented carbide tools and the productivity was approximately the same, PCD was the best choice both from the technological and economic point of view. This advantage may be even increased by further improvement of PCD cutter. For instance, by increasing the number of teeth.

Conclusions

According to the considerations presented in this paper, we may draw the following conclusions.

The machinability of difficult to cut materials is of great interest in literature. Despite of several studies are focused on the machinability of copper based alloys, the machinability of Nickel-Silver alloy is not deeply investigated.

Nickel-Silver alloy is widely used as row material for the production of sidewinder keys. Moreover, key producers apply different surface coatings in order to increase their wear resistance and the aesthetic appearance. However, this reduces the machinability of the material, thus increasing the production costs. For this reason, experimental studies for identifying innovative tool coatings to increase tool life in key-code cutting process were required.

The comparison on the performances of different tool coatings on tool life during milling Nickel-coated Nickel-Silver alloy evidenced that the application of tool coating significantly increase the tool life, however, no clear correlation between tool performance and coatings' characteristics was found out.

On the other hand, experimental data demonstrated that tool life of the PCD tool was significantly higher than all other tools. Accordingly, PCD cutter was the best choice both from the technological and from the economic point of view because the production cost of one component including the costs of machining time and tool was smaller than that obtained when applying the other tools.

It would be interesting to continue the research in this field in order to deepen the understanding of physical and tribological phenomena underlying Nickel-Silver alloy machinability and to investigate other innovative tool core materials and coatings.

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