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Review

High-performance coatings for cutting tools

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ABSTRACT

Cutting tools with hard coatings have been successfully employed in the industry for almost 50 years. Nowadays, 85% of all cemented carbide tools are coated. There is an increasing demand for ever more efficient tools driven by the use of new workpiece materials as well as the demand for increased productivity of manufacturing processes. A historical review of the development of CVD and PVD processes shows a continuous improvement of successful coating materials through adjustments of the chemical composition and the coating architecture. Especially nanostructured PVD coatings managed to establish themselves on the market surprisingly quickly. Cutting tools are an excellent example for how the development of coated products is traced methodologically by means of a holistic view over the application. The demand for innovative tooling concepts will continue to exist in the future, as will the high potential for this aim to be achieved through high-performance coatings on improved cutting materials with adjusted tool design.

Contents

The global market of cutting tools

In their study “Cutting Tools 2014”, Dedalus Consulting, New York analyses the global market for cutting tools, making prognoses for the years 2012–2018 as shown in [1]. According to the statistic, the world market volume of 2013 was 16.33 billion US-Dollars. The most strongly represented technology is milling with 39%, closely followed by turning with 30%. Generally, the annual growth is assumed to be 4–5%, however milling and drilling are expected to show slightly higher growing rates than turning and other cutting technologies (Fig. 1).

The distribution of the cutting material (Fig. 2) shows that 53% is covered by cemented carbide, and 20% is covered by high-speed steel. Prognoses assume the highest growing rates to be in super-hard cutting materials such as ceramic, PcBN and PCD, which together already accounted for 19% of all cutting materials used in 2013. The forecast of a growing rate of 10.4% until 2018 puts PCD in clear lead. The main reasons for changes on the tool market are changes of workpiece materials as well as modified cutting parameters [7].

In [2], H. Voggenreiter, chairman of VDI-GME affirms: “Over 60% of all product innovations are based on new or improved materials as well as on methods in manufacturing and processing of those.” This becomes especially evident in traffic engineering where there is a trend towards weight reduction, a necessary progress made possible by increasing the use of light alloys based

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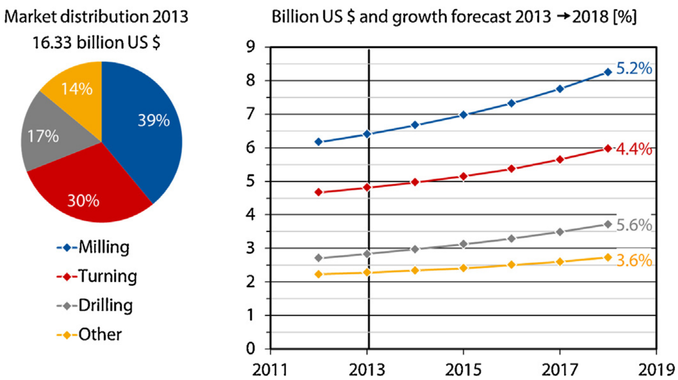

Fig. 1. Global market for cutting tools by tool type (Dedalus Consulting, New York [1]).

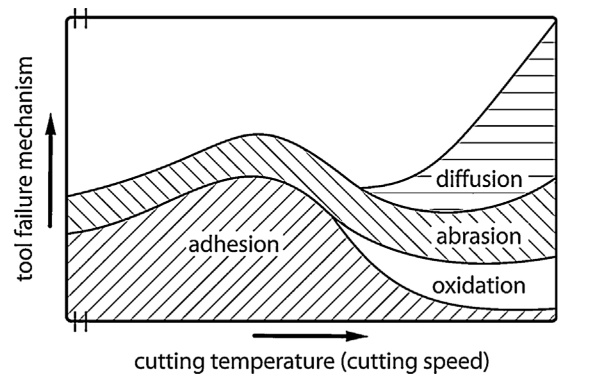

Fig. 3. Dominant failure mechanisms influencing cutting tools depending on the cutting temperature [9].

on Al, Ti, and Mg. Moreover, this trend towards lightweight designs also triggered the dynamic advancement of new grades of high-strength as well as super high-strength steel. Apart from their improved mechanical properties, they serve to reduce the weight by reduced volumes. A third group of materials used for lightweight designs are composite materials which enable to combine the seemingly contradictory requirements of high tensile strength and low weight as in for instance carbon fibre-reinforced plastic (CFRP). Due to environmental regulations, aircraft engines have shown an increase in combustion temperatures and pressures, the result of which being an increased demand for improved high-temperature materials. Common solutions include improved superalloys based on Ni on one hand, and intermetallics such as TiAl and NiAl on the other. Ceramic matrix composites (CMC) act as a third possibility with considerable potential for weight reduction together with high-temperature resistance. In theory, the list could be continued indefinitely. Ultimately, it all leads to the overall finding that, the main technological factor affecting change in the global cutting tools market is the use of new workpiece materials [1].

Moreover, the increased product demands made on the tools are the result of measurements taken in order to increase the productivity and sustainability of machining processes [3–5] such as:

- Minimum quantity lubrication.
- High-speed cutting.
- High-performance cutting.
- Hard machining.

Therefore the past few years have shown a clear trend towards increased cutting temperatures. Additionally, the thermal load rises when the workpiece material has a low thermal conductivity, as is the case with, for instance, austenitic, high-alloyed steels or Ni-based superalloys. Here, the thermal energy resulting from the cutting process cannot be sufficiently dissipated through neither the chip nor the workpiece itself with the result that the thermal load is left with the tool. The damage caused takes different forms with increasing machining temperatures (Fig. 3), and especially the thermally induced failure mechanisms diffusion and oxidation dominate the process. All of the four types of failure mechanisms presented in Fig. 3 occur on the surface of the tools. This means they are all results of interactions on the phase interfaces between tool and workpiece or tool and ambient medium respectively. The logical approach deriving from this given fact is to protect the tools by means of suitable coatings. This means that volume properties and surface properties can be designed independently from each other this means they can be designed individually regarding the application. This way, CVD and PVD tool coatings have greatly contributed to increases in performance of modern cutting processes ever since the 1970s [6–8].

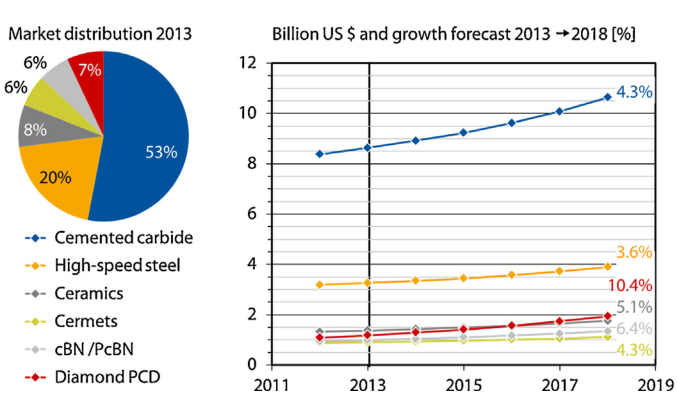

Fig. 2. Global market for cutting tools by product grade (Dedalus Consulting, New York [1]).

The history of hard coatings for cutting tools

From the beginning, the focus of the coating development has been on wear protection against abrasion and adhesion. The higher the cutting temperatures get, the more the focus of research and development shifts towards the high temperature properties of coatings. Beside the important requirement for tool coatings to provide protection against oxidation, they are also requested to function as a diffusion barrier between the tool and the workpiece. In order to provide an adequate protection against abrasion even when faced with high temperatures, the coating material needs sufficient high-temperature strength. The compound of tool material and coating needs to withstand mechanical and thermal loads. The requirements for the compound are especially intensified by the cyclic loadings co-occurring with interrupted cuts, as this can lead to thermally and/or mechanically induced crack formation.

The fracture toughness is crucially influenced by the internal stresses present within the composite coating/substrate. In every stage of the tool production, thermal and mechanical loads induce internal stresses in the material. Moreover, these internal stresses have an impact on each other. Therefore, the resulting internal stresses vary across the stages of the production, from sintering and grinding of the cemented carbide, over pre-treatments all the way to the coating process and also possible post-treatments. Detailed analyses can be found in [10–14]. The available knowledge on internal stresses can specifically be used for the tool production process. On a moderate level, residual compressive stresses have a positive effect on the fracture toughness. An impact

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