Previous books for Springer Verlag by the author:

*Advanced Machining: The Handbook of Cutting Technology* (1989)

CNC Machining Technology series:

*Book 1: Design, Development and CIM strategies*  
*Book 2: Cutting, Fluids and Workholding Technologies*  


Cutting Tool Technology

Industrial Handbook
Just over twenty years ago I began writing a book, the forerunner to this present volume for Springer Verlag, entitled: *Advanced Machining – The Handbook of Cutting Technology*. This original book covered many of the topics discussed here, but in a more general and less informative manner. Since this previous volume was published, many of the tooling-related topics are now more popular, or have recently been developed. Typical of these latter topics, are both High-speed and Hard-part machining that have now come to the fore. While Micro-machining and Artificial Intelligence (AI) coupled to neural network tool condition monitoring have become important, the latter from a research perspective. These machining and tooling topics, plus many others have been included herein, but only in a relatively concise manner. It would have been quite possible to write a book of this length just concerned with say, drilling techniques and associated tooling technologies alone.

With the concerns raised on the health hazards to operational personnel exposed to cutting fluid mists in the atmosphere, the permissible exposure levels (PELs) have been significantly reduced recently. Further, with the advent of Near-dry and Dry-machining strategies, they have played a important role of late, particularly as their disposal and attendant costs have become of real consequence. Tool management issues previously discussed in the ‘Advanced Machining’ book have hardly changed, because when I wrote this chapter over two decades ago, most of today's tooling issues by then had been addressed. However, the tool-presetting machines and associated software now, are far more advanced and sophisticated than was the case then, but the well-organised and run tool preparation ‘rules’ are still applicable today.

One area of cutting tool development that has seen significant design novelty, is in the application of Multi-functional tooling. Here, the chip control development is facilitated by both chip-narrowing and vectoring, being achieved by computer-generated insert design, to position raised protrusions – ‘embossed dimples’, on the top face. Further, some cutting insert toolholders are designed for controlled elastic compliance – giving the necessary clearance as the tool is vectoried along and around the part's profile, allowing a range of plunge-grooving and forming operations to be simultaneously undertaken by just this one tool. Coating technology advances have enabled significant progress to be made in both Hard-part machining and for that of either abrasive and work-hardened components. Some coating techniques today approach the hardness of natural diamond, particularly the aptly-named ‘diamond-like coatings’ (DLC). Recently, one major cutting tool company has commercially-introduced an ‘atomically-modified coating’, such is the level of tool coating sophistication of late.

Potential problems created by utilising faster cutting data often without benefit and use of flood coolant in cutting technology applications, has had an influence on the resulting machined surface integrity of the component. This sub-surface damage is often disguised, or not even recognised as a problem, until the part catastrophically fails in-service – as a result of the instability produced by the so-called ‘white-layering effect’. While another somewhat unusual factor that has become of some concern, is in either handling, or measuring miniscule components produced by Micro-machining techniques. Often a whole month’s mass production of such diminutive machined parts could easily be fitted into a small shoebox!

All of these previously mentioned tooling-related challenges and many others have to a certain extent, now become a reality. While other technical and machining factors are emerging that must be techni-
cally-addressed, so that cutting tool activities continue to expand. It is a well acknowledged fact that if one was to list virtually all of our modern-day: domestic; medical; industrial; automotive; aerospace, etc; components and assemblies, they would to some extent rely on machining operations at a certain stage in their subsequent manufacturing process. These wide-ranging manufactured components clearly show that there is a substantive machining requirement, which will continue to grow and thus be of prime importance for the foreseeable future.

This present book: ‘Cutting Tool Technology – Industrial Handbook’, has been written in a somewhat pragmatic manner and certain topics such as ‘Machining Mechanics’ have only been basically addressed, as they are well developed elsewhere, as indicated by the referenced material at the end of each chapter. Any book that attempts to cover practical subject matter such as that of cutting technology, must of necessity, heavily rely on information obtained from either one’s own machining and research experiences, or from industrial specialist journals. I make no apology for liberally quoting many of these industrial and research sources within the text. However, I have attempted – wherever possible – to acknowledged their contributions when applicable, in either the references, or in the associated diagrammatical and pictorial figures herein. Further, it is hoped that the ‘machining practitioner’ can obtain additional information and some solutions and explanations from the relevant appendices, where amongst other topics, are listed a range of ‘trouble-shooting guides’.

Finally, it is hoped that this latest book: ‘Cutting Tool Technology – Industrial Handbook’ will offer the ‘machining practitioner’ the same degree of support as the previous book (i.e. Advanced Machining – The Handbook of Cutting Technology) achieved, from the significant feed-back obtained from practitioners and readers who have contacted me over the past decades.

Graham T. Smith
Fortuna, Murcia, Spain
First and foremost, I would like to express my sincere thanks to my wife Brenda for her support and for the time I have taken, whilst writing this book: *Cutting Tool Technology – Industrial Handbook*. I could not have achieved such an in-depth treatment and reasonably comprehensive account of the subject matter without her unstinting co-operation and help.

A book that relies heavily on current industrial practices could not have been produced without the unconditional support from specific tooling manufacturers and the machine tool industries. I would like to particularly single-out one major cutting tool company, to genuinely thank everyone at Sandvik Coromant who have provided me with both relevant and significant: information; photographic; and diagrammatic support – the book would have been less relevant without their indefatigable co-operative help and discussion. Likewise, other tooling companies have been of much help and assistance in the preparation of this book, such as: Seco Tools; Kennametal Hertel and Kennametal Inc; Iscar Tools; Ingersoll; Guhring; Sumitomo Electric Hardmetal Ltd; Mitsubishi Carbine; Horn (USA); Shefcut Tool and Engineering Ltd; Rotary Technologies Corp; Diashowa Tooling; Centreline Machine Tool Co Ltd; DeBeers – element 6; Walter Cutters; Widia Valenite; TRW – Greenfield Tap and Die; Triple-T Cutting Tool, Inc; Hydra Lock Corp; Tooling Innovations; and Microbore Tooling Systems. Several machine tool companies have been invaluable in providing information, notably: Cincinnati Machines; Yamazaki Mazak; Dorries Scharmann; DMG (UK) Ltd; Giddings and Lewis; Starrag Machine Tool Co; and E. Zoller GmbH and Co KG. While other tooling-based and associated companies have also provided considerable information, including: Renishaw plc; Kistler Instrumente AG; Taylor Hobson plc; Mahr/Feinprüf; Cimcool; Kuwait Petroleum International Lubricants; Edgar Vaughan; Pratt Burnerd International; Lion Precision; Westwind Air Bearings Ltd; Third Wave AdvantEdge; Susta Tool Handling; Tooling University.

I have listed the main companies above, rather than attempting to name individuals within each company, otherwise the list would be simply vast. However, I would like to express my gratitude to each one of them, personally. I would also like to acknowledge the breadth and depth of information obtained from industrially-based journals, such as: Cutting Tool Engineering; American Machinist; Metalworking Production; Machinery and Production Engineering.

The publishers of this book Springer, have been most patient with me as I have attempted to meet extended deadlines for the manuscript, for which I am indebted to and can only offer my sincerest thanks. Lastly, if any unfortunate mistakes have inadvertently slipped into the text, or misinterpretations in the draughting of any line diagrams have occurred, it is solely the author’s fault and does not represent any of the companies, or their products, nor that of the individuals mentioned.

Graham T. Smith
Contents

1 Cutting Tool Materials ........................................ 1
  1.1 Cutting Technology – an Introduction ........ 2
    1.1.1 Rationalisation ............................... 2
    1.1.2 Consolidation ............................... 4
    1.1.3 Optimisation ............................... 4
  1.2 The Evolution of Cutting Tool Materials .... 7
    1.2.1 Plain Carbon Steels ......................... 7
    1.2.2 High-Speed Steels ........................ 7
    1.2.3 Cemented Carbide ........................ 8
    1.2.4 Classification of Cemented Carbide Tool Grades .......... 12
    1.2.5 Tool Coatings: Chemical Vapour Deposition (CVD) .......... 14
    1.2.6 Diamond-Like CVD Coatings ............... 14
    1.2.7 Tool Coatings: Physical Vapour Deposition (PVD) .......... 17
    1.2.8 Ceramics and Cermets ...................... 19
    1.2.9 Cermets – Coated ................................ 23
    1.2.10 Cubic Boron Nitride (CBN) and Poly-crystalline Diamond (PCD) .......... 25
    1.2.11 Natural Diamond ........................... 29

2 Turning and Chip-breaking Technology ........... 33
  2.1 Cutting Tool Technology ......................... 34
    2.1.1 Turning – Basic Operations .................. 34
    2.1.2 Turning – Rake and Clearance Angles on Single-point Tools ........ 34
    2.1.3 Cutting Insert Edge Preparations ............ 36
    2.1.4 Tool Forces – Orthogonal and Oblique ............... 39
    2.1.5 Plan Approach Angles ........................ 41
    2.1.6 Cutting Toolholder/Insert Selection .......... 43

2.2 History of Machine Tool Development and Some Pioneers in Metal Cutting .......... 50
    2.2.1 Concise Historical Perspective of the Development of Machine Tools .......... 50
    2.2.2 Pioneering Work in Metal Cutting – a Brief Resumé .......... 51

3 Drilling and Associated Technologies .......... 87
  3.1 Drilling Technology ............................... 88
    3.1.1 Introduction to the Twist Drill’s Development .......... 88
    3.1.2 Twist Drill Fundamentals .................. 88
    3.1.3 The Dynamics of Twist Drilling Holes .......... 96
    3.1.4 Indexable Drills ............................ 103
    3.1.5 Counter-Boring/Trepanning ................. 107
    3.1.6 Special-Purpose, or Customised Drilling and Multi-Spindle Drilling .......... 110
    3.1.7 Deep-Hole Drilling/Gun-Drilling .......... 113
    3.1.8 Double-Tube Ejector/Single-Tube System Drills .......... 115
Contents

3.1.9 Deep-Hole Drilling – Cutting Forces and Power ........ 117
3.2 Boring Tool Technology – Introduction 117
3.2.1 Single-Point Boring Tooling ........ 118
3.2.2 Boring Bar Selection of: Toolholders, Inserts and Cutting Parameters ........ 122
3.2.3 Multiple-Boring Tools ........ 124
3.2.4 Boring Bar Damping ........ 126
3.2.5 ‘Active-suppression’ of Vibrations ........ 127
3.2.6 Hard-part Machining, Using Boring Bars ........ 128
3.3 Reaming Technology – Introduction ........ 133
3.3.1 Reaming – Correction of Hole’s Roundness Profiles ........ 135
3.3.2 Radially-Adjustable Machine Reamers ........ 139
3.3.3 Reaming – Problems and Their Remedies ........ 142
3.4 Other Hole-Modification Processes ........ 142

4 Milling Cutters and Associated Technologies ........ 149
4.1 Milling – an Introduction ........ 150
4.1.1 Basic Milling Operations ........ 151
4.1.2 Milling Cutter Geometry – Insert Axial and Radial Rake Angles ........ 155
4.1.3 Milling Cutter – Approach Angles ........ 158
4.1.4 Face-Milling Engagement – Angles and Insert Density ........ 160
4.1.5 Peripheral Milling Cutter Approach Angles – Their Affect on Chip Thickness ........ 163
4.1.6 Spindle Camber/Tilt – when Face-Milling ........ 166
4.2 Pocketing, Closed-Angle Faces, Thin-Walled and Thin-Based Milling Strategies ........ 169
4.3 Rotary and Frustum-Based Milling Cutters – Design and Operation ........ 172
4.4 Customised Milling Cutter Tooling ........ 177
4.5 Mill/Turn Operations ........ 177

5 Threading Technologies ........ 181
5.1 Threads ........ 182
5.2 Hand and Machine Taps ........ 182
5.3 Fluteless Taps ........ 189

6 Modular Tooling and Tool Management ........ 211
6.1 Modular Quick-Change Tooling ........ 212
6.2 Tooling Requirements for Turning Centres ........ 216
6.3 Machining and Turning Centre Modular Quick-Change Tooling ........ 221
6.4 Balanced Modular Tooling – for High Rotational Speeds ........ 230
6.5 Tool Management ........ 233
6.5.1 The Tool Management Infrastructure ........ 238
6.5.2 Creating a Tool Management and Document Database ........ 240
6.5.3 Overall Benefits of a Tool Management System ........ 244
6.5.4 Tool Presetting Equipment and Techniques for Measuring Tools ........ 245
6.5.5 Tool Store and its Presetting Facility – a Typical System ........ 261
6.5.6 Computerised-Tool Management – a Practical Case for ‘Stand-alone’ Machine Tools ........ 264

7 Machinability and Surface Integrity ........ 269
7.1 Machinability ........ 270
7.1.1 Design of Machinability Tests and Experimental Testing Programmes ........ 270
7.2 Machined Roundness ........ 285
7.2.1 Turned Roundness – Harmonics and Geometrics ........ 291
7.3 Chatter in Machining Operations ........ 294
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6.4</td>
<td>Artefact Stereometry: for Dynamic Machine Tool Comparative Assessments</td>
<td>486</td>
</tr>
<tr>
<td>9.7</td>
<td>HSM: Rotating Dynamometry</td>
<td>493</td>
</tr>
<tr>
<td>9.8</td>
<td>Complex Machining: of Sculptured Surfaces</td>
<td>496</td>
</tr>
<tr>
<td>9.8.1</td>
<td>Utilising the Correct Tool for Profiling: Roughing and Finishing</td>
<td>496</td>
</tr>
<tr>
<td>9.8.2</td>
<td>Die-Cavity Machining – Retained Stock</td>
<td>498</td>
</tr>
<tr>
<td>9.8.3</td>
<td>Sculptured Surface Machining – with NURBS</td>
<td>502</td>
</tr>
<tr>
<td>9.8.4</td>
<td>Sculptured Surface Machining – Cutter Simulation</td>
<td>505</td>
</tr>
<tr>
<td>9.9</td>
<td>Hard-Part Machining</td>
<td>507</td>
</tr>
<tr>
<td>9.9.1</td>
<td>Hard-Part Turning</td>
<td>508</td>
</tr>
<tr>
<td>9.9.2</td>
<td>Hard-Part Milling</td>
<td>511</td>
</tr>
<tr>
<td>9.10</td>
<td>Ultra-Precision Machining</td>
<td>516</td>
</tr>
<tr>
<td>9.10.1</td>
<td>Micro-Tooling</td>
<td>518</td>
</tr>
<tr>
<td>9.10.2</td>
<td>Micro-Machine Tools</td>
<td>525</td>
</tr>
<tr>
<td>9.10.3</td>
<td>Nano-Machining and Machine Tools</td>
<td>526</td>
</tr>
<tr>
<td>9.11</td>
<td>Machine Tool Monitoring Techniques</td>
<td>531</td>
</tr>
<tr>
<td>9.11.1</td>
<td>Cutting Tool Condition Monitoring</td>
<td>531</td>
</tr>
<tr>
<td>9.11.2</td>
<td>Adaptive Control and Machine Tool Optimisation</td>
<td>535</td>
</tr>
<tr>
<td>9.11.3</td>
<td>Artificial Intelligence: AI and Neural Network Integration</td>
<td>538</td>
</tr>
<tr>
<td>9.11.4</td>
<td>Tool Monitoring Techniques – a ‘Case-Study’</td>
<td>538</td>
</tr>
<tr>
<td>Appendix</td>
<td></td>
<td>549</td>
</tr>
<tr>
<td>About the Author</td>
<td></td>
<td>587</td>
</tr>
<tr>
<td>Subject Index</td>
<td></td>
<td>589</td>
</tr>
</tbody>
</table>
Cutting Tool Materials

‘What is the use of a book’, thought Alice, ‘without pictures or conversations?’

LEWIS CARROLL

(1832–1898)
[Alice in Wonderland, Chap. 1]
1.1 Cutting Technology – an Introduction

Previously, many of the unenlightened manufacturing companies, having purchased an expensive and sophisticated new machine tool, considered cutting tool technology as very much an afterthought and supplied little financial support, or technical expertise to purchase these tools. Today, tooling-related technologies are treated extremely seriously, as it is here that optimum production output, consistency of machined product and value-added activities are realised. Often companies feel that to increase productivity – to offset the high capital investment in the plant and to amortise such costs (i.e. pay-back), is the most advantageous way forward. This strategy can create ‘bottlenecks’ and disrupt the harmonious flow of production at later stages within the manufacturing environment. Another approach might be to maximise the number of components per hour, or alternatively, drive down costs at the expense of shorter tool life, which would increase the non-productive idle time for the production set-up. Here, the prime tooling factor should not be for just a marginal increase in productivity and efficiency, nor the perfection of any particular operation. If ‘bottlenecks’ in component production occur, they can readily be established by piles of machined parts sitting on the shop floor awaiting further value-added activities to be undertaken. These ‘line-balance’ production problems need to be addressed by achieving improved productivity across the whole operation, perhaps by the introduction of a Taguchi-type component flow analysis system within the manufacturing facility. The well-known phrase that: ‘No machine is an island’ (i.e. for part production) and that manufacturing should be thought of as ‘One big harmonious machine’ and not a lot of independent problems, will create a means by which increases in productivity can be achieved.

The cutting tool problems, such as: too wide a range of tooling inventory, inappropriate tools/out-dated tooling, or not enough tools for the overall operational requirements for a specific manufacturing environment, can be initially addressed by employing the following tooling-related philosophy – having recently undertaken a survey of the current status of tooling within the whole company:

- Rationalisation
- Consolidation
- Optimisation

NB These three essential tool-related factors in establishing the optimum tooling requirements for the current production needs, will be briefly reviewed.

1.1.1 Rationalisation

In order to be able to rationalise the tools within the current production facility, it is essential to conduct a thorough appraisal of all the tools and associated equipment with the company. This tooling exercise will be both time-consuming and costly, because it necessitates a considerable manpower resource and needs a means of identifying all the tools and inserts currently utilised, in some logical and tabulated manner. Such surveys are often best conducted by utilising a primitive but efficient tool-card indexing system in the first instance. Details, such as: tool type and its tooling manufacturer, quantity of tools in use and the current levels of stock in the tool store, their current location(s), feeds and speeds utilised, together with any other relevant tool-related details are indexed on such cards. Once these tooling facts have been established, then they can be loaded into either a computerized tool management system database, or recorded onto an uncomplicated tooling database for later interrogation.

Having established the current status of the tooling within the manufacturing facility, this allows for a tooling rationalisation campaign to be developed. Tool rationalisation (Fig. 1) consists of looking at the results of the previous tooling survey and significantly reducing the number of tooling suppliers for particular types of tools and inserts. This initial rationalisation policy has the twin benefits of minimising tooling suppliers with their distinct varieties of tools, while enabling bulk purchase of such tools from the remaining suppliers, at preferential financial rates of purchase. Moreover, by using less tooling companies whilst purchasing bulk stock, this has the bonus of making you one of their prime customers with their undivided at-
Figure 1. Rationalisation of cutting inserts, can have a dramatic effect on reducing the tooling and workholding inventory. [Courtesy of Sandvik Coromant]
tention, should the need for later ‘tool problem-solving’ of manufacturing clichés in production occur.

1.1.2 Consolidation

For any tooling that remains after the rationalisation exercise, these should be consolidated, by reducing the number of insert grades, by at least half – which often proves to have little effect on production capability. By grouping inserts by their respective sizes, shapes and say, nose radius for example, this will eliminate many of the less-utilised inserts, enabling the potential for bulk purchase from the tooling supplier, with an attendant reduction in tool costs. From this consolidation activity, it may now be possible to purchase higher-performance grade cutting inserts, that meet a wider application range, enabling the consolidation to be even more effective. Furthermore, such improved inserts, will probably have a longer tool life and can be utilised at higher speeds, which probably negates their extra cost, over the previously used inserts. If fewer grades of insert are stocked, the tooling/application engineers will be acquainted with them much more thoroughly and this will result in a added effectiveness and a consistent application, for the production of machined components – more will be said on this latter point in the next section on Optimisation.

1.1.3 Optimisation

By consolidating the tooling, it allows productivity to be boosted by optimisation of the cutting insert grades. For example, in turning operations, the depth of cut can probably maximised and, as a result, the number of passes along, or across the part can be minimised. It can be argued that increasing the depth of cut leads to a reduction in the subsequent tool life (in terms of parts per edge). However, there are fewer cuts per part, so each machined workpiece requires less overall cutting and as a result, many more parts per edge can be produced. More important, are that the cycle times for roughing operations be reduced: a reduction in the number of roughing passes from three to one, results in a 66% reduction in the cycle time. This increase in productivity may justify any potential decrease in tool life, on the basis that it could reduce, or eliminate a potential ‘bottleneck’ in latter production processes of the part’s manufacture. To extract the maximum productivity from today’s high-performance grades, they must be worked hard and pushed to their fullest capabilities.

When tool life is reduced by increasing the depth of cut, there are several ways that a such loss can be minimised. For example, it is known that the size of the insert’s nose radius has a pronounced effect on tool life, so by doubling the depth of cut this can, in the main, allow for a larger nose radius – assuming that the component feature allows access. If an increase in nose radius cannot be utilised, then increasing the insert’s size will help to offset any higher wear rates, by providing a better heat dissipation for the action of cutting.

The accepted turning practice when roughing-out, is that no more than half the insert’s cutting edge length should be utilised, because as the depth of cut approaches this value, a larger insert is recommended. Where large depths of cut are used in combination with high feedrates, a roughing grade insert geometry promotes longer tool life, than a general-purpose insert. Often, by using a single-sided insert rather than a double-sided one for roughing cuts, this has the twin benefits of increased productivity and longer tool life (in terms of machined parts per edge). Normally, single-sided inserts are recommended whenever the depth of cut and feedrate are so high that the surface speed must be reduced below the grade’s normal range, in order to maintain an adequate tool life. Such inserts should be considered if erratic insert breakage occurs.

Later to be discussed in the chapter on Machinability and Surface Integrity, is the fact that the highest temperature region on the tool’s rake face is not at the cutting edge; but in the vicinity on the chip/tool interface where chip curling occurs – this is some distance back and where the crater is formed. The position for this highest isothermal region can vary, depending upon the feedrate. For example, if the feedrate is increased, the highest temperature zone on the insert’s face will move away from the cutting edge; conversely, if the feedrate is now reduced, this region moves toward the cutting edge. This phemonena means that if the feedrate is too low for the chosen insert geometry and edge preparation, heat will be concentrated too near the cutting edge and insert wear will be accelerated. Thus, by increasing the feedrate, it has the affect of moving the maximum heat zone away from the insert’s edge and is so doing, extends tool life – in terms of minutes of actual cut-time per edge. As a result, each machined part will be produced in less time and at higher feeds, so the tool life in terms of parts per edge will also increase.
As a result of the inappropriate use of cutting data, such as incorrect feedrates employed for the chosen insert geometry, this can produce a number of undesirable symptoms. These symptomatic problems include: extremely shortened tool life, edge chipping and insert breakage are likely if feedrates are too high, whereas if feeds are too low, chip control becomes a problem. Once the insert grades have been consolidated with their associated geometries, it is relatively easy to determine the feedrates for a selected grade of workpiece materials. Tooling suppliers can recommend a potential insert grade for particular component part material, with an initial selection of insert grade, such surface speeds being indicated in the Appendix. These inserts can be optimised by ‘juggling’ the grades and geometries marginally around the specified values, this may allow feedrates to be increased and should provide a significant pay-off in terms of improved productivity, at little, or no additional capital expenditure.

If the cutting speed is increased rather than the feed, a point is reached where any increase in surface speed will result in a decrease in productivity. In other words, cutting too fast will mean spending more time changing tools than making parts! Equally, by cutting too slowly, the tool will last much longer, but this is at the expense of the number of machined parts produced per shift. If these statements are correct, what is the ‘right’ surface speed? This question will now be discussed more fully.

If we return to the theme previously mentioned, namely: ‘No machine is an island’ and treat the production shop as: ‘One big machine’, it can be stated that every shop should determine its own particular manufacturing objectives – when considering both cutting speeds and tool life. Typical objectives for tool life might be the completion of a certain number of parts before indexing the insert, or adopting a ‘sister tool’; or alternatively, insert indexing after one/part of a shift. If very expensive components are being machined, the main goal is to avoid catastrophic insert failure, which on a finishing cut, would probably result in scrapping the part. When exceedingly large parts are to be machined, the objective may simply be to complete just one part per insert, or in an even more extreme situation, just one pass over the part. When small parts are being produced, then the tool life can be controlled in order to minimise dimensional size variation with in-cut time. This strategy of tool life control, reduces the need for frequent adjustment of tool offset compensations in the CNC controller. However, one idea shared by all of these strategic production approaches, is that by optimising the surface speed, the manufacturing objectives will be realised. As a consequence of this approach to production, there is no correct surface speed for any specific combination of material and insert grade, the optimum surface speed depends upon the company’s manufacturing requirements at this time.

When long production runs occur, these are ideal because it allows cutting data experimentation to discover the optimum speed for a particular production cycle. Sometimes it is not possible to find the speed to exactly meet the production demands and, a change of insert grades, to one of the higher-technology materials may be in order. If short production runs are necessary, this can often rule out any experimentation with insert grades, but by consultation with a ‘cutting tool expert’, or reference to the published cutting literature the answer may be found to the problem of insert optimisation. However a cautionary note, care must be taken when utilising published recommendations, as they should only be employed as guidelines, to help initiate the job into production.

Comparison with a known starting point within the recommended range for specific production conditions, namely for: large depths of cut, high feedrates, very long continuous cuts, significant interrupted cuts, workpiece surface scale and the absence of coolant, would all suggest that reductions in surface speed should be initially considered. Conversely, production conditions that result in: short lengths of cut, shallow depths of cut, low feedrates, smooth uninterrupted cuts, clean pre-turned, or bright-drawn wrought workpiece materials and flood coolant, having a very rigid setup, suggests that the recommended ranges for the insert could be exceeded, while still maintaining an acceptable tool life.

It should be remembered that the main requirement is for an overall increase in production output and not perfection. After the analysis, when the tooling inventory has been consolidated, there will be fewer and

---

2 ‘Sister tooling’ is the term that refers to a duplicate tool (i.e. having the same tool offsets) held in the turret/magazine and can be automatically indexed to this tool, to minimise down-time when changing tools. Such a ‘sister tool’, can be pre-programmed into the CNC controller of the machine tool, to either change after a certain number of parts has been produced, or if the tool life has been calculated, then when the feed function on the CNC has decremented down to this preset value, then the ‘sister tool’ is selected.
more versatile insert grades and geometries that need to be considered. This smaller insert inventory allows a detailed appreciation of how to optimise the speeds and feeds in combination with depths of cut more effectively, for the desired production objectives. By optimisation here of the machining parameters, this allows full utilisation of the capital equipment, with the result that large improvements in overall manufacturing efficiency can be expected.

It is evident from this discussion concerning optimisation, that the parameters of: tool life, feedrate and cutting speed form a complex relationship, which is illustrated in Fig. 2a. Consequently, if you change one parameter, it will affect the others, so a compromise has to be reached to obtain the optimum performance from a cutting tool. Preferably, the *ideal* cutting tool should have superior performance if five distinct areas (see Fig. 2b):

- **Hot hardness** – is necessary in order to maintain sharp and consistent cutting edge at the elevated temperatures that are present when machining.

  NB If the hot hardness of the tooling is not sufficient for the temperature generated at the tool’s tip, then it will degrade quickly and be useless.

- **Resistance to thermal shock** – this is necessary in order to overcome the effects of the continuous cycle of heating and cooling that is typical in a milling operation, or when an intermittent cutting operation occurs on a lathe (e.g. an eccentric turning operation).

  NB If this thermal shock resistance is too low, then rapid wear rates can be expected, typified in the past, by ‘comb cracks’ on High-speed steel (HSS) milling cutters.

- **Lack of affinity** – this condition should be present between the tool and the workpiece, since any degree of affinity will lead to the formation of a built-up edge (BUE) – see the chapter on Machinability and Surface Integrity.

  NB This BUE will modify the tool geometry, leading to poorer chip-breaking ability, with higher forces generated, leading to degraded workpiece surface finish. Ideally, the cutting edge should be *inert* to any reaction with the workpiece.
1.2 The Evolution of Cutting Tool Materials

1.2.1 Plain Carbon Steels

Prior to 1870, all turning tooling materials were produced from plain carbon steels, with a typical composition of 1% carbon and 0.2% manganese – the remainder being iron. Such a tool steel composition meant that it had a low ‘hot-hardness’ (i.e., its ability to retain a cutting edge at elevated temperatures), as such, the cutting edge broke down at temperatures approaching 250°C, this in reality kept cutting speeds to approximately 5 m-min⁻¹. These early cutting tools frequently had quench cracks present which severely weakened the cutting edge, as a result of water hardening at quenching rates greater than 1000°C/second (i.e., necessary to exceed the critical cooling velocity – to fully harden the steel), upon manufacture. By 1870, Mushet (working in England), had introduced a more complex steel composition, containing: 2% carbon, 1.6% manganese, 5.5% Tungsten and 0.4% chromium, with the remainder being iron. The advantage of this newly developed steel was that it could be air-hardened, this was a significantly less drastic quench than using a water quenchant. Mushet’s steel had greater ‘hot-hardness’ and could be utilised at cutting speeds up to 8 m-min⁻¹. This turning tool material composition, was retained until around 1900, but with the level of chromium gradually superseding that of manganese.

1.2.2 High-Speed Steels

Around the turn of the century in the United States, fundamental metallurgical work was being undertaken by F.W. Taylor and his associate M. White and by 1901, these researchers had greatly improved the overall tool steel and slightly modifying its composition with a material that was to be known as High-speed steel (HSS), enabling cutting speeds to approach 19 m-min⁻¹. High-speed steel was not a new material, but basically an innovative heat treatment procedure. The typical metallurgical composition of HSS was: 1.9% carbon, 0.3% manganese, 8% tungsten, and 3.8% chromium, with iron the remainder. Taylor and White’s tool steel mainly differed from that of Mushet’s by an increased amount of tungsten and a further replacement of manganese by chromium. By 1904, the content of carbon had been reduced, allowing for more ease in forging this HSS. Further rapid development of the HSS occurred over the next ten years, with tungsten content increased to improve its ‘hot-hardness’. Around this time, Dr J.A. Matthews found that vanadium additions had improved the material’s abrasion resistance. By 1910, the content of tungsten had increased to 18%, with 4% chromium and 1% vanadium, hence the well-known 18:4:1 HSS had arrived, its metallurgical composition continued with only marginal modifications over the next 40 years. Of the modifications to HSS during this time, of note was that in 1923 the so-called ‘super’ HSS was developed, although this variant did not become commercially viable until 1939, when Gill reduced the tungsten content to enable the tool steel
to be successfully hot-worked. Around 1950 in the United States, M2 HSS was introduced, having some of the tungsten content replaced by that of molybdenum. This gave the approximate M2 HSS metallurgical composition as: 0.8% C, 4% Cr, 2% V, 6% W and 5% Mo – Fe being the remainder. In this form, the M2 HSS could withstand machining temperatures of up to 650°C (ie the cutter glowing dull red) and still maintain a cutting edge.

In 1970, Powder Metallurgy (P/M) by metallurgical processing via hot isostatic pressing (HIP), was introduced for the production of HSS, with careful control of elemental particle size; afterward the sintered product is forged then hot-rolled. This HSS (HIP) processing gave a uniformly distributed elemental matrix, overcoming the potential segregation and resulting non-homogenous structure that would normally occur when ingot-style HSS forging. Such P/M processing techniques enable the steel-making company to ‘tailor’ and specify the exact metallurgical composition of alloying elements, this would allow the newly-developed sintered/forged HSS tooling to approach that of the performance of cemented carbides, in terms of inherent wear resistance, hardness and toughness. In Fig. 3, a comparison of just some of the tooling materials is highlighted, here, fracture toughness is plotted against hardness to indicate the range of influence of each tool material and the comparative relative merits of one material against another, with some of their physical and mechanical properties tabulated in Fig. 3b. A typical sintered micro-grained HSS of today, might contain: 13% W, 10% Co, 6% V, 4.75% Cr and 2.15% C – Fe the remainder. One reason for the ‘keen’ cutting edge that can be retained by sintered micro-grained HSS, is that during P/M processing the rapid atomisation of the particles produces extremely fine carbides of between 1 to 3 µm in diameter – which fully support the cutting edge, whereas HSS produced from an ingot, has carbides up to 40 µm in diameter. By way of illustration of the benefits of the latest micro-grained HSS – in the uncoated condition – when compared to its metallurgical competitor of cemented carbide, HSS has a bend, or universal tensile strength of between 2,500 to 6,000 MPa – this being dependent on metallurgical composition, whereas cemented carbide tooling has a bend strength of between 1,250 to 2,250 MPa. These metallurgical tool processing techniques have significantly improved sintered micro-grained HSS enabling for example, high-performance drilling, reaming and tapping to be realised.

Coating by either single-, or multiple-coating has been shown to significantly enhance any tooling material, but this is a complex subject and more will be said on this subject shortly.

1.2.3 Cemented Carbide

Possibly the widest utilised cutting tool materials today are the cemented carbide family of tooling, of which the group derived from tungsten carbide is most readily employed. Prior to discussing the physical metallurgy and expected mechanical/physical characteristics of cemented carbides, it is worth looking into the complex task of insert selection.

In Fig. 4, just a small range of the material types, grades, shapes of inserts and coatings by a leading cutting tool company is depicted. Highlighting the complex chip-breaker geometries, necessary to both develop and break chips and evacuate them efficiently from the workpiece’s surface region. To give a simplified impression of just some of the tooling insert variations and permutations available from a typical tooling manufacturer, if 10 insert grades are listed, in 6 different shapes, with 12 differing chip breakers and five nose radii in the tooling catalogue, this equates to $10 \times 6 \times 12 \times 5$, or 3,600 inserts. In reality, there are a number of other important features that could extend this cutting insert permutation to well over five significant figures – for potential insert selection. When the permuted insert number reaches this level of complexity, selecting the optimum combination of insert characteristics becomes more a matter of luck than skill.

Tungsten (synonym Wolfram, hence the chemical symbol W), is the heaviest metal in the group VIB in Mendeleev’s Period Chart (i.e. atomic number 74). It was named after the German word wolfram – from the mineral wolframite – as it was derived from the term wolf rahm, because the ore was said to interfere with tin smelting – supposedly devouring the tin. Whereas the term tungsten, was coined from the Swedish tungsten, meaning heavy stone. Hence, in 1923, the German inventor K. Schröter produced the first metal matrix composite, known today as cemented carbides. In these first cemented carbides, Schröter combined tungsten monocarbide (WC) particles embedding them in a cobalt matrix – these particles acted as a very strong binder. Cemented carbide is a hard transition metal carbide ranging from 60% to 95% bonded to cobalt, this being a more ductile metal. The carbides vary, ranging from having hexagonal structures, to a solid solution of titanium, tantalum and niobium carbides to that of a NaCl structure. Tungsten carbide does not dissolve
any transition metals, but it can melt those carbides found in solid solution. Powder metallurgy processing route – liquid-phase sintering – is utilised to produce cemented carbides, as melting only occurs at very high temperatures and there is a means of reducing tungsten powder using hydrogen from chemically purified ore. Ore reduction can be achieved by the manipulation of the processing conditions, enabling the grain size to be controlled/modified as necessary. The uniform grain sizes of tungsten carbide today can range

(a) Cutting tool material comparisons:

(b) Material Characteristics:

<table>
<thead>
<tr>
<th>Hard Materials</th>
<th>Hardness (HV)</th>
<th>Energy Formation (kcal/g · atom)</th>
<th>Solubility in Iron (% at 1250°C)</th>
<th>Thermal Conductivity (W/m·K)</th>
<th>Thermal Expansion (× 10⁻⁶/k)</th>
<th>Tool Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>&gt; 9,000</td>
<td>–</td>
<td>Highly Soluble</td>
<td>2,100</td>
<td>3.1</td>
<td>Sintered Diamond</td>
</tr>
<tr>
<td>CBN</td>
<td>&gt; 4,500</td>
<td>–</td>
<td>–</td>
<td>1,300</td>
<td>4.7</td>
<td>Sintered CBN</td>
</tr>
<tr>
<td>Si₃N₄</td>
<td>1,600</td>
<td>–</td>
<td>–</td>
<td>100</td>
<td>3.4</td>
<td>Ceramics</td>
</tr>
</tbody>
</table>

Figure 3. Cutting tool materials – toughness versus hardness – and their typical material characteristics. [Courtesy of Mitsubishi Carbide]
from 0.2 to 7 µm – enabling a final sintered product to be carefully controlled. Moreover, by additions of fine cobalt at a further processing stage, then wet milling the constituents, allows for precise and uniform control of the grain size – producing a fine powder. Prior to sintering, the milled powder can be spray-dried giving a free-flowing spherical powder aggregate, with the addition of lubricant to aid in its consolidation (i.e. pressing into a ‘green compact’). Sintering normally occurs at temperatures of 1500°C in a vacuum, which reduces the porosity from about 50% that is in the ‘green state’, to less than 0.01% porosity by volume in the final cutting insert condition. The low level of porosity in the final product is the result of ‘wetting’ by the liquid present upon sintering. The extent of this ‘wetting’ during liquid-phase sintering, being dependent upon molten binder metal dissolving to produce a pore-free cutting insert, this has excellent cohesion between the binder and the hard particles (see Fig. 5, for typical cemented carbide powders and resulting microstructures). It should be stated that most of the ‘iron-group’ of metals can be ‘wetted’ by tungsten carbide, forming sintered cemented carbide with excellent mechanical integrity.

Figure 4. Cutting inserts indicating the diverse range of: shapes, sizes and geometries available, with compositions varying from: cemented carbide, ceramics, cermets, to cubic boron nitride derivatives. [Courtesy of Sandvik Coromant]
(a) Cemented carbide is a product of the mixing, lubrication, consolidation and sintering of powders, to produce a powder metallurgical (P/M) compact.

(b) Cemented carbide metallurgical structures:

- **α and β content coarse grain:** (ISO=K20)
- **α and β content fine grain:** (ISO=K10)
- **α, β and γ content large amount of binder:** (ISO=P40)
- **α, β and γ content small amount of binder:** (ISO=P10)

*Figure 5.* Cemented carbide powders and typical microstructures after sintering. [Courtesy of Sandvik Coromant]
The desirable properties that enable tungsten carbide to be tough and readily sintered, also cause it to easily dissolve in the iron, producing the so-called ‘straight’ cemented carbide grades. These ‘straight’ grades normally contain just cobalt and have been used to predominantly machine cast iron, as the chips easily fracture and do not usually remain in contact with the insert, reducing the likelihood of dissolution wear. Conversely, machining steel components, requires alternative carbides such as tantalum, or titanium carbides, as these are less soluble in the heated steel at the cutting interface. Even these ‘mixed’ cemented carbide grades will produce a tendency to dissolution of the tool material in the chip, which can limit high speed machining operations. Today, the dissolution tool material can be overcome, by using cutting insert grades based on either titanium carbide, or nitride, together with a cobalt alloy binder. Such grades can be utilised for milling and turning operations at moderate cutting speeds, although their reduced toughness, can upon the application of high feed rates, induce greater plastic deformation of the cutting edge and induce higher tool stresses. These uncoated cutting inserts were very much the product of the past and today, virtually all such tooling inserts are multi-coated to significantly extend the cutting edge’s life – more will be said on such coating technology later.

1.2.4 Classification of Cemented Carbide Tool Grades

Most cemented carbide insert selection guides group insert grades by the materials they are designed to cut. The international standard for over 30 years used for carbide cutting of workpiece materials is: ISO 513-1975E Classification of Carbides According to Use\(^3\) – which has a colour-coding for ease of identification of sub-groups. In its original form, this ISO 513 code utilises 3 broad letter-and colour classifications (see Fig. 6 for the tabulated groupings of carbides and their various colours, designations and applications):

- **P (blue)** – highly alloyed workpiece grades for cutting long-chipping steels and malleable irons,
- **M (yellow)** – lesser alloyed grades for cutting ferrous metals with long, or short chips, cast irons and non-ferrous metals,
- **K (red)** – is ‘conventional’ tungsten carbide grades for short-chipping grey cast irons, non-ferrous metals and non-metallic materials.

Under this previous ISO system (Fig. 6), both steels and cast irons can be found in more than one category, based upon their chip-formation characteristics. Each grade within the classification is given a number to designate its relative position in a continuum, ranging from maximum hardness to maximum toughness. This original ISO 513 Standard, has been modified over the years by many tooling manufacturers, introducing more discretion in their selection and usage. Typical of this manufacturer’s modified approach, is that found by just one American tooling company, forming a simple colour-coding matrix, such as the three designated manufacturer’s chip-breaker grades (such as: F, M and R) and three workpiece material grades (i.e. Steel, Stainless steel and Cast iron) – producing a nine-cell grid. While another manufacturer in Europe, has produced a more discriminating matrix, based upon adding the ‘machining difficulty’ into the matrix, producing a 3 × 3 × 3 matrix – producing a twenty seven cell grid. In this instance, the tooling manufacturer uses the workpiece material to determine the tool material needed. The insert geometry is still selected according to the type of machining operation to be undertaken, while the insert grade is determined by the application conditions – whether such factors as interrupted cuts occur, forging scale on the part are present and the desired machining speed being designated as: good, average, or difficult.

**NB** These manufacturer’s matrices for the tooling insert selection process will get a user to approximately 90% of optimum, with the ‘fine-tuning’ (optimisation) requiring both technical appreciation of information from the manufacturer’s tooling catalogue/recommendations from ‘trouble-shooting guides’ and any previous ‘know-how’ from past experiences – as necessary.

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\(^3\) The workpiece categories are arranged according to their relative chip production characteristics and certain metallurgical characteristics, such as casting condition, hardness and tensile strength. ISO 1832–1991 has designations: ‘P’ (Steels, low-alloy); ‘M’ (Stainless steels); ‘K’ (Cast irons); ‘N’ (Aluminium alloys); ‘H’ (Hardened steels)
<table>
<thead>
<tr>
<th>Distinguishing colours</th>
<th>Designation</th>
<th>Material to be machined</th>
<th>Application</th>
<th>Direction of increase in characteristic</th>
<th>Of cut</th>
<th>Of carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLUE</td>
<td>P01</td>
<td>Steel, steel castings</td>
<td>Finish turning and boring; high cutting speeds, small chip section, accuracy of dimensions and fine finish, vibration-free operation</td>
<td>Increasing feed</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>P10</td>
<td>Steel, steel castings</td>
<td>Turning, copying, threading and milling, high cutting speeds, small or medium chip sections</td>
<td>Increasing feed</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>P20</td>
<td>Steel, steel castings</td>
<td>Turning, copying, milling, medium cutting speeds and chip sections</td>
<td>Increasing feed</td>
<td>↑</td>
<td>♣</td>
</tr>
<tr>
<td></td>
<td>P30</td>
<td>Steel, steel castings</td>
<td>Turning, milling, planing, medium or low cutting speeds, medium or large chip sections, and machining in unfavourable conditions</td>
<td>Increasing feed</td>
<td>♣</td>
<td>♣</td>
</tr>
<tr>
<td></td>
<td>P40</td>
<td>Steel, steel castings</td>
<td>Turning, planing, slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavourable conditions for operations requiring tough carbide; turning, planing, slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavourable conditions</td>
<td>Increasing feed</td>
<td>♣</td>
<td>♣</td>
</tr>
<tr>
<td></td>
<td>P50</td>
<td>Steel, steel castings</td>
<td>For operations demanding very tough carbide; turning, planing, slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavourable conditions</td>
<td>Increasing feed</td>
<td>♣</td>
<td>♣</td>
</tr>
<tr>
<td>MOTTED</td>
<td>M10</td>
<td>Steel, steel castings, manganese steel, grey cast iron</td>
<td>Turning, medium or high cutting speeds; small or medium chip sections</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>M20</td>
<td>Steel, steel castings, austenitic or manganese steel, grey cast iron</td>
<td>Turning, milling; medium cutting speeds and chip sections</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>M30</td>
<td>Steel, steel castings, austenitic steel, grey cast iron, high-temperature-resistant alloys</td>
<td>Turning, milling, planing; medium cutting speeds, medium or large chip sections</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>M40</td>
<td>Mild free-cutting steel, low tensile steel, Non-ferrous metals and light alloys</td>
<td>Turning, parting off</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td>RED</td>
<td>K01</td>
<td>Very hard grey cast iron, chilled castings of over 85 Shore, high silicon–aluminium alloys, hardened steel, highly abrasive plastics, hard cardboard, ceramics</td>
<td>Turning, finish-turning, boring, milling</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>K10</td>
<td>Grey cast iron over 220 Brinell, malleable cast iron with short chips, hardened steel, silicon–aluminium alloys, copper alloys, plastics, glass, hard rubber, hard cardboard</td>
<td>Turning, milling, drilling, boring, broaching</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>K20</td>
<td>Grey cast iron up to 220 Brinell, non-ferrous metals (copper, brass, aluminium)</td>
<td>Turning, milling, planing, boring, broaching, demanding very tough carbide</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>K30</td>
<td>Low-hardness grey cast iron, low tensile steel, compressed wood</td>
<td>Turning, milling, planing, slotting, for machining in unfavourable conditions and with the possibility of large cutting angles</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
<tr>
<td></td>
<td>K40</td>
<td>Soft wood or hard wood, Non-ferrous metals</td>
<td>Turning, milling, planing, slotting, for machining in unfavourable conditions and with the possibility of large cutting angles</td>
<td>Increasing speed</td>
<td>←</td>
<td>↑</td>
</tr>
</tbody>
</table>

When applying coated inserts it must be borne in mind that these are basically intended for turning operations, and will in many cases be multi-purpose covering a number of groups and sub-groups.
1.2.5 Tool Coatings: Chemical Vapour Deposition (CVD)

Rather quaintly, the idea of introducing a very thin coating onto a cemented carbide cutting tool originated with the Swiss Watch Research Institute, using the chemical vapour deposition (CVD) technique. In the 1960’s, these first hard coatings were applied to cemented carbide tooling and were titanium carbide (TiC) by the CVD process (Fig. 7 shows a schematic view of the CVD process) at temperatures in the range 950 to 1050°C. Essentially, the coating technique consists of a commercial CVD reactor (Fig. 8a) with cutting tools, or inserts to be hard-coated placed on trays (depicted in Fig. 8b).

Prior to coating the tooling situated on their respective trays, these tools should have a good surface finish and sharp corners should have small honed edges – normally approximately 0.1 mm. With the CVD technique, if these honed tool cutting edges are too large, they will not adequately support the coating, but if they are even greater, the cutting edge will be dulled and as a result will not cut efficiently. These tooling trays (Fig 8b) are accurately positioned one above another, being pre-coated with graphite and are then loaded onto a central gas distribution column (i.e tree). The ‘tree’ now loaded with tooling to be coated is placed inside a retort of the reactor (Fig. 8a). This contained tooling within the reactor, is heated in an inert atmosphere until the coating temperature is reached and the coating cycle is initiated by the introduction of titanium tetrachloride (TiCl₄) together with methane (CH₄) into the reactor. The TiCl₄ is a cloud of volatile vapour and is transported into the reactor via a hydrogen carrier gas (H₂), whereas CH₄ is introduced directly. This volatile cloud reacts on the hot tooling surfaces and the chemical reaction in say, forming a TiC as a surface coating, is:

\[ \text{TiCl}_4 + \text{CH}_4 \rightarrow \text{TiC} + 4\text{HCl} \]

The HCl gas is a bi-product of the process and is discharged from the reactor onto a ‘scrubber’, where it is neutralised. When titanium is to be coated onto the tooling, then the previously used methane is substituted by a nitrogen/hydrogen gas mixture.

For example, if a simple multi-coated charge is required for the tooling, it is completed in the same cycle, by firstly depositing TiC using methane and then depositing TiN utilising a nitrogen/hydrogen gas mixture. As the TiN and TiC are deposited onto the tooling, they nucleate and grow on the carbides present in the exposed surface regions, with the whole CVD coating process taking approximately 14 hours, consisting of 3 hours for heating up, 4 hours for coating and 7 hours for cooling. The thickness of the CVD coating is a function of the reaction concentration, this being the subject of various gaseous constituents and their respective flow rates, coating temperature and the soaking time at this temperature. The CVD process is undertaken in a vacuum together with a protective atmosphere, in order to minimise oxidation of the deposited coatings. However it should be noted that, in the case of high-speed steel (HSS) tooling such as when coating small drills and taps, the elevated coating temperatures employed, necessitate post-coating hardening heat treatment.

1.2.6 Diamond-Like CVD Coatings

Crystalline diamond is only grown by the CVD process on solid carbide tools, because of the high temperatures involved in the process, typical diamond coating temperatures are in the region of 810°C. Such diamond-like tool coatings (Fig. 9), make them extremely useful when machining a range of non-ferrous/non-metallic workpiece materials such as: aluminium-silicon alloys, metal-matrix composites (MMC’s), carbon composites and fibre-reinforced plastics. Although such workpiece materials are lightweight, they have hard, abrasive particles present to give added mechanical strength, the disadvantage of such non-metallic/metallic inclusions in the workpiece’s substrate are that

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[4] Graphite shelves are most commonly employed, as it is quite inexpensive compared to either stainless steel, or nickel-based shelving, with an added benefit of good compressive strength at high temperature.

[5] Some limitations in the CVD process are that residual tensile stresses of coatings can concentrate around sharp edges, possibly causing coatings to crack in this vicinity – if edges are not sufficiently honed – prior to coating. Additionally, the elevated temperatures cause carbon atoms to migrate (diffuse) from the substrate material and bond with the titanium. Hence, this substrate carbon deficiency – called ‘eta-phase’ is very brittle and may cause tool failure, particularly in interrupted-cut operations.
PVD PROCESSING CAN APPLY COATINGS TO A RANGE OF TOOLS FROM MINUTE INDEXABLE CUTTING INSERTS, TO LARGE TOOLING SUCH AS THIS GEAR-CUTTING HOB AND ENORMOUS BROACHES. HERE, BOTH TOOLS HAVE BEEN TIN-COATED: [Courtesy of Multiarc Oberflächentechnik GmbH]

DETAIL OF A TOOL’S FRACTURE SURFACE, HAVING AN TiAlN-COATING (PVD) - OFTEN UTILISED FOR HIGH-SPEED MACHINING, AS THE ELEMENTAL ADDITIONS OF ALUMINIUM SIGNIFICANTLY INCREASES RESISTANCE TO OXIDATION: [Courtesy of Multiarc Oberflächentechnik GmbH]

Chemical Vapour Deposition (CVD)
Physical Vapour Deposition (PVD)

Figure 7. A PVD-coating, with coated tooling, plus a schematic representation of the CVD and PVD coating processes. [Courtesy of Sandvik Coromant]
(a) Modern cutting tool / insert coating plant for efficient processing of tooling.

(b) A tray of sintered cutting inserts, prior to being vertically stacked-up in volume ready for coating.
they become extremely difficult to machine with ‘conventional tooling’ and are a primary cause of heat generation and premature face/edge wear. Here, the high tool wear is attributable to both the abrasiveness of the hard particles present and chemical wear promoted by corrosive acids created from the extreme friction and heat generated during machining.

Such diamond-coated tooling is expensive to purchase, but these coatings can greatly extend the tool life by up to 20 times, over uncoated tooling, when machining non-metallic and certain plastics, this more than compensates for the additional cost premium. Such diamond-like coated tools, combine the (almost) high hardness of natural diamond, with the strength and relative fracture toughness of carbide.

The extreme hardness of diamond-like coatings enable the effective machining of non-ferrous/non-metallic materials and, by way of an example of their respective hardness when compared to that of a PVD titanium aluminium nitride coated tool, they are three times as hard (see Fig. 3a). Although, these diamond-like coatings do not have the hardness properties of crystalline diamond, they are approximately half their micro-hardness value. Diamond-like coatings can range from 3 to 30 µm in thickness (see Fig. 9 – bottom), with the individual crystal morphology present measures between 1 to 5 µm in size (Fig. 9 – top).

Recently, a diamond-coating crystal structure called ‘nanocrystalline’ has been produced by a specialised CVD process. The morphology has diamond crystals measuring between 0.01 to 0.2 µm (i.e. 10 to 200 nanometres), with a much finer grain structure and smoother surface to that of ‘conventional’ diamond-like coatings. This smoother ‘nanocrystalline’ surface morphology presents less opportunity for workpiece material built-up edge (BUE) at the tool/chip interface, significantly improving both the chip-flow across the rake face of the tool and simultaneously giving a better surface finish to the machined component.

**1.2.7 Tool Coatings: Physical Vapour Deposition (PVD)**

In 1985 the main short-comings resulting from the CVD process were overcome by the introduction of the physical vapour deposition process (Fig. 7), when the first single-layer TiN coatings were applied to cemented carbide. There are several differences between PVD and CVD coating processes and their resulting coatings. Firstly, the PVD process occurs at low-to-medium temperatures (250 to 750°C), as a result of lower PVD temperatures found than by the CVD process, no eta-phase forms. Secondly, the PVD technique is a line-of-sight process, by which atoms travel from their metallic source to the substrate on a straight path. By contrast, in the CVD process, this creates an omni-directional coating process, giving a uniform thickness, but with the PVD technique the fact that a coating may be thicker on one side of a cutting insert than another, does not affect its cutting performance. Thirdly, the unwanted tensile stresses potentially present at sharp corners in the CVD coated tooling, are compressive in nature by the PVD technique. Compressive stresses retard the formation and propagation of cracks in the coating at these corner regions, allowing tooling geometry to have the pre-honing operation eliminated. Fourthly, the PVD process is a clean and pollution-free technique, unlike CVD coating methods, where waste products such as hydrochloric acid must be disposed of safely afterward.

In general, there have been many differing PVD coating techniques that have been utilised in the past to coat tooling, briefly some of these are:

- **Reactive sputtering** – being the oldest PVD coating method, it utilises a high voltage which is positioned between the tooling to be coated (anode) and say, a titanium target (cathode). This target is bombarded with an inert gas – generally argon – which frees the titanium ions, allowing them to react with the nitrogen, forming a coating of TiN on the tools. The positively-charged anode (i.e. tools) will attract the TiN to the tool’s surface – hence the coating will grow.

- **Reactive ion plating** – relies upon say, titanium ionisation using an electron beam to meet the target, which forms a molten pool of titanium. This titanium pool then vaporises and reacts with the nitrogen and an electrical potential accelerates toward the tooling to subsequently coat it to the desired thickness.

- **Arc evaporation** – utilises a controlled arc which vaporises say, the titanium source directly onto the inserts – from solid.
CUTTING INSERTS ARE AVAILABLE IN A WIDE RANGE OF: SHAPES, GEOMETRIES, COATINGS AND COMPOSITIONS:

Figure 9. A vast array of differing cutting inserts, together with diamond coated cemented carbide. [Courtesy of Sandvik Coromant]

COATING MORPHOLOGY & CROSS SECTION OF A DIAMOND-COATED INSERT.

Figure 9. A vast array of differing cutting inserts, together with diamond coated cemented carbide. [Courtesy of Sandvik Coromant]
dimpled surface appearance\textsuperscript{6}, than are found by the ‘blocky-grained’ surface by the CVD technique. A typical tooling tungsten carbide substrate that has been PVD multi-coated is depicted in Fig. 10a. Such multiple coating technology allows for a very exotic surface metallurgy to be created, which can truly enhance tool cutting performance. In general and in the past, CVD coatings tended to be much thicker than their PVD alternatives, having a minimum coating thickness of between 6 to 9 µm, whereas PVD coatings tended to be in the range: <1 to 3 µm. Today, by employing sophisticated coating plant technology with lateral rotating arc cathodes, it is possible to have a nano-composite coating, typical of these coatings on the tooling, might be a nano-crystalline AlTiN coating embedded in an amorphous silicon nitride (Si\textsubscript{3}N\textsubscript{4}) matrix. This nano-composite structure creates an enormously compact and resistance surface structure, not unlike that of a honeycomb. These nano-composite structures have been proven to deliver a coating hardness of between 40 to 50 gigaPascals (i.e. 1 GPa equals 100 HV) and a heat resistance of up to 1,100°C, enabling the tooling to be employed on dry, high-speed machining operations. An advantage of using a nano-composite surface structure, is that they can provide both hardness and toughness to nano-layers \textit{without} the complexity and precision required to apply individual nano-layer coatings.

The range and diversity of metallic and non-metallic coatings applied to tooling is simply vast and ever-changing and is outside the present remit of this book. However, it is worth mentioning just one of the newly-developed ‘super-glide’ coatings that are currently utilised by tooling manufacturers today. These ‘super-glide’ coatings have a hardness that is comparable to chalk, or talc and acts as a solid lubricant coating on the hard-coated substrate. This type of coating works really well when dry machining of: aluminium alloys, alloyed steels, nickel-based super-alloys, titanium alloys and copper. In particular, the more demanding machining operations such as small-diameter drilling and reaming, deep-hole drilling and tapping, etc, are particularly suited to such ‘soft’ coatings. A typical ‘super-glide’ coating is molybdenum disulphide (MoS\textsubscript{2}) which is normally applied by the PVD modified magnetron sputtering process (see Fig. 11 for a schematic of a typical MoS\textsubscript{2} ‘super-glide’ coating). The high-vacuum coating process is performed at a relatively low temperature (200°C). This low temperature coating process prevents the substrate from annealing, while maintaining dimensional stability. The applied MoS\textsubscript{2} ‘super-glide’ coating has a micro-hardness of between 20 to 50 HV; it is deposited 1 µm thick, typically over a previous titanium nitride (TiN) coating, or a ‘bright’ tool. These MoS\textsubscript{2} coatings can have over 1,200 applied molybdenum disulfide layers present, each measuring a few angströms (i.e. one angström – denoted by the symbol Å – is equal to one 10-millionth of a mm).

The atomic structure of the molybdenum disulfide coating, has a dendritic\textsuperscript{7} crystal structure, being similar to graphite and has weak atomic bonds between the crystal layers, allowing easy movement of the adjacent planes of the crystalline layers (Fig. 11). Such an MoS\textsubscript{2} coating, tends to reduce the likelihood of adhesive wear and seizure, yet allowing sharp edges to the coated tooling.

1.2.8 Ceramics and Cermets

The oldest cutting tool materials date back to over 100,000 BC and were ceramic (flints), as stone-aged people used these specially-prepared broken flints to cut and work into hunting tools such as arrowheads, spears and for knives when eating their hunted prey. The first modern-day industrial applications of ceramics as cutting tools occurred in the 1940’s. These early ceramic tools had the promise of retaining their hardness at elevated temperatures, while being chemically inert to the ferrous workpieces they were originally designed to machine. These advantages over the cemented carbide tools, allowed them to exploit higher cutting speeds that were now becoming available on the newly-developed machine tools of that time. These ceramic tools offered virtually negligible plastic deformation, with the cutting edge being inert to any dissolution wear. The main problem with the early ceramic tooling was that they lacked toughness and resistance to both mechanical and thermal shock (see Fig. 2b).

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\textsuperscript{6} Smoother surfaces present in the PVD processes, create less thermal cracking which might lead to potential chipping and premature edge failure, while improving the resistance to repeated mechanical and thermal stresses thereby minimising interface friction, resulting in lower flank wear rates.

\textsuperscript{7} Dendritic derives from the Greek word for ‘tree-like’ (\textit{i.e. dendron}), hence its appearance as a crystalline structure.