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МОДУЛЬНЫЕ РЕЖУЩИЕ ИНСТРУМЕНТЫ

Пособие для студентов и магистрантов
машиностроительных специальностей

MODULAR CUTTING TOOLS

Manual for students and masters
of engineering specialities

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2015

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INTRODUCTION

These days the modular principle is a very popular method in the design of the automobile, diesel engine, home appliances, information devices, industrial equipment, and so on. This trend can be considered as one of the great contributions of modular design of machine tools to those working in other industries.

One of the promising directions of development of structures boring tool is to use the modular principle of their construction. Using the modular design of cutting tools increases their reliability and improved operating conditions by reducing the diversity of structures of modules. In addition, the use of modules in the design reduces the time and complexity of design allows the use of new methods of design, for example, to use computer-aided design procedure using a computer.

This textbook is intended for master students and graduate students of engineering specialties, and also is recommended for students of engineering specialties in the study courses "Cutting theory", "Cutting tool", "Tool systems", "Process equipment" for further study, as well as specialists of machine-building enterprises.

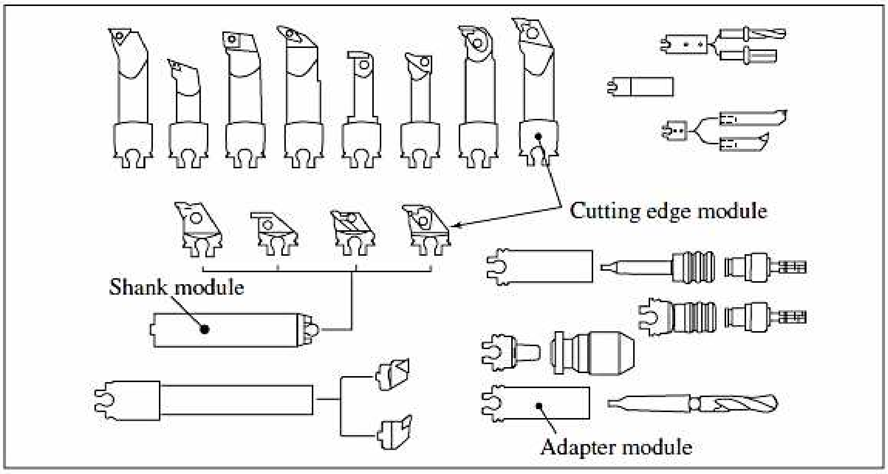
The textbook contains information about the general terms of modular design in mechanical engineering, modular quick-change tools, their requirements, configure, build, and information about the own development of the department of "Technology and equipment of machine-building production" of Polotsk state University in the field of modular cutting tools.

1. GENERAL TERMS OF MODULAR DESIGN IN MECHANICAL ENGINEERING

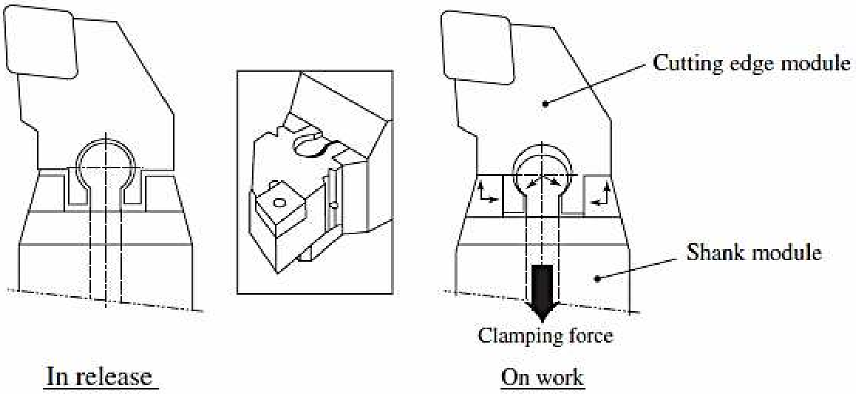
In retrospect, the predecessor of the current modular design appeared explicitly at the beginning of 1930s, and since then the related technologies have been duly advanced, revealing the remarkable impact of the modular principle not only on the machine tool design itself, but also on other products. The machine tool engineer is proud of the modular design. However, there are, in contrast, some difficulties in understanding exactly what modular design is and its historical background, which dates to the beginning of the 1930s. For example, the modular design can be classified into a considerable number of variants, depending on the idea, aims, and scope of the application, application area, expected advantages, and so on. In addition, the terminology of modular design itself has changed together with the hierarchical ramifications of its meaning, as already described in Terminologies and Abbreviations. It is thus very difficult to represent modular design in a simple sentence; however, we need a quick statement to understand the essential features of modular design. At present, employment of modular design in the manufacturing sphere ranges from the tool, jig, and fixture, through the machine tool, to the manufacturing system. In the following, several illustrations and some typical examples will be shown.

Figure 1.1 shows a representative modular tooling system proposed by Sandvik Co. in the middle of the 1980s. The tooling system was marketed under the commercial name Block Tool System, and it was duly characterized by its wider tooling flexibility, which can be realized by exchanging the cutting edge module in accordance with the machining requirements. Actually, a tooling system consists of the shank (fixing), adapter (extension), and cutting edge modules, and the adapter module may assist to reinforce the further flexibility. This tooling system was employed on a CNC (computerized numerical control) lathe of the George Fischer make (type NDM-16), in which the cutting edge modular was stored in the tool magazine of drum type and transferred to the machining space by the overhead traveling robot.

Figure 1.2 displays another modular tooling system produced by Nikken Co., showing the effectiveness of the modular concept even in the year 2000. The modular principle was furthermore applied to the tool layout on the turret, e.g., base and tool holding blocks, as shown in Fig. 1.1 – 1.3.



Assembly diagram



Clamping mechanism of cutting edge to shank modules

Fig. 1.1. Modular tooling system in 1980’s: basic ideas

Note: Courtesy of Sandvik Co.

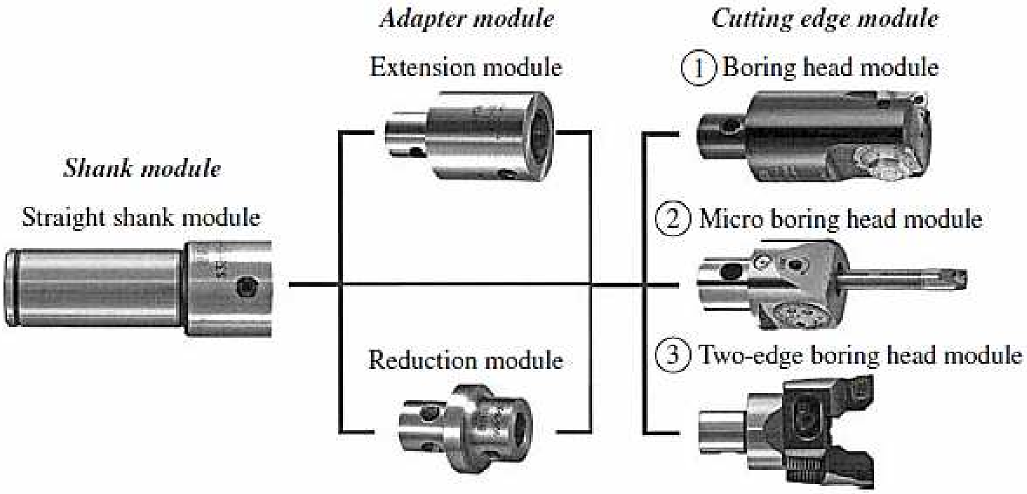


Fig. 1.2. Modular boring system

Note: Courtesy of Nikken Kosakusho Works.

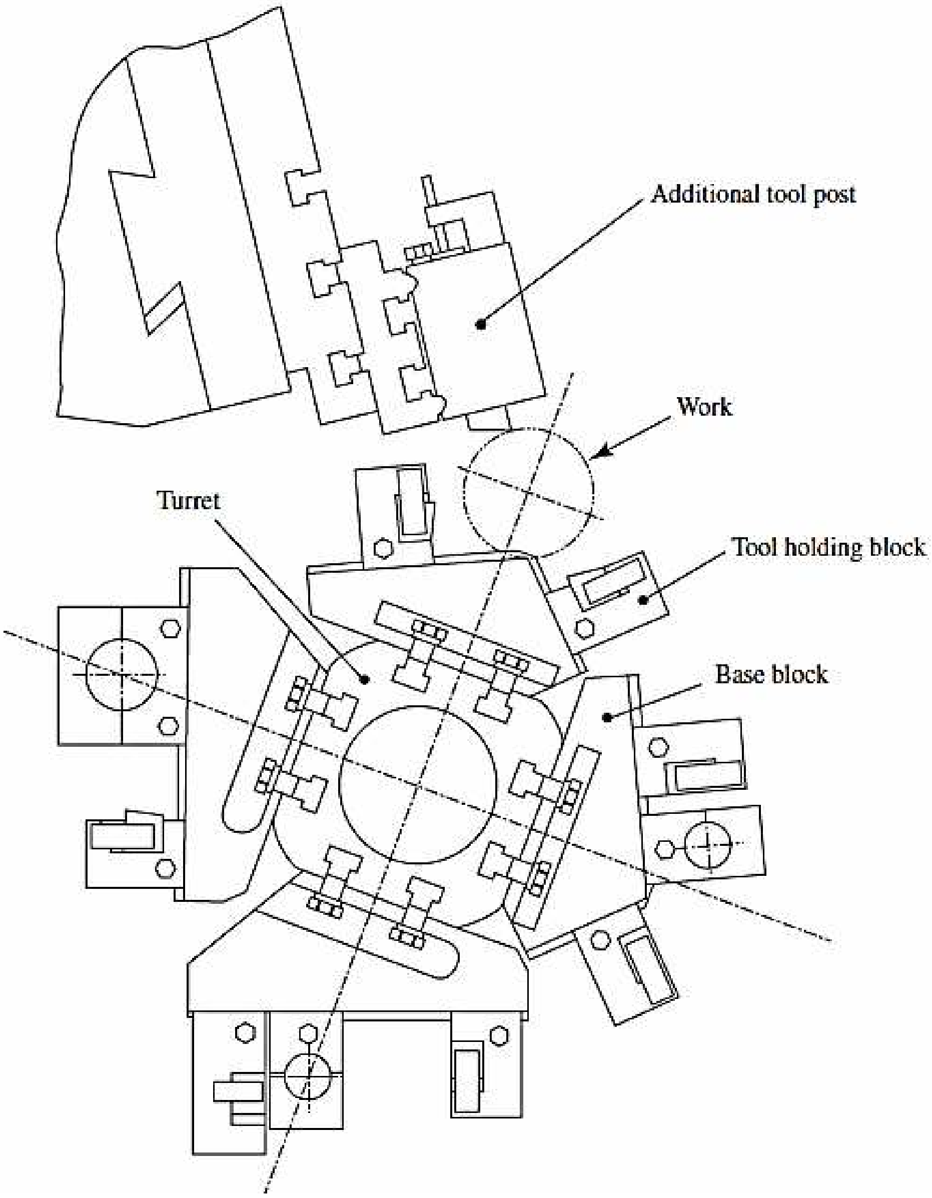


Fig. 1.3. Modular principle applied to tool layout on turret by Dietz

Note: Courtesy of Carl Hanser.

Figure 1.4 shows an advanced variant of MC (machining center) of Ikegai make (type MX3: maximum spindle speed 4500 rpm, allowable torque 3.6 kg m, spindle taper no. 40) in the beginning of the 1980s, which is a column traveling type. As can be seen, the modular design is preferably employed to produce 10 variants, ranging from the FMC (flexible manufacturing cell) of pallet pool type, through the station of FTL (flexible transfer line), to a five-face processing machine. In this case, the leading modules are the column, base, rotary table, tool magazine, main motor, and so on. This machine appears to be a typical predecessor of current five-face processing machines.

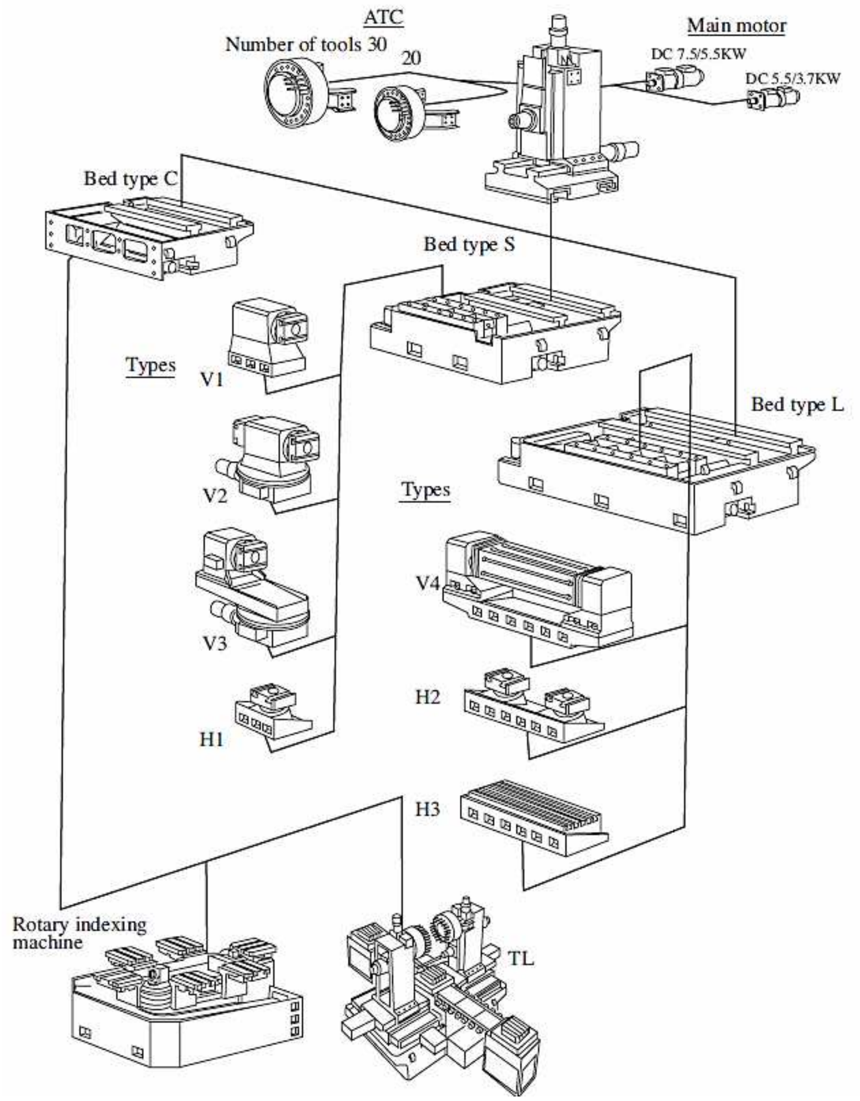


Fig. 1.4. Modular design in MC

Note: Courtesy of Ikegai Iron Works.

In the late 1990s, we can observe another eminent example of the application of modular design to the turning machine of the hanging spindle type (Index-Werke brand, commercial name: Verticalline). As shown in Fig. 1.1 – 1.5, the major modules of the machine are those for several structural body components, hanging spindle, turret head with either rotating tools or stationary tools, tool post fixed on the platter, and work pool stand. The platter can furthermore accommodate the motor-driven cutting tool and gang head on itself, resulting in greater flexibility in machining when varying the combination with the turret head. In addition, the machine can be characterized by some functions for laser welding, hardening, grinding, and assembly operation. The machine can be thus called the processing complex and appears to be a successor of the prototype named the “Complex Processing Cell of T-form.” This prototype has been developed so far by the Japanese Big National Project entitled “Complex Production Systems Using High Efficiency Laser Processing”.

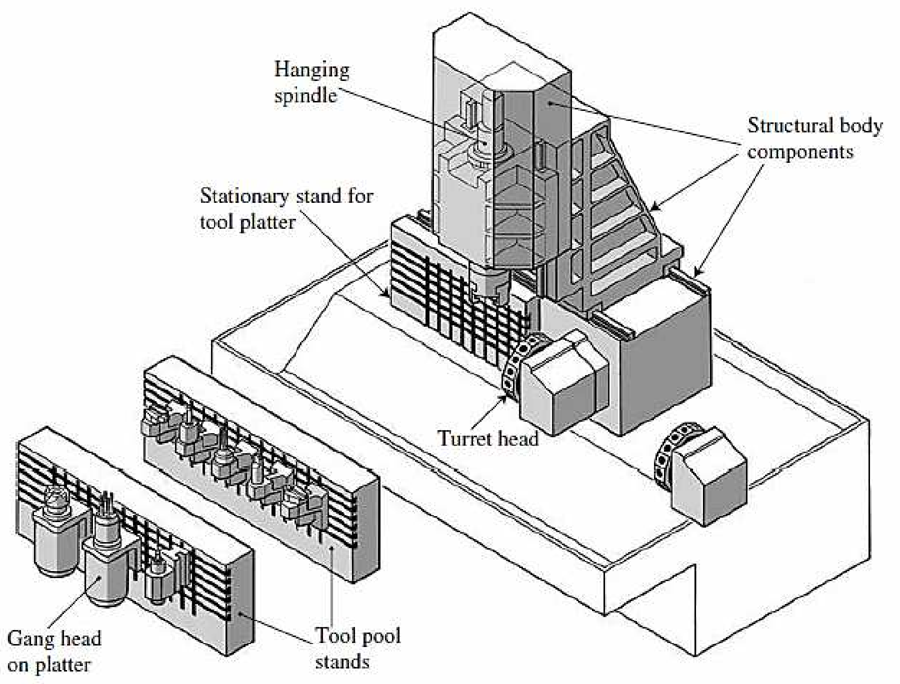


Fig. 1.5. An application of modular design to the turning machine

Note: Type Vertical Line, 1999, courtesy of Index.

Within a system context, a typical modular design can be observed in the FTL of Diedesheim brand, as shown in Figure 1.6, and its core machining function consists of the head changers of modular type called Variocenter. Importantly, there are two types of FTL depending on the basic module and flexibility of the transfer line of asynchronous type. In the FTL of simple line flow type shown in Figure 1.6 (a), the basic module is that of Variocenter itself, resulting in less flexibility in the work transfer function, whereas in another FTL shown in Figure 1.6 (b) the basic module is of FMC to enhance the flexibility in both the machining and transfer functions. More specifically, the FMC can be formed from the Variocenters of various types in addition to having both the subtransfer line, i.e., transfer shuttle conveyor, and the work waiting station, which are capable of the leapfroglike work transportation, resulting in greater flexibility in the transfer function of the system. The FTL in Figure 1.6 (b) has been installed at Opel to handle the increasing number of engine varieties. In fact, the kernel of Variocenter is a hexagonal turret having a group of cutting tools to machine the objective work. The turret and work can be transported to the machining space by using the overhead crane and the carrier on the floor, respectively. Thus, the system can facilitate drilling, deep hole drilling, counterboring, reaming, spot facing, tapping, precision milling, precision facing, and inspection. Then the system is available, for example, for the manufacture of cylinder heads and cylinder blocks made of gray cast iron, high alloy cast iron, and die cast aluminum alloy. According to the report of Siegfried at the International Symposium on Automotive Technology and Automation in 1984 held in Milan, 80 percent of the system can be reused in the event of product changes.

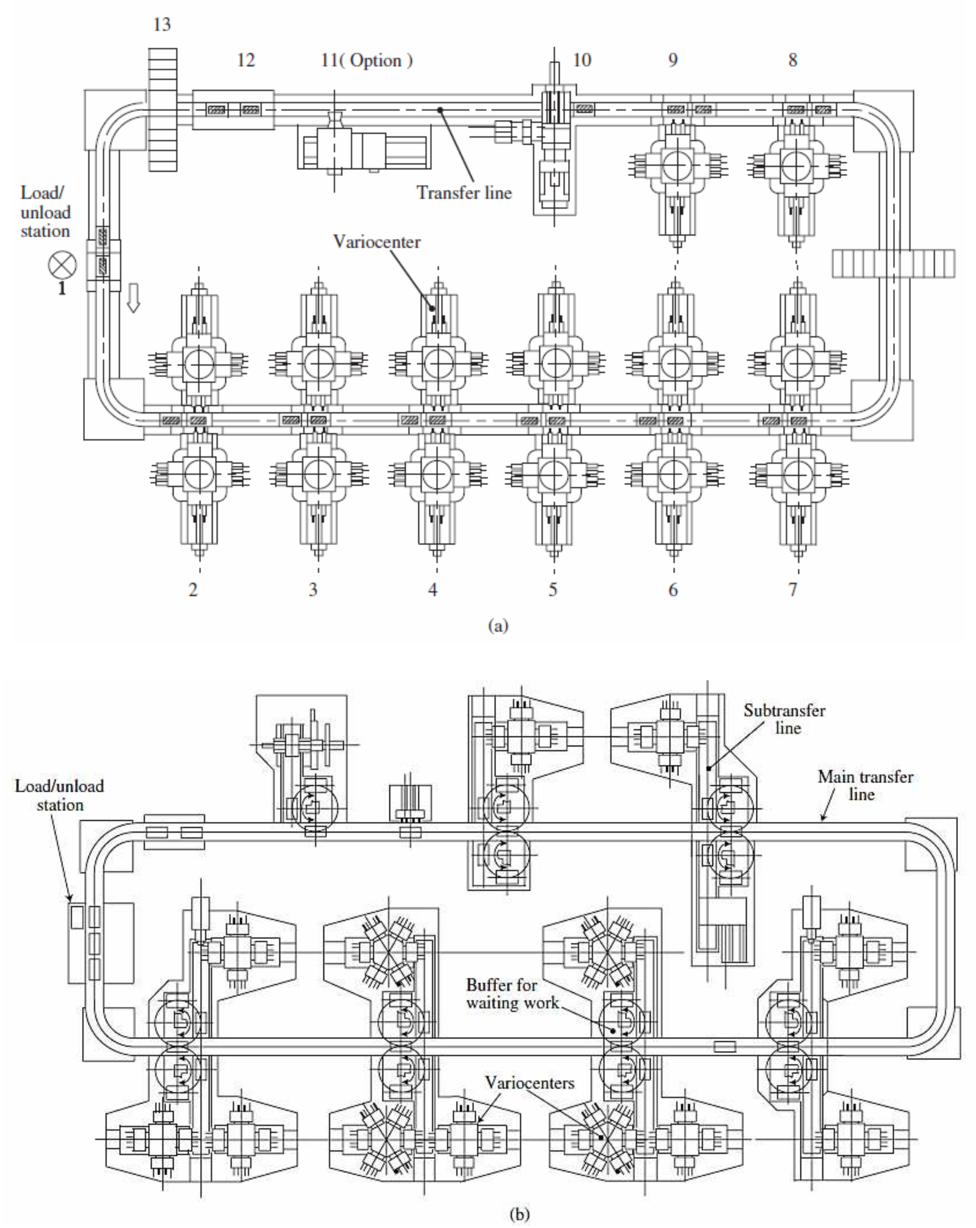


Fig. 1.6. FTL for producing automobile parts:
(a) Line flow type and (b) FMC-integrated type

Note: 1980s, courtesy of Diedesheim.

As can be readily seen, flexible manufacturing of the FMC-integrated type was an eminent contrivance from the modular design viewpoint, and even in the year 2000 it was the leading system design methodology. In due course, the FMS (flexible manufacturing system) of FMC-integrated type was to become a reality by the ZF (Zahnrad Fabrik Friedrichshafen GmbH), one of the representative mission gearbox manufacturers in Germany, for producing gears on that occasion. In the case of FMS of ZF make, one of the marked features was that it facilitated the inheritance of the craftsmanship by using the job rotation between the FMS and the traditional factory. This feature leads us later to an idea of the modular design of culture- and mindset-harmonized type.

These examples may help the reader to imagine what modular design is to some extent; however, we must discuss these in detail to best use the modular design. In this chapter, first we give a quick summary to deepen the reader's understanding of the essential features and to point out the advantages and disadvantages of modular design.

2. MODULAR QUICK-CHANGE TOOLING

The modular tooling concept was developed by cutting tool manufacturers from the long-standing tooling cartridges (figure 2.1 indicates a typical self-contained cartridge), which had been previously available for many years. Initially, the modular tooling was designed and developed for turning operations (fig. 2.2) and was demonstrably shown to offer amazing versatility to a whole range of machine tools and, not just the CNC versions. The original ‘modular tooling concept’, termed the block tooling system – allowing efficient and fast ‘qualified’ tooling set-ups for non-rotating tooling on both conventional lathes and turning centers.

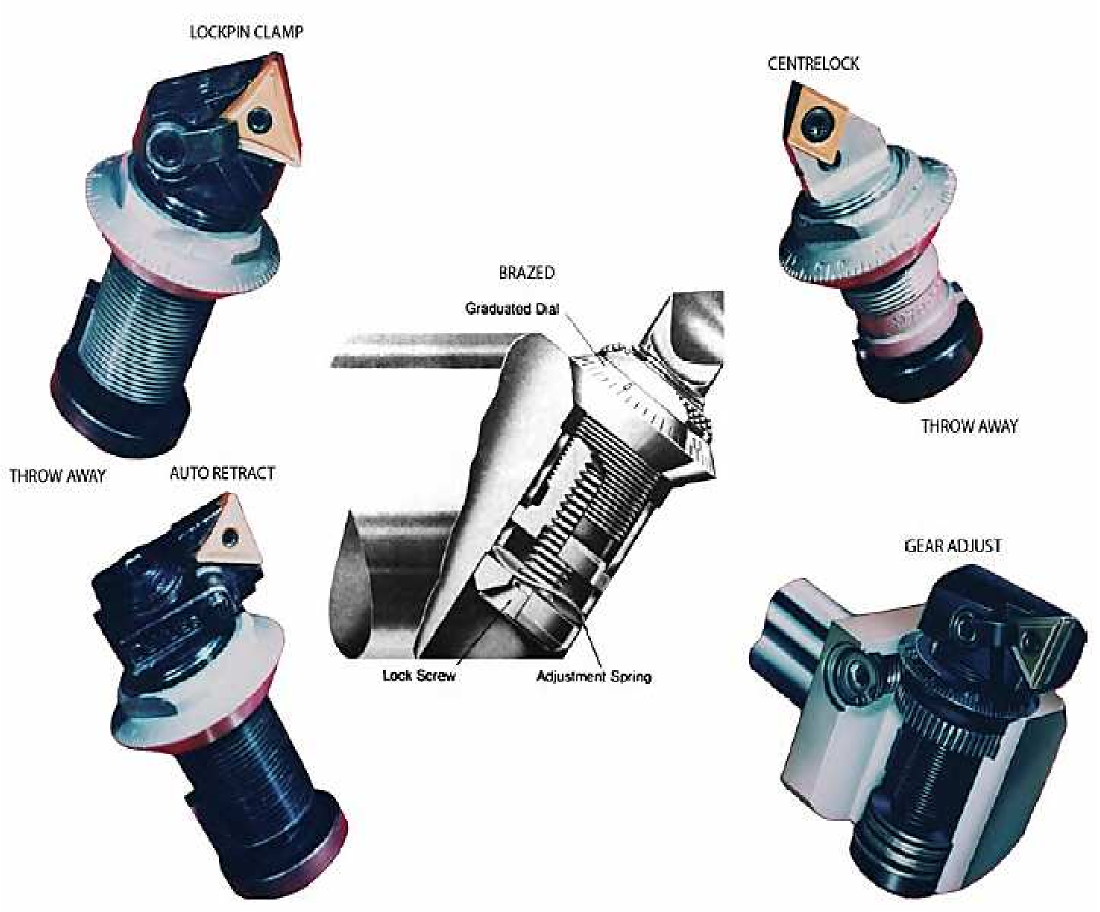


Fig. 2.1. Microbore (adjustable) modular cartridges, with indexable inserts

Note: Courtesy of Microbore. Tooling Systems.

The point that the tooling is a key element in the whole manufacturing process was not lost when in the early 1980’s the United States Government commissioned a ‘Machine Tool Task Force Survey’ on machine tools and tooling, to determine their actual utilization level. Here, the US findings compared favorably with a similar survey undertaken in Germany some years later.

Fig. 2.2. Modular tooling system

Note: Courtesy of Sandvik Coromant.

It was a surprising fact that on average only between 700 to 800 hours per annum, were spent actually ‘adding-value’ by machining operations on components. This particular outcome becomes even more bizarre, when one considers that the theoretically available annual loading time for a machine tool of 364 days × 24 hours per day yielded a potential machine tool availability of 8736 hours – representing a meagre ≈8% as actual cutting time. This ≈8% value is shown on the diagram in Figure 2.3 (a), where an attempt has been made to identify and show actual individual blocks of time allocated to both shift-wastage and nonproductive time. This massive potential machine tool availability, is further compounded when one considers the rapid advances in both machine and cutting tool developments of late, where tool utilization time and in particular the lead-times would significantly benefit from using a modular quick-change tooling strategy.

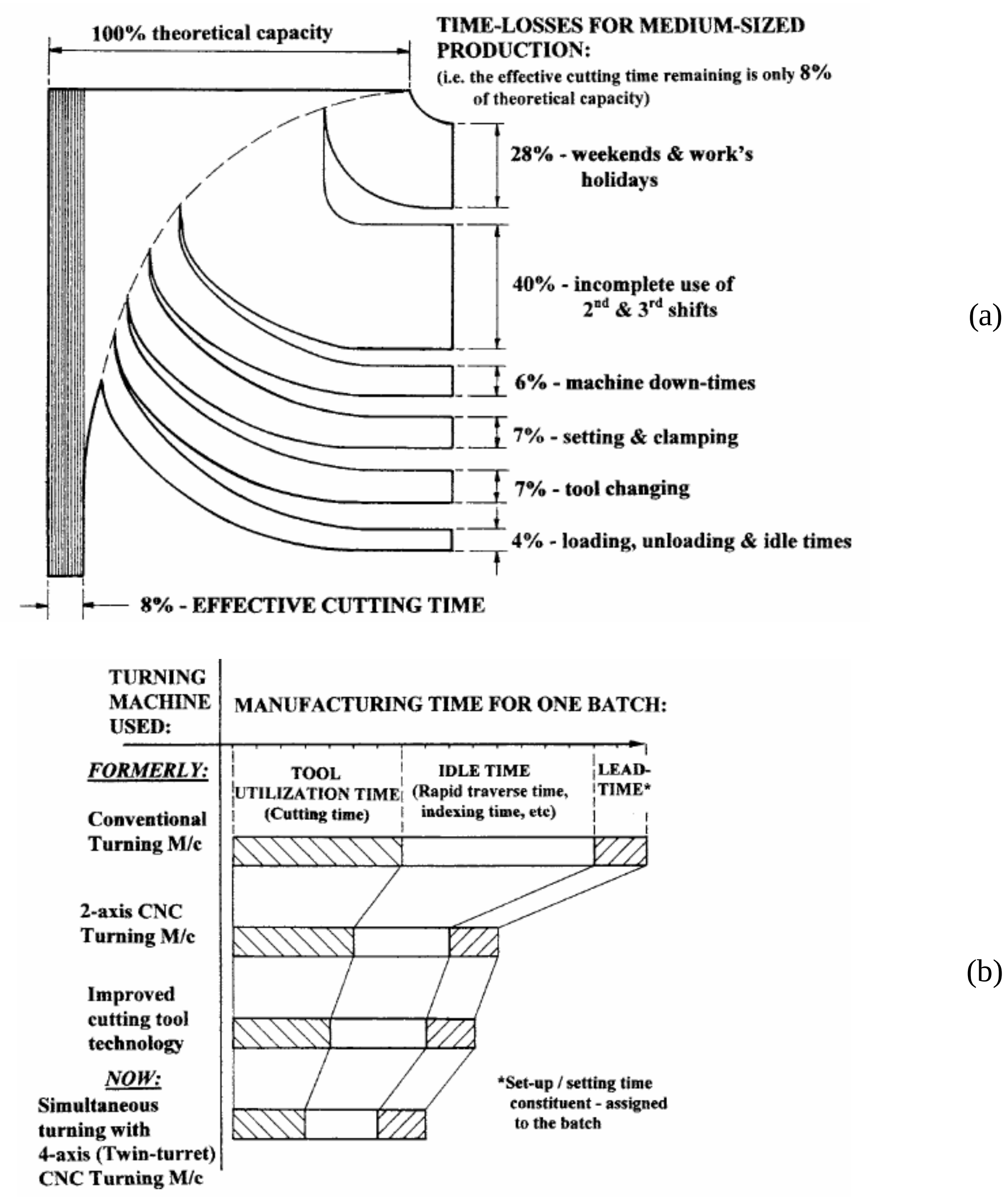


Fig. 2.3. Cutting availability and cycle times can be dramatically improved with efficient tooling strategies: (a) time-loss constituents in medium batch manufacture; (b) cycle time reduction with both advanced machine tools and high-technology cutting tooling

Note: Courtesy of DMG Machine Tolls.

Prior to a discussion of ‘modular tooling concepts’, it is worth briefly mentioning that in many instances, conventional tooling correctly applied can make significant productivity savings, whether the emphasis is on increased production – through longer tool life, or on a reduction in the cycle time for each part. The machining trend in recent times has been to increase the productive cutting time of expensive machine tools and, in order to achieve this objective it is necessary to minimize tool-related down-time.

Cutting tool manufacturers have not been slow in developing and producing modular quick-change tooling systems. Their initial steps into such systems occurred in the early 1970's, with one solution involving changing the indexable insert itself: the major drawback here was that the insert-changer was complex in design and could only change one type of insert. This fact limited it to long-running turning applications and even here, it suffered with the advent of CNC. Yet other approaches involved changing both the tool and its toolholder, in a similar manner to current practice on CNC machining centers. This system also imposed restrictions, owing to the relatively high weight and dimensional size of the tool-changer, which meant that its load-carrying capacity was limited. Even where a tool magazine is present – such as is found on certain types of turning and machining centers, its capacity becomes rapidly exhausted, so that fully-automated operation over a prolonged period is not possible. Further, the multitude of geometries and clamping systems necessary causes impossible demands on an automatic tool-changer, with the problem being exacerbated still further by the fact that indexable inserts may not be suitable for all machining operations. Therefore, a completely different approach was necessary for automatic tool-changing systems, to overcome these disadvantages.

Prior to a discussion concerning modular quickchange systems in use today, it is worth mentioning that many machine tool manufacturers can offer extra capacity tool magazines, holding almost 300 tools – in certain instances (Figure 2.4).

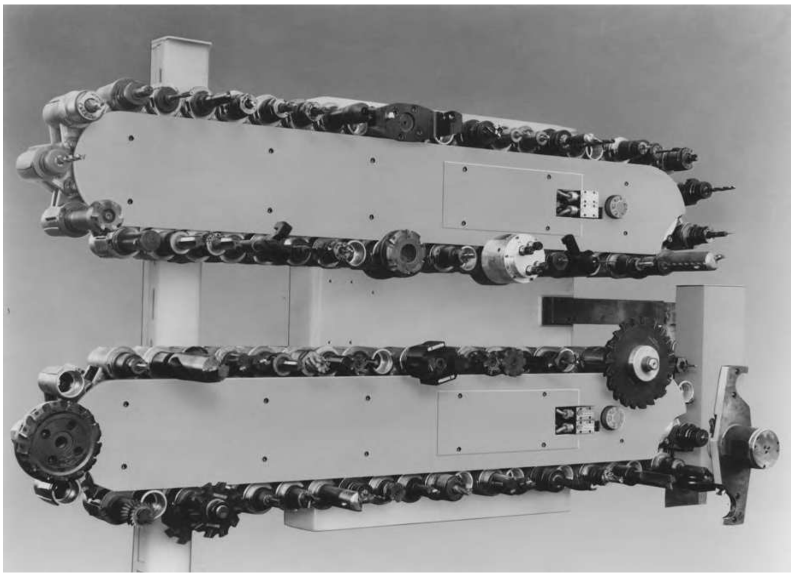


Fig. 2.4. A 90-tool capacity, auto-toolchanger magazine (chain-type), three such magazines can be slotted together, to give a 270-tool capacity

Note: Courtesy of Cincinnati Machines.

So the question could rightly be asked: ‘Who needs such modular quick-change tooling, when machines can be provided with their own in-built storage and tool-transfer systems?’ This is a valid point, but a very high capital outlay is necessary for these extra-large magazines (i.e. as depicted in Figure 2.4) and, even then, only a finite tooling capacity can be accommodated and its variety would be considerably reduced if a ‘sister tooling’[1] approach was adopted. This tooling-capacity problem becomes acute in the case of Figure 2.4, where some large tools have to be held in the magazine and empty tool pockets have to left either side of it – as shown by the large tool situated on the lower chain on the extreme left. Machine tool builders have spent considerable time and effort on reductions in the non-productive activities, such as ‘cut-to-cut times’[2]. Modular quick-change tooling will further reduce set-up times and for any subsequent tool maintenance activities, more will be said on the topic later in this chapter under the guise of ‘tool management’.

So far, these introductory remarks have addressed some of the issues concerning early techniques for quick-change tooling and the machine tool builder’s approach to overcoming the problem. So again, one can state: ‘Why does one need modular quick-change tooling?’ One of the most important aspects of utilizing such tooling systems on for example, machining centers, has been to standardize and thereby reduce tooling inventories (i.e. rationalize and consolidate the remaining tools), whilst simultaneously giving the tools more flexibility in their cutting requirements which occur during a production run. Now that many turning centers are equipped with full C-axis headstock control – for contouring capabilities, together with driven/live tooling from their turret pockets (i.e. termed: mill/turn centers), their requirements for modular tooling are similar to those of a machining center.

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[1] ‘Sister tooling’ – is where there is at least one duplication of the most heavily utilized tools within the tooling magazine/ turret. This multiple loading of duplicate tooling, is normally operated as follows: once the first tool of the duplicates is nearing the end of its active cutting life, it is exchanged for a ‘sister tool’ and will not be called-up again during the unmanned production cycle. This duplication strategy can significantly extend the untended machining environment, through perhaps, a ‘lights-out’ night-shift, if necessary.

[2] ‘Cut-to-cut times’ , having reductions in tool transfer on: turning centers – with bi-directional turret rotation, or on machining- and mill/turn-centers equipped with either tool carousels/ magazines, enabling rotational indexing to the correct tool pocket, prior to load/unload of tooling, tool transfer – reducing the idle-times to the next machining operation to just a few seconds. If the machine has facility for either automatic jaw-changing on a say, a mill/turn center, or pallets on a machining center, this non-productive operation is undertaken simultaneously with the tool-changing/ tool-indexing – on the latest machine tools, thereby further reducing idle times.

From the previous discussion, it is now evident that significant reductions in the machine tool's non-productive times can be accomplished, by minimizing the downtime associated with utilizing cutting tools. If a manufacturing company incorporates modular quick-change tooling systems on its machining and turning centers, or even on some conventional machine tools – involved in large batch runs, then great productivity benefits will accrue over a relatively short pay-back period. This will be the theme for the discussion over the next sections. Firstly, we will consider the tooling requirements for turning centers and secondly, the applications for modular quick-change tooling on machining centers.

3. TOOLING REQUIREMENTS FOR TURNING CENTERS

Perhaps of all the machine tools that use either single-, or multi-point cutters, the turning center has undergone the greatest changes. The vast spectrum of these turning-based machine tools, include at the one end: basic CNC lathes – often equipped with conventional square-shanked toolholders and round-shanked boring bars, that are manually-loaded, to highly sophisticated co-axial spindled twin-turret mill/turn centers. These highly productive multi-axis machine tools, have features such as: full C-axis control – for part contouring; robot/gantry part-loaders – for efficient load/unload operations; automatic jaw-changers for flexible component work-holding; programmable steadies – for supporting long and slender parts; toolprobing systems – having the ability to apply automatic tool offset adjustment with the capabilities of tool-wear sensing/monitoring and control; work-probing inspection – for automated work-gauging of the workpiece's critical features. With respect to these latter multi-axis highly-productive machine tools, the capital outlay for them is considerable and in order to recoup the financial outlay and indeed, cover the hourly cost of running such equipment, they must not only increase productive cutting time – with an attendant reduction in cycle times, while simultaneously reducing any direct labor costs associated with the machine's initial set-up and maintenance. It is often this final aspect of labor-cost reduction, which becomes the most attractive cost-saving factor, as it is usually constitutes a large component in the overall production cost in any manufacturing facility.

When a company specifies a new turning center for its production needs, they might want to increase its versatility by specifying a rotating tooling with a full C-axis capability, giving the ability to not only contour-mill part features, but cross-drill and tap holes while in-situ – termed 'one-hit machining'. These secondary machining operations may even eliminate the need for any post-turning machining operations, on for example, a machining center, giving yet further savings in production time – work-inprogress (WIP) and minimizing the need for an additional machine tool. If floor-space is at a premium, then one highly productive and sophisticated multi-axis mill/turn center, may be the solution to this problem.

Previously, justification for the need to employ a modular quick-change tooling strategy for turning centers has been made. Some of these modular tooling systems will now be reviewed, many of which are now being phased-out, while others have recently become popular. Basically, there are two types of modular quick-change tools available today, these being categorized as follows: Cutting-unit systems, or Tool adaptor systems. The two systems vary in their basic approach to the quick-change tooling philosophy and, whether they are designed to be utilized on turning, or machining centers separately, or alternatively, for a more universal approach. The cutting-unit system was one of the first to be developed by a leading cutting tool manufacturer and is universally known as the 'Block tool system' (see Figure 2.1, 3.1, 3.2).

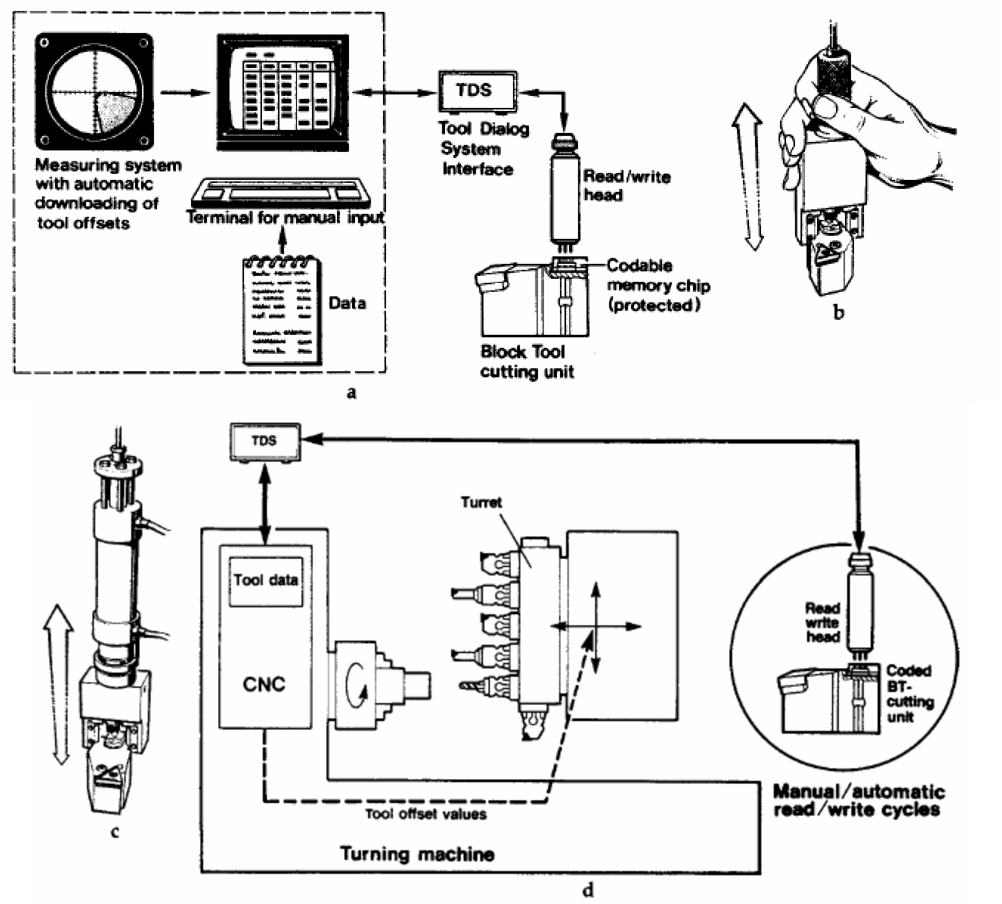

Fig. 3.1. Tool data processing employing modular quick-change tooling on a turning center, via the 'intelligent/tagget' tooling concept

Tooling operation: (a) – Scheme of tool date input/output tool preparation. Offsets are automatically downloaded. Tooling and other required date are entered manually and can be freely edited. Any simple date already existing in the memory chip can be overwritten or retained as required. (b) – During tool preparation all date is written into (input) or read from the chip using a simple read/write assembly. (c) – In the machine an automated assembly reads from and writes to each tool data carrier in the magazine. (d) – Scheme of CNC turning machine showing two-way tool data exchange between tool and CNC. An automated read cycle at the tool magazine is performed each time a tool is loaded, to update the CNC's tool data file. Automated tool data processing eliminates offset and tool changing errors.

Note: Courtesy of Sandvik Coromant.

This system (see Figure 2.1), is based on a replaceable cutting unit (i.e. 'club head') utilizing a square-shanked toolholder, with the coupling providing a radial repeatability to within ±0.002 mm. This high-level of repeatability to ± 2 μm, is necessary in order to minimize the coupling's effect on the diameter to be turned. To ensure that the generated cutting forces do not deflect the 'Block tool', a clamping force of 25 kN is used. 'Club head' clamping may be achieved in a number of ways, either: manually – with an Allen key, or either by semi-automatic clamping, or automatically. The clamping force is normally provided by using a certain number of spring-washers, these being pre-loaded to provide a reliable clamping force. These cutting units can be released by compressing the washers so that the draw-bar can move forward. In the case of the automated cutting unit system, a small hydraulic cylinder mounted on the carriage behind the turret causes the draw-bar to release it, this being timely-activated by a command at the correct sequence within CNC program.

Previously, mention was made of the cutting unit's repeatability and its associated clamping forces, together with techniques for releasing the 'Block tool'. Now, consideration will be given to how the cutting units are precisely located in their respective toolholders. The 'Block tool' is located in the following manner: the cutting unit slips in from above the coupling (i.e. of the receiving toolholder) to firmly rest on a supporting face situated at the bottom of the clamping device. This tool ledge supports the cutting unit tangentially during the machining operation. Once the cutting unit is seated on the bottom face (i.e. tool ledge), the draw-bar is activated – either manually – with a key, or by the hydraulic unit – in the case of automatic cutting unit loading. This draw-bar activation provides a rigid and stable coupling, that can withstand the loads produced during cutting. Both internal and external machining cutting units (see Figure 2.1) can be supported.

A major advantage of all modular quick-change systems is ease and speed of tool-changing, producing shorter cut-to-cut times, in comparison to that of conventional tooling. If an operator is present whilst machining, the added bonus here is one of reduced operator-fatigue, since tool handling – particularly with heavy tools – can be minimized particularly when using either semi-automatic, or automatic tool-changing methods. As a result of the smaller physical size of these modular tools, they can be more readily stored in a systematic 'tool-management' manner, allowing them to be efficiently located and retrieved from the stores, with the added bonus of reducing tool-stock space.

The benefit of just using the 'entry-level' manual 'Block tool' system over conventional toolholders, may be gleaned from the following tabulated example, depicted in Table 1, where the numerical values in the table form the basis for the comparisons. The figures in the left-hand column are typical for most two-axis turning centers, where: manual tool-changing is employed, securing the tool in its pocket and maintenance takes place.

Table 1

Comparison between utilising conventional and quick-change tooling

Operation	Conventional toolholder:	Block-tool system:
Setting-up time (min)	30	15
Tool-changing time (min)	3	1
Measuring-cut time (min)	5	0

This data can now be applied to the practical situation for an environment of mixed production containing small batches of turned components, where the actual cutting time represents 15% of the total machine-shop time. If one assumes that an average of 30% of the tools needed measuring cuts (e.g. component diameters to be machined and measured, then these values input into the machine tool's CNC controller) and, that 200 set-ups were required per year on the machine, necessitating some 1580 tool changes during these tasks per year. So, under such production parameters, the quantitative strategic benefits of utilising the modular quick-change tooling system over conventional tooling, are as follows:

- Setting-up time – differences would be: 15 × 200 = 3000 minutes per year.
- Tool-changing time – differences are: 2 × 1580 = 3160 minutes per year.
- Measuring-cut times – differences amount to: 1580/3 × 5 = 2630 minutes per year.

These timesavings mean that a total difference of 8790 minutes would be accrued, or 146 hours, which equates to a saving of 18 working days. Hence, this simple 'Block tool' system allows for a significant increase in available production time over this time-period. Alternatively, this time-saving can be multiplied by the machine's running cost per hour, to further reinforce the correctness of the decision to purchase a quick-change tooling system, since it quickly buildups the pay-back on the initial investment for this type of tooling strategy. The simple example given above, clearly demonstrates the real benefits of either using a manual quick-change tooling system, on a conventional lathe, or turning center.

So far, the merits of utilizing a quick-change tooling system have been praised, but one might ask the question: 'What type of batch size can justify the financial expense of using such a 'Block tool' system?' To answer this, we will consider the two manufacturing extremes of both large-batch production and, small-batch production usage – the latter using one-offs.

Today, large batches and even mass production runs are increasingly performed in 'linked' turning centers. The manufacturing objective here is to limit operator involvement and for planned stoppages and tool changing/setting to occur according to an organized pattern, so that they usually happen in between shifts, or at recognized scheduled stops in the production schedule.

For example, utilizing the 'Block tool' system allows tool changes to be organized and made very efficient, especially so when the tool changes are semi-automatic, or automatic in operation. These modular quick-change cutting 'club-heads' are small, light and easily organized for tool changing. Moreover, they can be preset outside the machine tool environment and as a result, their accuracy is assured by the precise mechanical coupling to that of its mating holder. It is also possible to give these 'Block tool' cutting unit's a degree of 'intelligence', by an embedding coded microchip, having a numbered tool data memory-coded identification – sometimes termed 'Tagged tooling'. In the early days of tool read/write microchips, they were of the 'contact varieties' (i.e. see Figures 3.1), but many of today's tool identification systems are of the non-contact read/write versions. Tool offset settings produced when initially measuring them on the tool-presetting machine, can have these numerical values stored in coded information within the in-situ microchip situated within the quick-change tooling 'club head'. An alternative approach to actual measurement of the tool offsets, is to utilize either a touch-trigger, or non-contact probe, situated on the machine tool – more will be said on this subject later in the chapter. These tooling aids also minimize the setter/operator activity and this will ensure that such vital information is correctly performed, thereby eliminating the risk of mistakes being made during any hectic machine stoppages. While another benefit of using a quick-change modular tooling strategy, is that the time needed to change tools is very short. It may even be possible to make an unscheduled tool change for critical tooling; if for example, their wear rate is unexpectedly high. This unscheduled tooling adjustment, will raise the overall cutting performance, which in turn leads to improved and economical tool utilization, particularly during a large production run. Where a company is involved in large-batch, or mass production runs, its should be obvious by now, that utilizing modular quick-change tooling offers considerable savings by reducing the non-productive cutting times. This modular tooling strategy is also true, but to a lesser degree, for either small batches and can even be relevant in the extreme case for certain one-offs, requiring many tool changes in the machining of a complex part geometry. This latter factor is particularly the case when 'part families'[3] are required to be produced.

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[3] 'Part families', refer to the machining of components that have either similar workpiece geometries – often termed 'aspect ratios', or comparable machining processes undertaken to complete the parts.

Frequently the problem that is present within a machine shop, is one of insufficient tool storage on the actual machine tool, this is particularly the case for single-turret turning centers – having limited pockets available for the tooling. Under such circumstances, the solution may be to use modular quick-change tooling. Using say, minimal levels of tooling automation, via semi-automatic quick-change tooling, extends the turret's capacity with minimal loss of productive cutting. Replacing a new cutting 'club head', simply requires the operator to lift out the old unit and push in another – at the press of the tool-release button.

Optional tool stops can be programmed into the CNC controller for just this purpose. By presetting the tooling, in conjunction with each cutting head, the coupling's guaranteed repeatability, ensures that the cutting edge is both accurately and precisely positioned relative to the workpiece's orientation and datum. This fact negates the need for the operator to have to individually adjust all of the tooling offsets for different workpiece configurations.

Yet another approach to the lock-up sequence and design of modular quick-change tool adaptor systems, is depicted in Figure 3.2. The mechanical-locking interface is via a Hirth gear-tooth coupling mechanism[4]. This system offers both a high positioning accuracy in combination with an almost perfect transmission of the torque effects induced by the offset in cantilevered turning and grooving tooling, whilst cutting. Clamping consists of draw-bar locking after insertion of the male and female gear teeth of the desired cutting unit into the adaptor. These changeable cutting units also require accuracy and precision in the manufacture, with their location and clamping being achieved through axial movement of a draw-bar. The draw-bar can be either manually, or automatically moved by using a torque motor. This draw-bar locating mechanism allows both the male and female coupling 'geared faces' to be firmly locked and assembled together.

The Hirth gear-tooth coupling has a repeatability of <±0.002 mm, with tooling system that can be mounted in either a: disk, drum, row, flat, or chain magazine. The Hirth coupling has a standardized installation, with identical dimensions of Ø40 and Ø63 mm, for the tooling system selected. These modular cutting mechanical interfaces are directly mated together, allowing internal coolant flushing and as such with use, will not become polluted during its lifetime's operation. As with all of these modular quick-change tools they can have

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[4] Hirth gear-tooth coupling mechanism is a well-known tried-and-tested mechanical-interface, which is often present on rotary axes for machining center pallets, allowing for accurate and precise pallet changeovers, between following parts requiring subsequent machining.

their tooling of internal, or external mounting (i.e. shown in Figure 3.2), and of different ‘hands’ in order to achieve universal turning/grooving machining applications on the widest variety of parts.

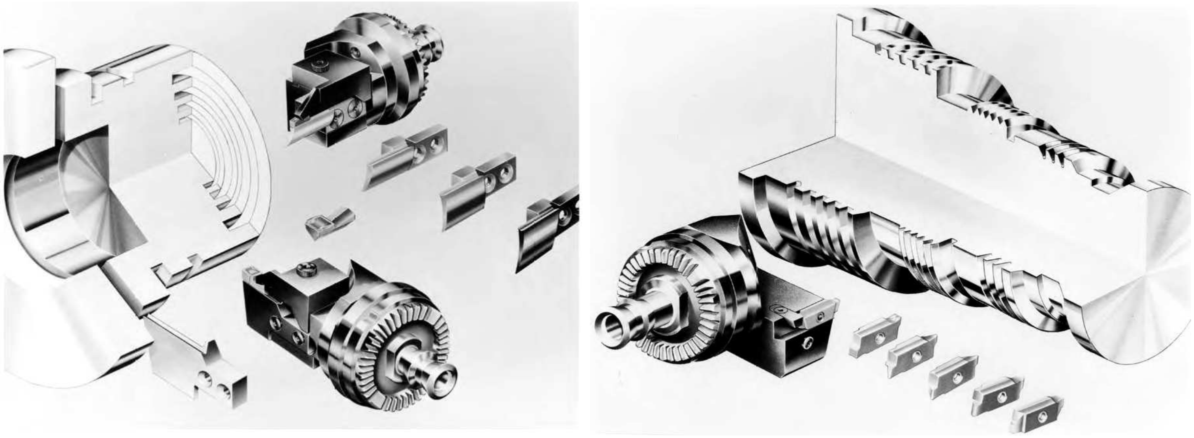

Fig. 3.2. The ‘modular tooling concept’ based upon attachment of ‘front’- and ‘back-ends’ by the Hirth coupling, illustrating both axial and transversal grooving of component features in this instance

Note: courtesy of Widia Valenite.

Despite all of this convincing evidence in favor of such tooling, some pessimistic manufacturing engineers may still remain skeptical as to the advantages to be gained from this additional tooling capital expenditure. While another factor preventing the purchase of a comprehensive modular quick-change tooling package, is that a company simply cannot afford the luxury of purchasing a complete tooling system. Under these financial constraints, it might be prudent to purchase just a few quick-change units initially and, at a later stage, appraise the situation in terms of the likely productivity increases and the operator’s own experiences with this new tooling concept. In this manner, only a relatively small financial outlay will have been necessary and the company will not become too disenchanted if the results prove unfavorable, perhaps owing to some extraneous circumstances that could not be initially accounted for when the original tools were purchased.

4. MACHINING AND TURNING CENTRE MODULAR QUICK-CHANGE TOOLING

Prior to designing this KM modular quick-change tooling system – which was introduced by several tooling companies in the late 1980‘s (i.e. see Figures 4.1 to 4.3) for both machining and turning centers, a number of key decisions had to be made. The basic criterion of the system’s configuration for use with either rotating, or stationary tooling, is that the coupling needed to have a round geometry and have a centerline datum. Moreover, for ease of use, the tool-changing and precision and accuracy required, that in the radial direction (i.e. X-axis), a tapered shank was mandatory. To ensure that an equal level of operational performance occurred in the axial direction (i.e. Z-axis), face contact at the mechanical interface was necessary. The cutting edge’s height was deemed to be a less critical factor and this allowed a reasonable design tolerance here, giving good results for the majority of machining operations using this newly-designed modular quick-change tooling concept.

Together and employing these stated design criteria, the following repeatability for the KM modular tooling concept was obtainable:

- Axial tolerance – ± 0.0025 mm.
- Radial tolerance – ± 0.0025 mm.
- Cutting-edge height – ± 0.025 mm.

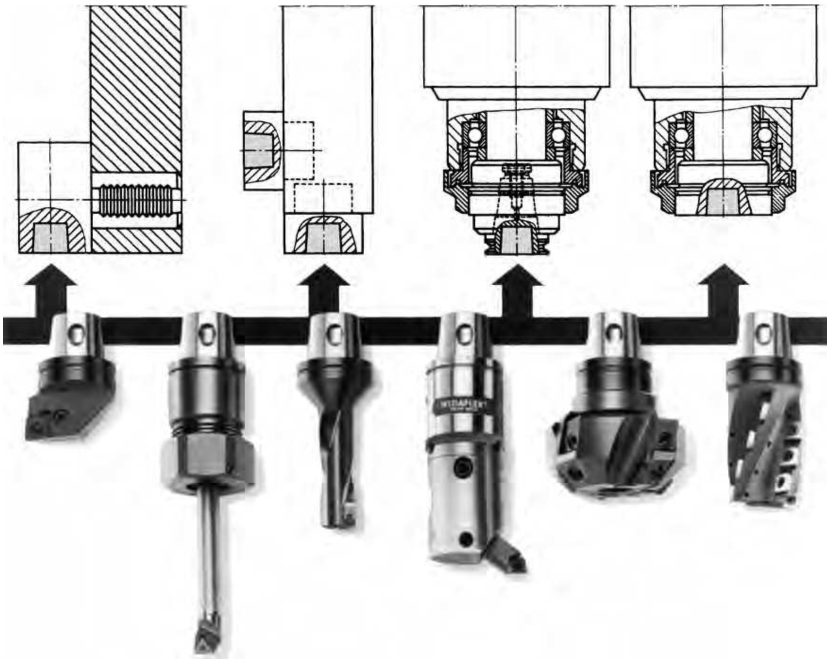

Fig. 4.1. The ‘modular tooling concept’ based upon both angular and face contact, illustrating a variety of rotating and stationary holders and machining operations

Note: courtesy of Widia Valenite.

On say, a turning center using this KM modular quick-change tooling – for the ‘intermediate’ size range, the ‘front-and back-ends’[5], can withstand tangential cutting loads of 12 kN. At this level of cutting force, the actual mechanically-clamped front-and back-ends closely approximates to that of a ‘solid’ 32 mm squareshanked toolholder – in terms of its mechanical integrity. However, when the initial KM tooling review was made concerning the ‘dimensional envelope’ of machines that might employ this modular quick-change system, it was found that a 40 mm round-shanked system was the largest that could be easily accommodated (i.e. see Figure 4.3). Hence, this diameter was selected for the coupling, with adaptors for sizes ranging from 25 to 80 mm, for use on both turning and machining centers.

Fig. 4.2. ‘Modular tooling concepts’ allow ‘qualified tooling’ to be set up with the minimum of adjustments, thereby significantly reducing downtime

Note: Courtesy of Kennametal Hertel.

Once the basic configuration had been established and selected, to meet both the dimensional and repeatability criteria, the actual shape of the mechanical coupling could be considered. It was evident that the male portion of the mechanical coupling would be used for the cutting tool unit, as it would present the smallest overhang, therefore being less influenced by deflections resulting from high tan-

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[5] ‘Front-and back-ends’, is general workshop terminology that refers to the cutting unit (i.e front-end) and its mating toolholder situated in either the pocket, of tool post (i.e. backend).

gential loading whilst roughing cuts were taken. A secondary, but nonetheless important operational factor, was that a male cutting unit would provide more protection for the taper and the locking mechanism, once the cutting unit was removed.

Fig. 4.3. 'KM' modular quickchange tooling system being manually- fitted/changed – using the T-bar wrench, into a turning center's turret

Note: courtesy of Kennametal Hertel.

With the taper's geometric configuration yet to be finally determined – more will be mentioned on this subject in the next paragraph, it was necessary to decide on the method of achieving contact between the taper and the face. From a design viewpoint, there are two basic methods of providing this face contact, these are:

1. Metal-to metal contact – by holding very close tolerances on both halves of the mating male and female couplings.
2. Elastic distortion at contact – by designing a small amount of elastic distortion into the coupling assembly.

As the male portion of the mechanical interface was located and attached to the cutting tool, any such deformation would take the form of expansion of the female taper in the clamping unit. In exhaustive testing procedures, an optimum performance occurred with a combination of pull-back force coupled to elastic deformation. This latter method of utilizing an elastic distortion design, resulted in improved static and dynamic stiffness, when compared to the much more costly manufacturing technique of metal-to-metal configuration of the alternative mechanical coupling.

When the design and geometry of the taper size was considered, it was determined that the gaugeline[6] diameter had to be as large as possible, in order to promote the highest possible stiffness to the tooling assembly. As the wall thickness would have been affected a compromise of 30 mm was decided upon. The final design decisions concerning the joint-coupling were concerned with its length and taper angle. For example, if a steep taper angle had been utilized, this greater angle would have caused an increase in the force required to produce the necessary elastic deformation in the female half of the coupling. Conversely, a slow taper – of smaller included angle, would have had the effect of increasing the force necessary to separate the male and female tapers – acting like a 'self-holding taper'. Therefore, after this design evaluation exercise, the latter 'self-holding' version was selected, as it produced the optimal taper, namely of: 1: 10 by 25 mm long. This taper angle and length gave the best combination of stiffness and forces for locking and unlocking the mating parts. The taper equated to the ubiquitous Morse taper and, had the added bonus that limit gauges[7] were commonly available for checking tolerances during their production.

Once the coupling geometry had been established, the locking mechanism could be considered. Using computer-aided design (CAD) techniques and in particular, sophisticated software, namely, finite element analysis (FEA), allowed for a full investigation of the locking mechanism in-situ within the relevant portions of the male and female tapers. Techniques such as FEA, were utilized on key portions of the mechanical-interface couplings, to ensure that the correct strength and durability levels occurred. Moreover, extensive 'life-testing' was also conducted, to avoid unexpected failures of the tools in-service, which might otherwise prove significantly costly to remedy. The locking mechanism (i.e. indicated by the sectional line diagrams in Figure 4.1 – top) used hardened precision balls to produce a system which has high mechanical advantage[8], cou-

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[6] 'Gauge-line', refers to the taper length and its respective diameter. From here, is where the taper's length is datumed, for tool offset measurement of the cutting unit in the tool-presetting machine, for 'qualifying tooling'.

[7] Limit gauges, are a form of attribute sampling of the Go and Not Go tolerances for this Morse taper.

[8] Mechanical advantage (MA), is the term used to obtain greater output from a smaller input, using some mechanical mechanism, such as by using either a: lever, pulley, discsprings, etc. A mechanism's mechanical advantage, can be expressed in the following manner:

MA = Load (N)/Effort (N) no units

For example, in this case the MA was 3.5: 1 for the ball-lockup sequence, using the 55° machined angle in the taper, giving: the resulting coupling a clamping force of >31 kN, this being produced by either a draw-rod, or disk-spring pulling force of 8.9 kN.

pled to low frictional losses and was a reasonably low-cost solution. This tooling mechanism employing a mechanical-interface for the ‘front- and back-end’, produced a locking force of > 31 kN, while fitting into the taper with a gauge-line of just 30 mm. The balllock mechanism used two balls that locked into the machined holes through the taper shank of the cutting unit (Figure 4.1 and 4.2). This lock-up configuration, allows either a Ø9 mm draw-rod, or disk-springs to be used to apply the necessary pull-back force. The holes in the tapered shank – into which the balls are seated, have a machined angle of 55°, this result in a mechanical advantage of 3.5: 1. As the disk-springs – used in this method – are pulled back, it forces the two balls radially outward until they lock into the tapered machined holes, as depicted in Figure 4.3 – where an Allen key T-bar is used to activate the lock-up sequence, via a series of back-to-back disk-spring washers. To release the cutting unit’s front-end, a force is applied by the T-bar, which pushes these disk-springs and releases the balls, while at the same time it ‘bumps’ the cutting head and in so doing, releases it from its selfholding taper.

Referring to the lock-up sequence once more. Once the cutting unit is inserted into the female taper (i.e. back-end), it makes contact at a stand-off distance of 0.25 mm from the face. Therefore, as the locking force is applied, a small amount of elastic deformation occurs at the front of the female taper. As the cutting tool is locked-up, there is a three-point contact that takes place: at the face, the gauge-line and at the rear of the taper. Finally, if one compares the coupling’s stiffness with that of a solid-piece unit which has been machined to identical dimensions, then when a 12 kN is applied – to simulate tangential cutting loads – the difference in deflection between them, would be only 5 µm. Hence, this modular coupling tooling assembly, closes approximates to that of the ultimate rigidity found if a solid-piece cutting tool was utilized.

Tooling Requirements for Machining Centres

Machining centers with their in-situ automatic load/unload tool-changers and tool-storage carousels, or magazines, have reduced cut-to-cut times significantly, allowing faster response times to the next machining requirement of the CNC program. If a tooling-appraisal is made of the tool-storage facility of machining centers, it would soon be apparent that less-than-total capacity occurs. This noticeable under-storage tooling capacity may be due to one, or more of the following reasons:

- Heavy tooling requirement in the tool-storage system – because of the tool storage system’s configuration – such as a chain-type magazine (Figure 2.4 – tools have to be widely-spaced to allow the magazine to be kept evenly-balanced.

- Large tools situated in the magazine – this normally requires that the adjacent pockets must be left empty, so avoiding them fouling each other upon magazine rotation (Figure 2.4).
- 'Sister-tooling' requirement – this allows for duplication of the most-commonly-used tools, as they are more susceptible to breakage, or wear, enabling longer overall machining time for the production run, prior to a complete tool changeover.

NB This latter point of employing a 'sister tool' strategy, has the effect of significantly reducing the variety of tools that can be held in the finite amount of pocket-space available on many magazines, carousels, etc.

In order to increase the capacity of a tool-storage system, while simultaneously expanding the range of tools that are available during a production run, modular tooling has been developed which further extends the machine's capability and versatility. With today's modular tooling all being of a 'qualified size'[9], they can be prepared from a centralised preparation/storage facility, then transported to the machine tool automatically – more will be said concerning this level of sophisticated tool management toward the end of the chapter.

So far, the relative merits of utilising a modular quick-change tooling system for machining centres has been discussed. Today, such systems can be used for both rotary and stationary tooling operations on machined workpieces. A 'tooling exemplar', of such tools, is the 'Capto system'[10], being an amalgamation of a self-holding taper and a three-lobed polygon (i.e. see Figures 4.4 to 4.6). This novel tooling mechanical interface design, features a tapered polygon, which is an extremely difficult geometric shape to manufacture for both male and female couplings (Figure 4.4 – bottom left). However, this tapered polygon offers multiple-point contact in a robust and precision coupling, allowing high torques to be absorbed for both rotating and stationary tooling (Figure 4.5). Complete 'Capto' systems – ranging in their available diameters – are presented for a variety of machine tool configurations, which are obtainable with a wide variety of 'back-ends' to suit many differing tool pocket styles (i.e. see Fig. 4.6 – e.g. ISO, VDI, ANSI, etc.).

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[9] 'Qualified tooling', this refers to all of the tool's offsets being known – this allows the tool to be fitted into its respective pocket in the tool storage facility, with the tool offset table updated, allowing the tools to be utilized, without the need for presetting on the machine tool, prior to use.

[10] 'Capto system', was developed by a leading tooling company, its name is derived from the Italian word for: 'I hold firmly' – which seems somewhat appropriate for an excellent mechanical interface between the 'front- and back-ends' on a modular tooling system.

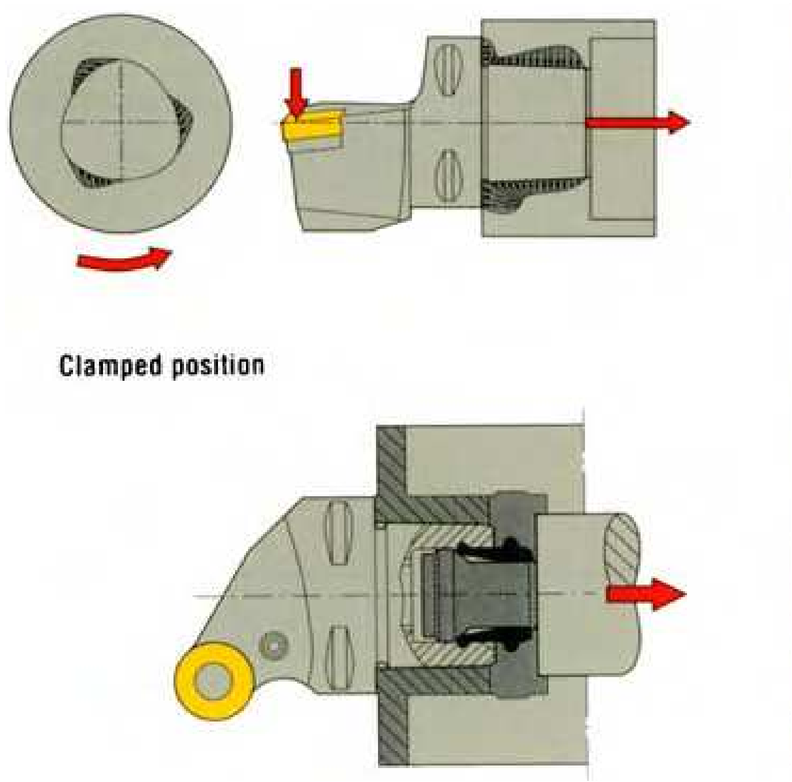

Fig. 4.4. Modular tooling ‘capto’ with tool security and precision location via face and lobed taper contact

Fig. 4.5. Modular tooling (Capto) illustrating stationary (turning) and rotational tooling (milling, drilling, etc.), with indentical lobed and tapered ‘back-ends’

In order to enhance the use of say, the ‘KM-type’ of modular tooling still further and to ensure that a positive location between mating faces occurs, it is possible to utilise an electronically-activated backpressure device, coupled to the CNC controller. With this system in-situ, the tool-locking procedure, could be as follows:

1. ‘Old tool’ is removed from ‘front-end’ – this occurs by either activation of the tool-changer (i.e. on a machining centre), or a tool-transfer mechanism (i.e. on a turning centre).
2. Compressed air purges the female taper – this has the effect of cleaning-out the debris – fines[11] – from the previous tool’s cutting operation.
3. ‘New tool’ is inserted into ‘back-end’ of toolholder – its male taper is cleaned, then it begins to seat itself in the female taper.
4. As it is pushed firmly home to register with its opposing taper – the back-pressure is electronically monitored and, a signal indicates that seating has taken place and this data is sent to the CNC controller, confirming coupling has been firmly locked.
5. Tool is ready for use – this unmanned operation allows the next turning, or machining operation to commence.

The spindle nose taper fitment is an important factor in obtaining the necessary accuracy from modular quick-change tooling. Here, the ‘spindle cone’ must run true to the spindle’s Z-axis and the pull-stud pressure should be checked to ensure that it is within the machine tool manufacturer’s guidelines. Often when problems occur at the spindle taper, it is the result of several factors:

- Pull stud pressure variation – this should be checked to ensure that it is within manufacturer’s specification.
- Spindle nose drift – this is the result of perhaps running the spindle at continuously high rotational speeds, resulting in the spindle nose cone ‘thermally-growing’, leading to the simultaneous: X-, Yand Z-axes drifting several micrometers (e.g. this thermal drifting can often account for around 10 μm of compound angular ‘spindle cone’ movement), which could present a problem for any close tolerance component features requiring machining.

Much more could be said concerning tool-changing techniques, where tool transfer arms are discarded in favour of the whole magazine, or tooling carousel being moved to the spindle to speed-up tool-changing even further. Alter-

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[11] ‘Fines’, are either minute particles resulting from the tool ‘recutting effect’ – in the form of small slivers of material, or is the result of dust/debris created when brittle-type material in particular, has been machined and these particles may electro-statically attach themselves to the machined mechanical interface coupling’s mating surfaces.

natively, gantry-type tool/work delivery systems are available, or complete turrets previously equipped with 'qualified' tooling can be delivered, for unmanned operations, in a 'lights-out'[12] environment. The techniques for tool delivery to keep machine tools in operation virtually continuously is a vast topic, which goes way beyond the current scope of this existing tooling-up discussion.

All of these rotational modular quick-change tools can be successfully utilized up to speeds of approximately 12,000-rev min^{-1}, without any undue problems. However, once rotational tooling speeds increase above this rotational level, then invariably it is necessary to redesign the tool assemblies, allowing them to be dynamically balanced, this will be the theme of the next section.

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[12] 'Lights-out' machining environments, refer to either completely un-manned machining, or minimal-manning levels. Some companies, run an fully-automated machining 'night-shift' without any personnel in attendance, allowing the lights to be turned out, thereby saving significant electrical power cost, when this factor is taken over the year's usage.

5. BALANCED MODULAR TOOLING FOR HIGH ROTATIONAL SPEEDS

When rotational spindle speeds are very high, the conventional ball-bearing spindles are limited and have an upper velocity of ≤80 m sec–1, this is where the balls lose contact with the journal walls and begin to promote 'Brinelling'[13] within the raceways. It is not usually the case, for a conventional milling spindle to be utilized at rotational speeds >20,000 rev min–1, without due regard for the: centrifugal force, frictional effects and spindle cone roundness levelling variations, that are likely to be present beyond these speeds. For any dynamic unbalance[14] of the tooling assembly to occur, this will happen, if the mechanical interface is not secure – more will be said on this subject in the chapter describing high-speed milling operations. With balanced tooling in mind, cutting tool assemblies were developed that minimized rotational unbalance, being based upon the HSK taper fitment, shown in Figures 5.1.

The most important advantages of this exemplary mechanical interface with its tapered hollow shank, coupled to its axial-plane clamping mechanism (i.e. based upon: HSK-DIN 69893), is as follows:

- High static and dynamic rigidity – the axial and radial forces generated in the tool shank, provide the necessary clamping force.
- High torque transmission and defined radial positioning – the 'wedging effect' between the hollow taper shank and holder/spindle, causes friction contact over the full taper surface and the face (Figures 5.1ci and cii). Two keys engage with the shank end of the toolholder, providing a 'form-closed radial positioning': thereby excluding any possibility of setting errors.
- High tool-changing accuracy and repeatability – the circular form engagement of the clamping claws within the hollow tool shank, provides an extremely tight connection between the shank and holder/spindle (Figure 5.1cii).
- High-speed machining performance – improves in both locking/clamping power and effectiveness with increased rotational speed. The direct initial stress between the hollow shank and the spindle holder, compensates for the generated spindle expansion promoted by centrifugal force and, in so doing, negates any radial play. The face contact clamping, prevents any slippage in the axial direction (Figure 21cii).

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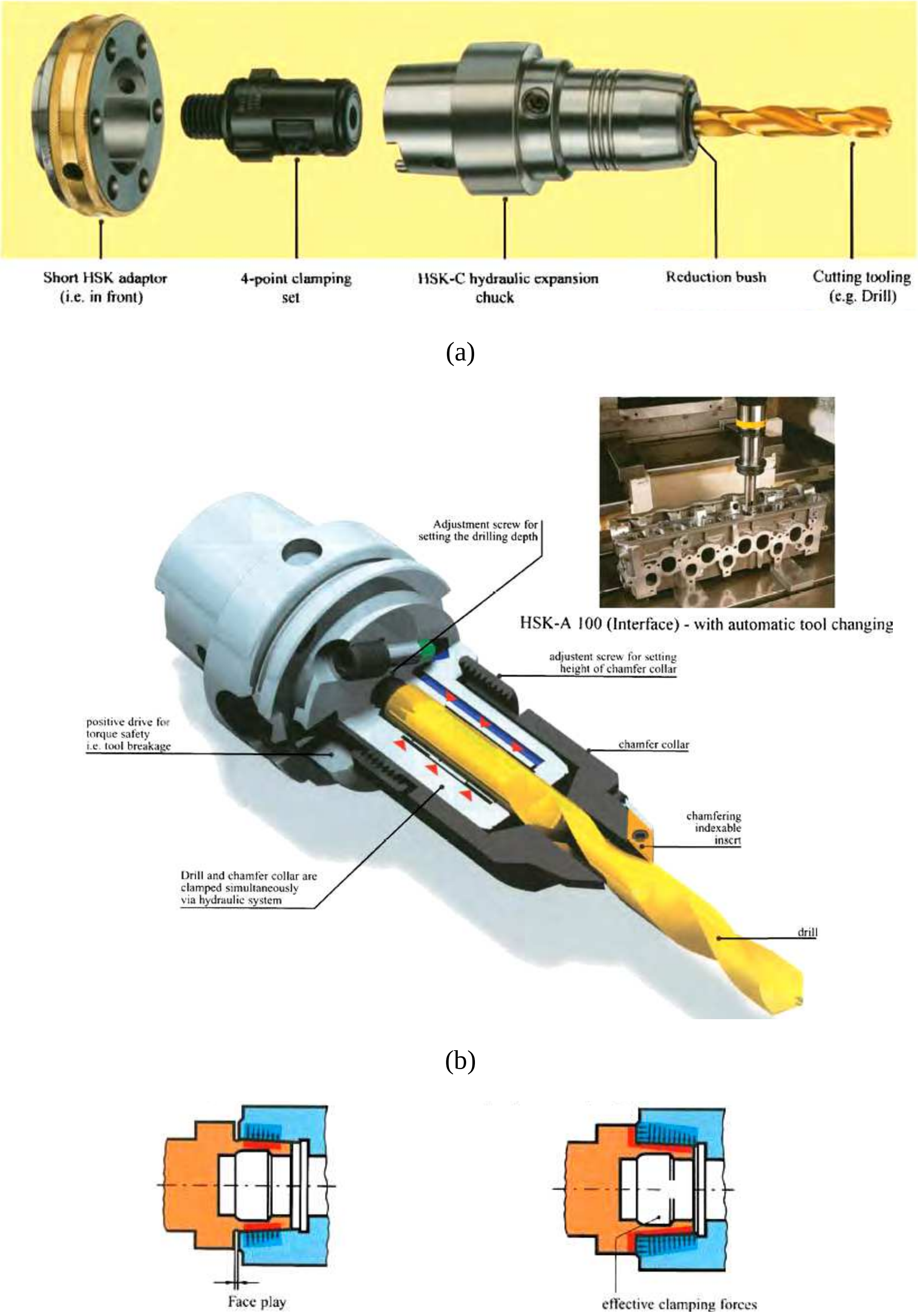
[13] 'Brinelling', creates break-down and delamination of the raceways as the 'unrestrained' hardened balls strike both the internal and external races at high speeds, causing them to prematurely and catastrophically fail in-service.

* Brinell hardness – uses a ø10 mm steel ball – hence the name.

[14] 'Dynamic unbalance', can occur in either of the two tooling planes, these are either radial, or axial movement, related to the high rotational speeds of the cutter assembly. In many cases, dynamic dual-plane balance can be achieved, using specialized tool assembly balancing equipment (i.e. see the chapter concerning high-speed milling applications).



(a)

(b)

(ci) (cii)

Fig. 5.1. HSK high-speed modular tooling,
for machining applications on turning/machining centers:
(a) HSK – an exemplary mechanical interface design;
(b) sectioned HSK: chuck, collar and sleeving; (ci) fitting position; (cii) clamping position

- Short tool changing times – due to much lighter tooling, when compared to a conventional ISO taper: the shank is about 1/3 of its length and, approximately 50% lighter in weight.
- Insensitive to ingress of foreign matter – the uninterrupted design of the ring-shaped axial plane clamping mechanism, simplifies coupling cleaning. During an automatic tool-change, compressed air purges mating surfaces and provides cleaning at the interface.
- Coolant through-feed – via centralized coolant feed by means of a duct, which also excludes ingress of coolant, as the front- and back-ends are entirely sealed – preventing fouling of the mechanical interface.
- Tool shank construction is both simple and economic to produce – as no moving parts are present, thus significantly minimizing any potential surface wear.

These major tooling advantages for the HSK-type tooling design, has shown a wide adoption by companies involved in high-speed machining applications, throughout the world today. In the following section, a case is made for tool-presetting both ‘on’ and ‘off’ the machine tool, with some of the important tooling factors that need to be addressed. The problems associated with tool-kitting and the area for undertaking such activities will be discussed, in order to ensure that the tools are efficiently and correctly assembled, then delivered to the right machine tool and at the exact time required – this is the essence of successful ‘Tool management’.

6. TOOL MANAGEMENT

Manufacturing industries involved in machining operations encompass a wide variety of production processes, covering an extensive field of automation levels. Not only will the cost of investment vary from that of simple 'stand-alone' CNC machine tools, to that at the other extreme: a Flexible Manufacturing Systems (FMS), but other factors such as productivity and flexibility play a key role in determining the tooling requirement for a particular production environment (Figure 6.1). Each machine tool, operating either in isolation (i.e. in a 'stand-alone' mode), or as part of a manufacturing cell/system, needs specific tooling (i.e. tool kits) to be delivered at prescribed time intervals. Such tooling demands are normally dictated by the devised sequence of production from some 'simple' form of manufacturing requirement, to that of a highly sophisticated computerized 'Master Production Schedule' (MPS).

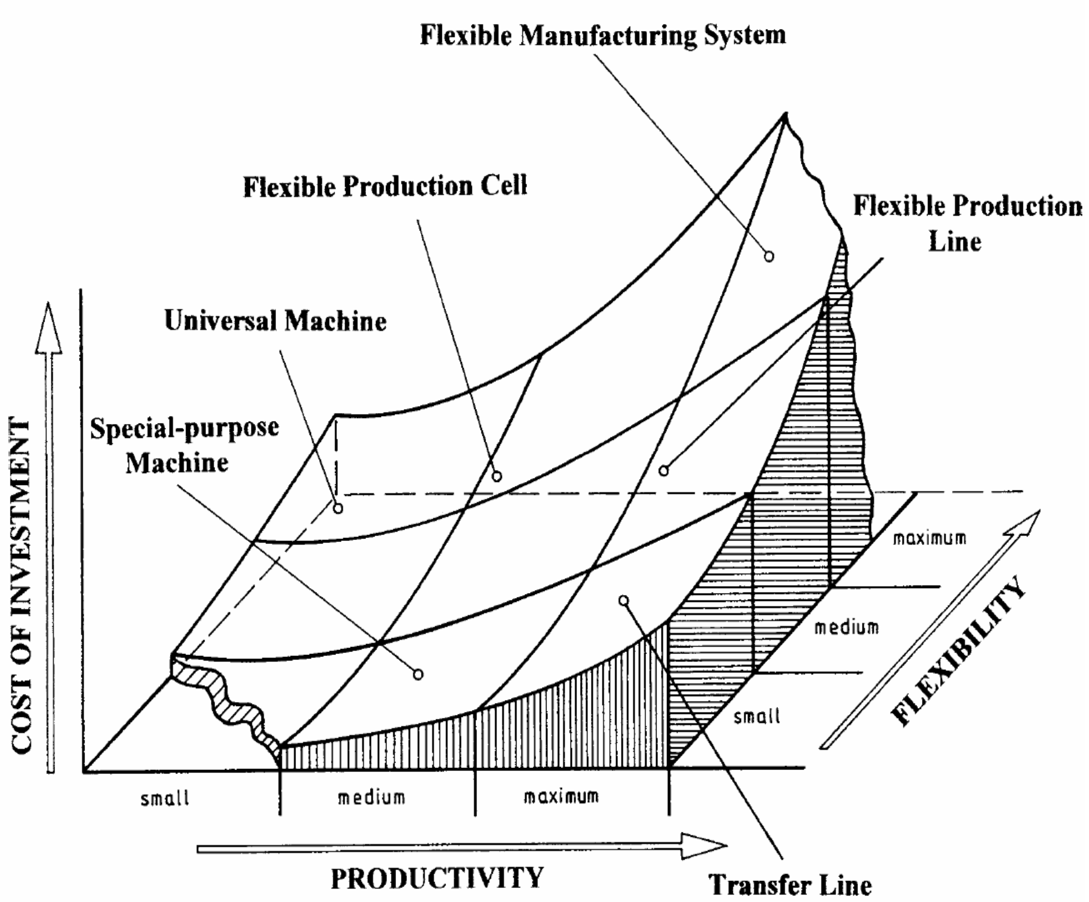


Fig. 6.1. A comparison of manufacturing systems based upon the following criteria: automation level, productivity and investment costs

Note: courtesy of Scharmann Machine Ltd.

With the introduction of CNC machine tools in the late 1970's, the drive has been towards smaller batch sizes, this has meant that some form of tool management has become of increasing importance in machining operations, in order to keep down-time[15] to a minimum. In an USA survey of tooling activities conducted some years ago into manufacturing companies involved in small-to-medium batch production using CNC machine tools, the tooling requirements and scheduling left a lot to be desired, in terms of efficient tool management – verging in some cases, on the chaotic! In Figure 6.2, the diagram depicts the typical 'fire-fighting' concerned with this lack of tooling availability, highlighting the tool problems that were found. Here (Figure 6.2), the diagram illustrates the actual time-loss constituents – in % terms, clearly showing that 'line-management' and operators spent considerable time and effort trying to find tools in the machine shop, or were simply looking for tools that did not exist!

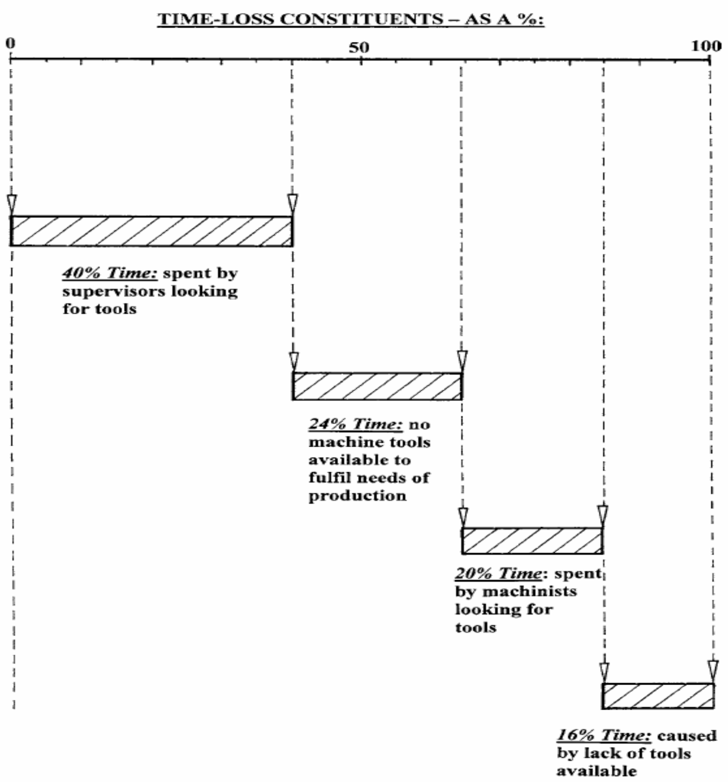


Fig. 6.2. A cutting tool survey of companies in the USA –
illustrating the tooling 'fire-fighting' solutions on the shop floor

Note: courtesy of Kennametal Inc.

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[15] 'Down-time', refers to the non-productive time that occurs when the machine tool is not actually involved in any machining operations. This 'down-time' might be the result of a range of individual, or inter-related factors, such as: unexpected machine tool stoppages, changing and adjusting tooling, setting-up the fixtures/jigs/pallets, planned maintenance, or tools that are simply not available for the machine tool when they are needed!

This chaotic state of affairs, meant that highly-productive machine tools were idle, while this ‘self-defeating activity’ was in progress. With the actual machine tool running costs being so high, this remedial action was somewhat futile and cost these companies considerable financial encumbrance, that would be difficult to estimate – in real terms. Today, some of these problems are still apparent in many machine shops throughout the world, so the tooling problems mentioned here are still valid. Had some form of ‘simple’ tool management system existed within these companies, then many, if not all of these tooling-related problems would have been eliminated. This fact was also confirmed in this tooling survey, by some of the more ‘enlightened’ companies that utilised tool management, either operating at the most elementary level, to that of a highly sophisticated computerised system, that encompassed: total tool control: servicing, presetting, delivery of kits, replenishment of tooling stock levels and monitoring of tooling and its utilisation level within the production operation in the machine shop.

It is not unreasonable to assume, that tooling inventories can be vast within a relatively moderately-sized machine shop (i.e. see Figure 6.3 as it visually indicates the problem of keeping some form of control of the tooling). Not only is keeping track of individual tools and their identification, tool-building, presetting and kitting, together with other tooling-related problems, becoming an almost impossible task, particularly when this is exacerbated by companies attempting to run a JIT[16] philosophy, coupled to that of an MRPII[17] production scheduling operation.

In the past and, for many ‘traditional’ CNC production environments, any form of ‘tool management’ was generally the province of the machine tool operator. So, alongside each machine would be situated a limited kit of tools, these being maintained and replenished with spares and consumables, via the operator’s liaison with the tool stores. Hence, a skilled setter/operator’s main tooling

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[16] ‘JIT’, refers to the manufacturing philosophy of ‘Just-in-time’, where the system was developed in Japan (Toyota – in the main), to ensure a philosophy and strategy occurred to minimize time and production wastages. The JIT policy has essentially six characteristic elements, these are: (i) Demand call – the entire manufacturing system is ‘led’ , or ‘pulled’ by production demands, (ii) Reduction in set-ups and smaller batches – minimizes time-loss constituents and reduces WIP*, (iii) Efficient work flow – thereby high-lighting potential ‘bottlenecks’ in production, *work-in-progress (WIP) levels, (iv) Kanban – this was originally based on a ‘card-system’ for scheduling and prioritising activities, (v) Employee involvement – using their ‘know-how’ to solve the ‘on-line’ production problems, (vi) Visibility – ensuring that all stock within the facility is visible, thereby maintaining ‘active control’.

[17] ‘MRPII’, Manufacturing Resource Planning (i.e. was developed from MRP) – essentially it is a computer-based system for dealing with planning and scheduling activities, together with procedures for purchasing, costs/accounting, inventories, plus planned-maintenance activities and record-keeping.

responsibility was to select the correct tooling, then devise cutting techniques and utilise the appropriate machining data necessary to efficiently cut the parts. This ‘working-situation’ enabled a process planner, or part-programmer to treat the machine tool and operator plus the tool-kit, as a single, ‘self-maintaining system’ – with a well-established performance. Such production circumstances, allowed work to be allocated to specific machine tools, whilst leaving the detailed cutting process definitions: tool offsets, tool pocket allocation, tooling cutting data (i.e. relevant speeds and feeds), coolant application, machining operational sequencing, etc., to that of the operator’s previous skills and knowledge.

Today, with the increasing diversity of work that can be undertaken on the latest CNC machine tools, which has occurred as a result of the flexibility of manufacturing in conjunction with reductions in economic batch quantities, this has change the pattern of working. In order to cope with such work diversity, some ‘stand-alone machine tools’[18] have acquired a very large complement of tools. However, a situation soon develops in which neither the operator, nor the part-programmer is sufficiently in control to accept responsibility for the range of tooling dedicated to any specific machine tool[19]. So, as a result of a full-deployment of CNC machine tools, the production organization related to tooling applications, would normally change to one in which:

- The production process is defined separately – being remotely situated from the shop floor.
- Machining programs and associated tool list are produced – these being sent down to both the machine tool and tool-kitting area via a suitable ‘DNClink’[20], with all of the process data and tooling ‘fully-defined’.

NB There may be some element of doubt concerning the quality of the tooling definition and even the cutting data produced when the part was originally programmed.

- Batch sizes become smaller – the operator is under increasing pressure to run the given program without alteration, which leads to ‘conservative cutting’ resulting in less-than-optimum machining.

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[18] ‘Stand-alone machine tools’, is a term that refers to highly productive CNC machines that are not part of an automated environment, such as either, a flexible manufacturing cell, or system (FMC/S).

[19] If the company has not purchased a computer-aided manufacturing (CAM) soft-/hardware system, then it will not be in a position to take full advantage of the complex aids for tooling-selection criteria available with many of the more sophisticated CAM systems now currently available.

[20] ‘DNC-link’, is a term that refers to the direct numerical control, this being associated with a shared computer for the distribution of part program data, via data lines to remote CNC machine tools and other CNC equipment in a system.

- Machine operator runs the program with the minimum of alteration – this means that the ‘fine-tuning’ of the operator’s past experiences are not utilized, thereby creating inefficiencies in part cycle times.

These factors make the whole operation critically dependent on the ability of the tool-kitting area to supply and support the part programmer’s specific tooling requirements. This is an unsatisfactory and ineffective tool-management system, with the major problem being that there is no feed-back of experiences gained from machining specific components, which is obviously undesirable. This situation results in the part programmer being oblivious to any problems encountered during component machining, causing a further lack of awareness in the tool-kitting area, producing a critical loss of tool management support.

To minimise the problems associated with the lack of information received by the part programmer and the tool-kitting area, feed-back can be established from the operators, which can be for the whole shop, or for each section of machines. Normally, a centralised system based around an appropriate tool file is essential, this activity in turn, would usually be controlled and managed by a file editor. The tool file can be either a manual-, or computer-based system, but will in general, be accessible to the following personnel: process engineer, part programmer, machine operator, tool stores staff, file editor and management, as necessary – with certain levels of access-codes allowing some form of tooling interrogation (i.e. for security reasons). A typical tool file must contain all the information relevant to the needs of all the relevant personnel concerning every tool available – more will be said on this topic later.

6.1. THE TOOL MANAGEMENT INFRASTRUCTURE

Whenever a tool management system has been developed, an organized and well-planned tool preparation facility is vital to prepare the specific tooling requirements – off-line, so that tooling might be:

- Built to pre-defined assemblies – from a range of standardized stocked parts, or from tool modules.
- Replacing worn cutting inserts on used tooling assemblies – these tools being returned for rebuilding, or servicing.
- Measuring tool offsets – then, when it is both timely and appropriate, sending tooling in the form of tool-kits to specified machine tools.
- Inspecting tooling – normally undertaken on tool pre-setters and by visual means, to ensure that they are fit for immediate use.
- Assembling: tooling, fixtures, gauges, etc., as a ‘complete tool-kit’ – to be issued to the appropriate machine tool at the correct time.

In order to ensure that consistent and accurate tool preparation occurs, a documented 'historical procedure' covering all tooling-related aspects, is necessary, such as: tool inspection, servicing and building, is required for each tool. These factors can be controlled by utilizing a computerized tool management system, as only the data files will need to be updated, together with tooling assembly instructions, with both servicing and inspection being undertaken by a step-by-step approach – if needed. Many of the more sophisticated tool management systems currently available, offer a link back to the original Computer-aided Design (CAD) software, allowing tools to be shown graphically assembled as tool parts.

As the these tools travel around the machining facility, through various stages of preparation and measurement, then assembled as 'qualified tool-kits' visiting machine tools and then travelling back to the tool preparation area for re-servicing, each stage of the tool-kit's cycle must be controlled. Information concerning the tool kit's progress, must be available at any instant and, a means of exercising control is to link each tooling station to a central computer via a DNC-link. As the unique data referring to any tool is stored within the central computer, its identity can be accessed allowing its 'logistical progress'[21] to be precisely tracked within the manufacturing facility. For some companies that are unable to justify such a complex tool management method of tooling control, then a much less costly and simpler 'manual system' using either printed labels, or bar-codes can be deployed for tool identification when delivering tooling to-and-from the required machine tool. A cautionary note concerning the use of paper labels for tool identification, is that they can more easily become detached during the machining cycle.

In an automated machining environment, there is no real alternative but to have a 'tooling requirement' and in particular, employing some form of 'intelligent/tagged' tooling, typically via permanent machine-readable tool identification. Such tool identification techniques, allow the necessary data to be interrogated and retrieved from critical areas around the production facility: machine tools, preparation area and storage, plus other peripheral areas – as required. Tooling equipped with 'intelligent' memory circuits embedded within them (i.e. typically shown in the case of the non-rotating 'Block tooling' in: Figures 3.1, 3.2), can automatically perform the functions of: tool identification, tool offsets and cutting data up-dating on the machine tool. Other information complement-

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[21] 'Logistical information and knowledge', in any production environment is vital and has been defined (i.e. by the Council of Logistics Management – CLM), in the following manner: Logistics is the process of planning, implementing and controlling the efficient, cost-effective flow and storage of: raw material, in-process inventory, finished goods and related information, from point of origin to point of consumption for the purpose of conforming to customer requirements.'

ing the tooling data-base pertaining to tool servicing needs can also be exploited by using these ‘tool-coded data chips’, which are securely situated within the ‘front-end’ of each tool.

So that ‘complete tooling control’ is maintained over all the items necessary relating to tool-kits, it is possible to extend stock control over all the tooling requirements out on the shop floor (Figure 6.3). Such tool-tracking is important and certain logistical questions must be known, such as: what tooling is where, is it timed to be there now and, what is its present condition, together with other specific questions, which need to be addressed, indicating the complex task of monitoring all tooling, via a computerized tool management system (Figure 6.4). Tool control software enables these physical transactions associated with the: tooling, servicing, kitting, recalibration, etc., to be achieved, without loosing track of any individual tool items. The tooling software will also continuously monitor stock levels, allowing replenishments be actioned, once any itemized tool stock level falls below a certain pres-set value.

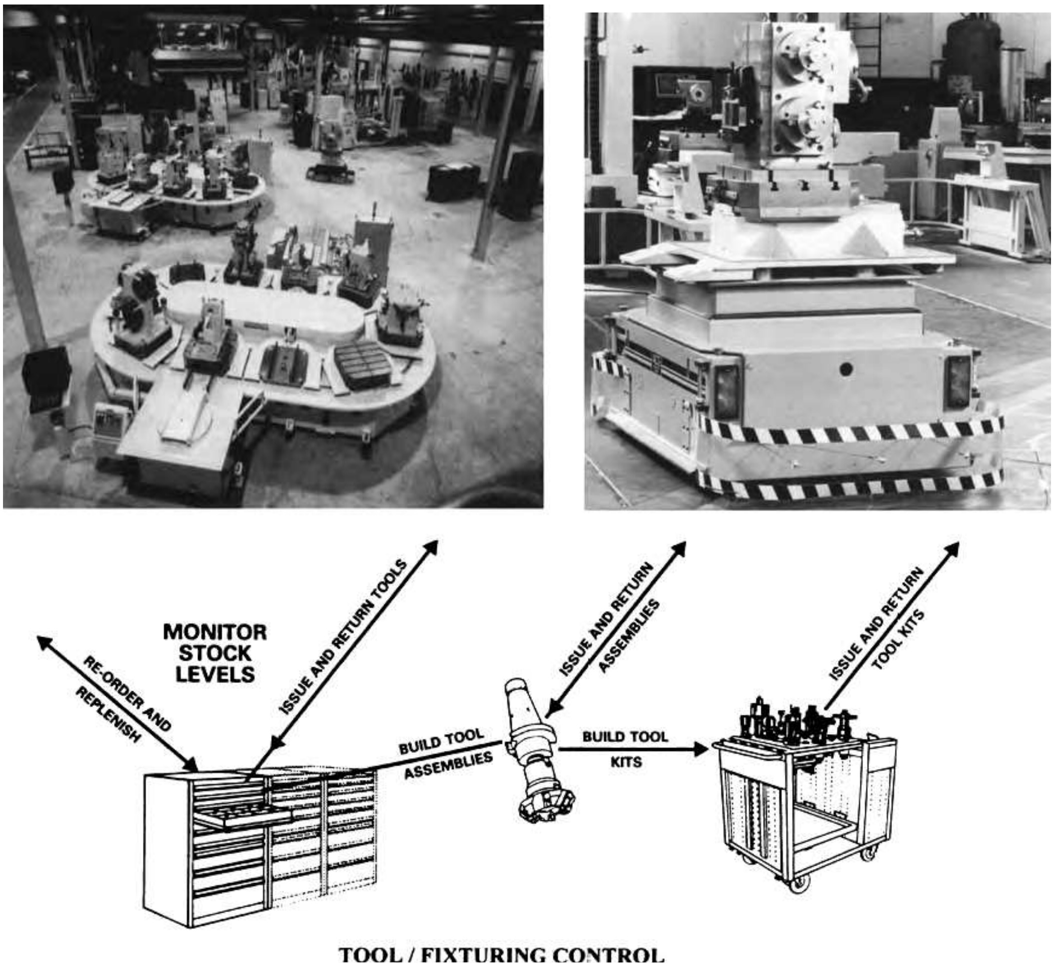

Fig. 6.3. Tooling and fixturing must be precisely controlled at the ‘focal-point’ of kit build-up/replenishment – at the tool preparation area

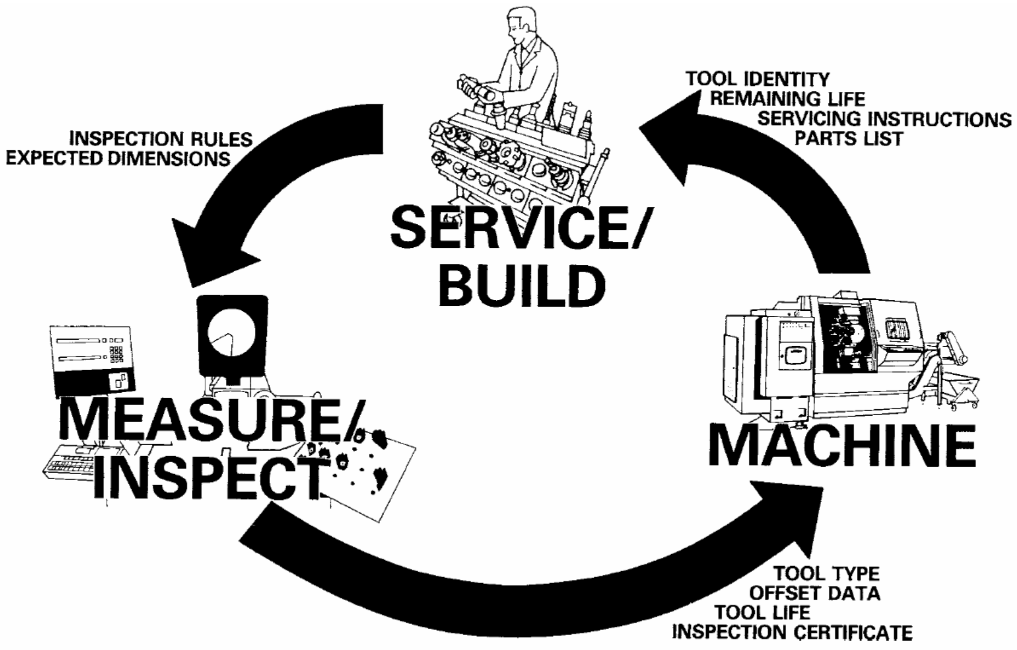

Fig. 6.4. Efficient tool management of tool kits around the manufacturing facility, requires some form of 'tool tracking and identification' – as 'kits' are: serviced and built, measured, the sent to an awaiting machine tool

Note: Courtesy of Sandvik Coromant.

Obviously, it is important to create a suitable tool management system, that can operate successfully in a company's machine shop and it needs to be customized to suit their particular tooling requirements from a relevant database. These tooling-related matters will form the basis for a discussion in the following section.

6.2. CREATING A TOOL MANAGEMENT AND DOCUMENT DATABASE

Prior to any new machining activities being undertaken and, in order to establish the 'true' production requirements of a company, it is essential that co-operation and information regarding the customer's potential product occurs. More specifically, this detailed dialogue should be between both the sales and manufacturing departments. The first requirement is an understanding of the manufacturing load, typically these being broken-down into the following batch and volume classifications[22]:

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[22] Optimum/economic batch size, this will vary, but if batch size is graphically-plotted against cost , for values of set-up cost and holding cost, then the overall total variable cost can be derived, with the lowest plotted value representing the minimum cost batch size 'Q'.

- Job shop – one-, or two-off specialised workpieces.
- Small batch – up to perhaps 50 workpieces.
- Medium batch – between 20 to 100 workpieces.
- Large batch/Volume production – >100 workpieces.

NB These classifications of batch size are open to considerably much wider interpretation, obviously depending upon a specific company's production requirements and the actual machined part's: complexity, material cost, machining operations and its dimensional size and so on!

At any workpiece quantity greater than the 'Job shop' levels having similar production processes undertaken, allows them to be grouped into 'families', according to their: dimensions, tolerances, workpiece materials, etc. This technique of allocating components to be machined into similar groupings is often termed 'Group Technology'[23].

It is vitally important that both the Sales and Marketing personnel are aware of the company's patterns of manufacture and their capabilities, if the company is to be able to rapidly respond to their customer's needs. The sales force will be able to relate a customer's requirements to the standard range of parts produced, with the manufacturer being in a position to 'fine-tune' even small production runs for maximum efficiency. By comprehending the manufacturing process for the company's standard-ranges, allows the optimum conditions of production to be utilized, even when 'modified standards', or even 'specials' have to be produced. Flexibility here, plus the ability to cater for unique customer needs, may offer new market opportunities for the company.

6.3. OVERALL BENEFITS OF A TOOL MANAGEMENT SYSTEM

By the correct implementation of a basic, but competent tool management control system, the following list highlights the 'rewards' that can be expected:

- Manpower is conserved and training requirement minimized.
- The number of tools lost, or misplaced is reduced.
- Timely and up-to-date information on tool usage is produced.
- Tool inventory shortages are identified and prevented.

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[23] 'Group Technology' (i.e. GT), is essentially utilized for 'groupings' in two distinct varieties: (i) Component geometry – the 'closeness of shapes', (ii) Similar production processes – such as: Milling, Drilling, Turning, etc. The benefits of utilizing a GT-approach to manufacture are: smoother logistical work-flow, simplified work control, more efficient plant layout and improved use of floor-space, contributing to enhanced manufacturing versatility and better response to variable workpiece shoploadings.

- The accuracy of the tooling inventory is improved.
- Inventory levels and excess purchasing are minimized.
- Time spent on re-ordering, etc., plus ‘piecemeal purchasing’ are reduced.
- Record-keeping functions are consolidated.
- Tool tracking and tooling availability within the machine shop is monitored.
- Tools in rework can be tracked.
- A record of scrapped tools can be kept.
- Obsolete tooling can be identified and then eliminated.
- The cost of the total tooling inventory can be critically-assessed.
- The gauges and fixtures supplied with the tool kits can be identified and tracked.
- Machine tool set-up, tool-return and withdrawal times are reduced.
- Possibility of pin-pointing over-use machining problems, by specific personnel.
- Improper charge-outs, losses, or pilferage can be minimized.
- Space requirements and overheads are reduced.
- Possibility of incorporating existing tool numbers and current mode of operation into an automated system, without making radical changes.

Tool management systems provide all of the above benefits, by allowing the operations to be easily reported, analyzed and corrected, enabling timely decisions to be made, concerning the tooling, with the minimum of manpower and operational changes necessary. So that the information required by a company can be obtained, the system should be organized to allow personnel responsible for the tools to record their activities. On the ‘shop floor’ , it is the usual practice to allow two basic groups of the workforce levels of responsibility/access to the system to provide both vital and helpful tooling information, these are the: Tooling-supervisor and Stores personnel.

So far, the information on Tool management systems has been principally concerned with the justification and benefits that accrue through the adoption by a company and the philosophy underpinning its practical application. In the ‘continuous circle’ of tool monitoring and control, the tool-kitting area is at the ‘heart’ of the overall tool management procedure. This vital day-to-day activity of tool preparation and setting, will be the subject of the following section.

6.4. TOOL PRESETTING EQUIPMENT AND TECHNIQUES FOR MEASURING TOOLS

Cutting tools that are to be utilized on CNC machine tools for the production of workpiece features, need to have exact measurement information regarding their offsets known, so that the CNC program can automatically displace (i.e. offset) the tool these dimensional distances, in order to perform the intended machining task. Otherwise, major errors in the machined component's dimensional features would result. Hence, cutting tooling can be classified under three distinct headings, these are:

1. Unqualified tools – these are tools that do not have known dimensions, therefore they must be independently measured and these values can then be located and placed into a 'suitable field' within the CNC Controller's tool table. Typical of such tooling, are special-purpose form tools that may be considered to fulfil this classification.

2. Semi-qualified tools – these are tools where not all of the tool measurement offset data are known. For example, a typical Jobber drill's diameter would be normally be known – say, Ø12 mm[24], but perhaps its length for the purposes of utilizing it immediately would not. Therefore, it would necessitate measuring the drill's length, once it has been suitably located and held in an appropriate chuck.

3. Qualified tools – are when all the tool offset data are known and this information can be readily input into the CNC controller's tool table. Typically, 'Modular quick-change tooling'[25], can be considered under this category.

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[24] Whenever a tool's dimensional size is known, it is necessary to refer-back to the individual tooling manufacturer's tolerance specification, in order to establish the limiting values when this data is utilised, when the tool is to be used without any form of pre-measurement being undertaken.

[25] Modular quick-change tooling, such as the 'front-end' cutting units, fitted into the already machine tool-pocketed and located 'back-ends' , typified by the 'KM tooling' ranges, would give the following repeatability readings:

- Axial tolerance ±0.0025 mm.
- Radial tolerance: ±0.0025 mm.
- Cutting-edge height tolerance: ±0.025 mm.

NB All of these tooling manufacturer's tolerances, limit the machining tolerances that can be held, unless they (i.e. already placed within quick-change tools in their respective holders) themselves are measured, which tends to negate the rationale for their original purchase!

Presetting on the Machine Tool – Tool Contacting

When setting an ‘unqualified’ tooling dimension – such as a drill’s length, on the machine tool, this being the crudest form of tool presetting. It is achieved on say, on a vertical machining center, in the following manner: the cutting tool’s tip is held in the machine’s spindle and is positioned over the table, being slowly ‘jogged-down’[26] until its just touches a suitable ‘setting block’[27]. The Z-axis position is then noted and its value is automatically entered into the tool table, giving a ‘semi-qualified’ tool offset, that can then be used for the important Z-axis motion – when coming down onto the workpiece’s surface to begin engaging in the first cut. If each tool length has to be input into the tool table’s ‘offsets’ , then this simple procedure has several disadvantages: it is labor-intensive, ties-up cycle considerable time, it is rather inaccurate and, it sets only one offset dimension. In the case of turning centers, the technique of determining offsets is different, but similar limitations still apply.

A tool presetting device is often used on many of today’s machine tools, this technique is typified by the ubiquitous ‘touch-trigger probe’[28]. Hence, this type of tool-contacting presetting probe fulfils a number of ‘quoted benefits’, such as:

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[26] ‘Jogging-down’ – sometimes referred to as ‘inching-down’, is a manual means of slowly lowering the tool’s tip down onto a surface – in this case a known height ‘setting-block’. This linearly-controlled action is achieved, by employing the ‘handwheel’, which allows the handwheels angular rotation to be equated to an operator preselected incremental amount. This incremental motion can be changed to a smaller value, as the block is slowly approached, to give a sense of ‘feel’ (i.e somewhat like using a ‘feeler-gauge’), as contact is made between the tool and the block.

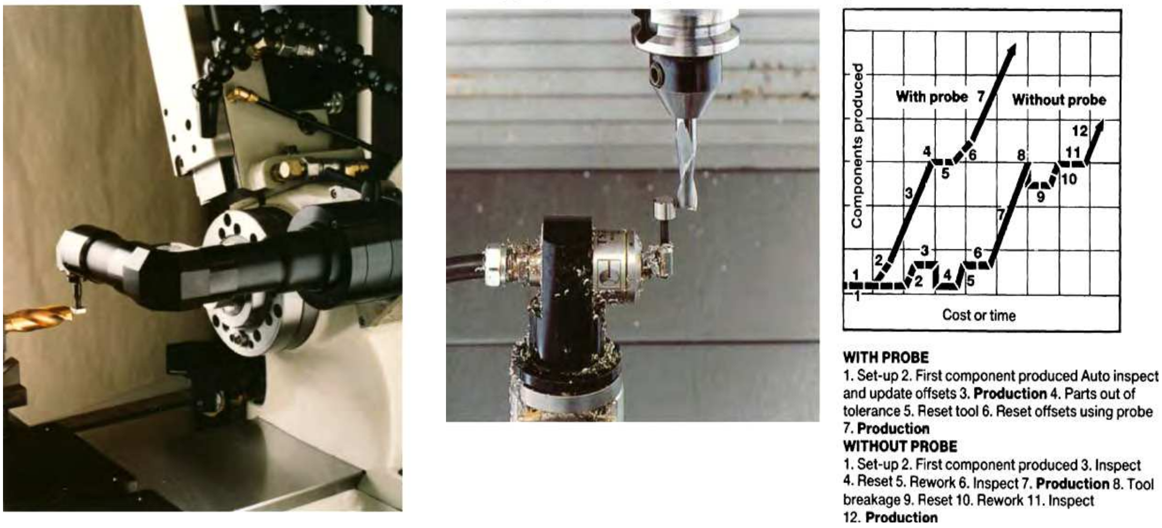
NB The tooling is usually kept stationary while this manual setting activity is undertaken.

[27] ‘Setting blocks’, are usually manufactured from hardened steel, that have been accurately and precisely ground to a known dimensional size and tolerance, nominally to some conveniently ‘round figure’ , for example:100 mm in height. These ‘blocks’ are usually either rectangular, or round in cross-section. The rectangular ones are preferred, because different nominal dimensions can be utilized for each adjacently flat and square face. The tolerance for the ‘Setting block’ should be ‘very close’, as any difference from the nominal size when input into the tool table, will impinge on the overall workpiece tolerance, in essence, somewhat reducing the tolerance’s ‘working range’.

[28] ‘Touch-trigger probes’, in the simplest form these ‘tool probes’ are omni-directional switches, that are sprung-loaded, which when the tool makes contact with either an attached setting cube, or a cylindrical ‘setting gauge’ (Fig. 133b), it immediately breaks the electrical circuit. This loss of electrical contact occurs when the three equi-spaced precision rods: each one seated on two precision balls (i.e. each rod being positioned at 120° to each other) in a simple kinematic seating mechanism, are lifted/pushed either individually, or ‘as one’ out of their respective seating(s), which triggers an ‘electrical pulse’ representing a nominal dimension and is automatically recorded as either a length, or radius – in the case of a rotating tool, which then automatically up-dates the tool table’s offsets for this tool.

- Setting/re-setting of tool length and diameter (Figure 6.5 (b)) – automatically up-dating, or correction of the respective tool table offsets, even while the tool is still rotating.
- Measurement of a complete tool station – automatically in just a few minutes.

NB A small vertical machining centre with a 12 to 15 tool station, would take at least 5 minutes per tool, with the traditional manual technique, mentioned above (i.e. see Figure 6.5 – bottom right, inset graph/description).



WITH PROBE
1. Set-up 2. First component produced Auto inspect and update offsets 3. **Production** 4. Parts out of tolerance 5. Reset tool 6. Reset offsets using probe 7. **Production**
WITHOUT PROBE
1. Set-up 2. First component produced 3. Inspect 4. Reset 5. Rework 6. Inspect 7. **Production** 8. Tool breakage 9. Reset 10. Rework 11. Inspect 12. **Production**

(a) (b)

Fig. 6.5. Cutting tool offsets being set on a turning and machining center: (a) tool-setting on a CNC Turning Centre with a 'tool eye' for automatic tool table offset up-dating; (b) tool offset measurement, employing a table-mounted tool setting touch-trigger probe for length & diameter compensation

- Elimination of manual setting errors – tools that are set manually, particularly tooling such as a large diameter face mill, it will be open to errors when setting both height and diameter offsets. This is because each cutting insert may ‘stand proud’ in its respective seating, giving a false offset reading – when stationary. Ideally, the whole tooling assembly needs to be rotated as its offset is set.
- No presetting of tools is necessary – as this is automatically undertaken on the machine tool.
- Accurate and precise ‘First-off machining’[29] – this is the result of confidence in the tool offsets, set by the ‘probing system’.

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[29] ‘First-off machining’, this term is self-explanatory, in that it is the first component produced in a batch which is simply known as the ‘First-off’ the machine. Invariably, this initial component produced, is subject to rigorous inspection procedures, being the ‘initiator’ for calculated data concerning the whole batch’s metrological and statistical variability/consistency.

- In-cycle tool breakage detection – at convenient and programmed pre-selected intervals, the tool's offsets can be checked for either: tool wear – to a prescribed level, or tool breakage, which will automatically stop the machine preventing either further workpiece damage, or part-scrappage.
- Improved confidence in unmanned machining – due to the fact that tool breakage detection periodically occurs, untended machining operations can be undertaken.

These are 'real benefits' that occur when using 'on-machine' tool presetting equipment, but the 'down-side' of such systems is they do utilize some potential in-cycle cutting time. This negative effect using some of the cycle-time, can be significantly reduced for the following presetting system, employing non-contact laser-based tool setting techniques.

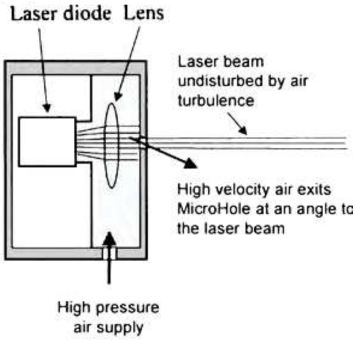
Presetting on the Machine Tool – Non-Contacting Tool Setting

In recent years, laser systems for tool setting and broken tool detection on CNC machining centers have become popular (Figure 6.6), as manufacturers realize the benefits of fast process set-ups and in-process feed-back on the tool's current condition, particularly on diminutive tooling that cannot be easily measured by the more usual contact-type sensors.

Laser non-contact tool setting systems, utilize a beam of laser light which passes between a transmitter and a receiver, located either on the bed of the machine, or on each side of it allowing the beam to pass through the 'working volume' (Figures 6.6 (a) and (b)). Hence, the tool's passage through this beam causes a reduction in light as seen by the receiver, which will then generate a 'trigger-signal'. This 'triggered-signal' for the machine's actual position, is instantly recorded and from which, the tool's dimensional characteristic can be derived. Not only can the system measure the required tool's dimensional parameters, it can also be used to detect broken tools. This tool breakage process involves rapidly moving the tool into a position where it can intersect the laser beam, so, if the light reaches the receiver, and then the tool's tip, or point, must be either missing, or broken. There are quite considerable benefits that accrue by the application of a non-contact laser tool setting system, these include:

- Rapid measurement of both tool length and diameter – tools can be moved into the laser beam at high speed, without risk, or any attendant damage and the tool offsets are automatically up-dated (Figure 6.6 (a)).
- Fast tool setting times can be achieved – tools can be measured at normal rotational speeds, allowing tooling assembly and taper fitment errors such as radial run-out, taper 'pull-back' to be identified, then compensated for by the system.
- Minute or delicate cutting tools can be conveniently measured – without any subsequent tool wear, or damage (Figure 6.6 (b)).

(a)



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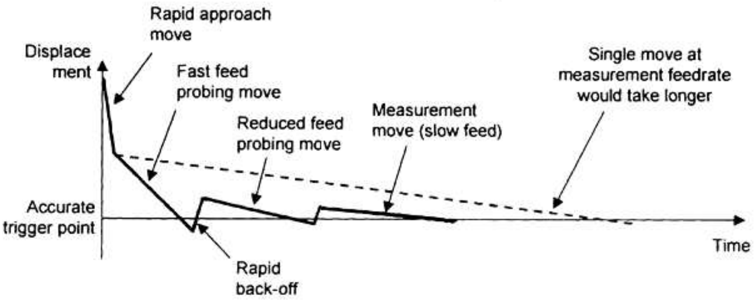
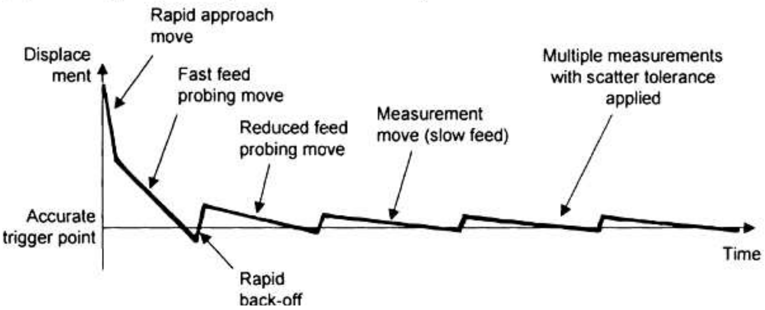
(b)



(c)



(d)

Fig. 6.6. Automatic cutting tool setting and tool breakage detection, utilising an ‘on-machine’ non-contact laser: (a) non-contact Laser tool setting – large tooling; (ai) Laser transmitter; (b) Laser tool setting - micro-tooling; (c) Multi-stage (Laser) tool measurement cycle;(d) Multiple (Laser) measurement cycle

• Tool breakage can be checked at very high feedrates – this efficient process minimises cycletime, while increasing confidence in untended machining applications.

• Multi-point tooling can have each facet checked – this is automatically undertaken while the tool rotates.

• Monitoring tool settings on the machine – enables compensation for any ‘thermal movement’[30] of the machine spindle.

Although the measurement process lasts for only a few seconds, this is long enough for the chance of a falling coolant drip to intersect the laser beam, possibly creating and attendant measurement error. Hence, the laser tool setting equipment, must be able to distinguish between reductions in light at the receiver, created by a ‘falling object’ (i.e. termed: ‘drip-rejection’) as compared to rotating tool, if it is to avoid ‘false-triggering’ producing tool measurement errors. This elimination of ‘false-triggers’, is achieved by the filtering-out of signals by the electronic interface, this value being set at a pre-determined ‘trigger-threshold’. It should be noted, that the laser tool setting system cannot cope with following circumstances: the presence of ‘floodcoolant’, cutter edge and profile checking, nor with radial broken tool rejection processes.

The cutting edge laser measurement is quite a complex process, when the tooling assembly is both rotating and in linear motion simultaneously. If one considers the relative motion of just one of these cutter’s teeth, then, its edge moves in a circular path and superimposed onto which will be the axial feedrate, this motion being perpendicular to the laser beam. Hence, for each of the tool’s revolutions, the prominent edge approaches the laser beam by an increment, this value is the feed per revolution. Such incremental movement introduces a potential error into measurement of the tool’s size. For instance, if a tool rotates at 1,000 rev min–1 while feeding toward the laser beam at 100 mm min–1, it will be seen to advance by 100 μm between intersections of its prominent cutting edge to that of the ‘stationary position’ of the laser beam – this being the maximum possible ‘feed per revolution’ error for any one particular reading. Conversely, an improved accuracy can be obtained by rotating the cutter faster, but advancing more slowly. For example, if one wants only a 1 μm rev–1 intersections, this level of accuracy can be obtained by rotating the tooling at 3,000 rev min–1, while advancing at only 3 mm min–1.

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[30] ‘Thermal movement’ of the machine spindle, is important, as the whole tooling assembly can effectively ‘grow’ due to thermal effects, which may present problems – if not compensated for – when very tight machining tolerances have to be held, or maintained across either a high-quality machined component, or for consistency in a large batch run.

In order to minimise cycle times, the tool measurement software, programs the machine tool to move the tooling into the beam initially from a ‘stand-off distance’ that is adequate to account for the uncertainty of tool assembly build-up – this is important when setting the tool’s length, if the tool is held in a collet, or similarly-designed toolholder. So, the initial move is a fast feedrate to gain an approximate position with respect to the laser’s beam, from which the tool is backed-off by a small linear distance. Here, the tool is ‘probed’ at a reduced reduced feedrate, this is necessary to more accurately find the tool’s location, from where a very short distance ‘back-off’ move is executed. Finally, a measurement move is completed at a very low feedrate, so that an accurate measurement is tenable. This complete tool checking process is considerable quicker than approaching with the laser beam at a constant, but low feedrate, from a larger ‘stand-off distance’ – see Figure 6.6 (c). While, yet another challenge to precise and accurate tool measurement, is the result of the presence of either coolant, or debris on the tool’s tip which is about to be measured. The most significant problem facing non-contact sensing, when compared to its equivalent contacting techniques – this latter method achieves ‘hard-contact’ with the tool and can thereby safely ignore any coolant films, or liquid drips – is that in the former case no actual tool contact occurs. This lack of contact in the presence of fluid media, can be overcome by rotating the cutting tool assembly at very high speeds, so as to dislodge any fluid residue, or perhaps another strategy is by utilizing an air-blast on the tool for non-contact measurement.

Yet another software technique that can be used, is the capacity to measure the tooling several times and apply a ‘scatter tolerance’ to check for any variation resulting from measuring ‘something’, other than the tool itself (Figure 6.6 (d)). This software routine will retake readings until it obtains several values within the required tolerance – these ‘tool-checking retries’, plus the ‘scatter tolerance bandwidth’ can be pre-selected by the user.

The detection of broken tools is somewhat less demanding than for tool measurement – in terms of accuracy and precision, although the cycle-time tends to be more critical. The demands on a laser broken tool detection system require it to be ‘active’ at the instant it is required and, be able to operate under the prevailing conditions, instantaneously after machining stops. The laser transmitter for the non-contact tool detection system shown in Figure 6.6 (ai), has been designed with a ‘MicroHole™’[31], this ensures that the presence of coolant does not

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[31] ‘MicroHole™’ – both for the laser transmitter and the optical receiver, incorporate an angled aperture of just 0.75 mm diameter, as this ensures that protection from: coolant, chips, swarf and other debris such as machined graphite fines occurs, because of a continuous stream of air that flows through and along the laser.

affect the integrity of the laser system. In practice, the laser system reliably operates under relatively 'harsh' workshop conditions and the broken tool detection system works in the following sequential manner:

1. Tool's end is moved at rapid traverse into the laser beam by 0.2 mm.
2. Tool breakage cycle is activated via an M-code from the CNC controller.
3. End of tool dwells in the laser beam for between 0.1 to 0.3 seconds.
4. If laser light is received by the optical receiver unit for more than a specified time-period, typically 10 μs, then this distinguishes a broken tool is present.
5. If laser light is not received by the optical receiver unit, then the tool's condition is satisfactory.
6. Tool is the moved rapidly to its respective home position – end of cycle.

NB This detection cycle also enables small tools to be inspected, even when in the presence of 'floodcoolant', thereby minimizing cycle-times.

These laser non-contact tool setting systems, offer many more software-based features, not described here, such as: cutter profile checking routines, together with many inspection/checking routines for either tool measurement, or broken tool detection. Furthermore, laser tool setting systems provide machining-based companies with a rapid, flexible, accurate and precise approach to control tooling dimensions and offer the techniques necessary to increase machining automation.

Universal Measuring Machine – for Checking Tooling

In many machining circumstances, the tool's profile becomes part of the contoured form for the final machined component. Therefore, it is important after the milling cutter has been multi-axes ground to a desired profile, that this form is rigorously inspected, as the cutter's 'rotated-shape' will become part of the final workpiece geometry. In order to establish this ground complex cutter profile, special-purpose universal tool measuring machines have been developed (Fig. 6.7).

Such multi-axes machines have a range of functions, from simply manually-checking elementary cutter forms, to that of fully-automatic assessment of a multi-faceted form cutters. The machine illustrated in Figure 6.7, is based upon 'sound' kinematic principles, equipped with three linear axes and two rotary axes. The high-precision linear guidance motions are controlled by re-circulating ballscrews[32], these being propelled by servo-motors.

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[32] Re-circulating ballscrews, their geometry is based upon the 'Ogival', or 'Gothic arch' principle. This geometry, ensures that point contact occurs between the ball, its nut and the screw, contributing low friction with better that 90% efficiency, at high-velocity slideway translations. Such 'Ballscrews' offer minimal backlash, with better than 5 μm accuracy/precision over 300 mm, typically having high stiffness values of up to 2000 N μm^{-1}.

The incident light measuring technology associated with this type of machine is quite sophisticated (Figure 6.7 (b)), offering 3-D image processing, to permit threedimensional geometrical cutter elements to be fullyautomatically measured – using a 'proximity method' of assessment. The camera, lens and the LED incident light in combination with its automatically dimmable segments, have been designed to operate with: ground, or eroded PCD, cemented carbide and HSS tooling. Special-purpose ambient light filters and an automatic lighting calibration function, ensure that tool coatings, such as: 'chemically-blackened', TiN-coating, or brightly-ground tool surfaces, can be scanned in 3-D, plus their respective profile geometries.

(a) (b)

Fig. 6.7. An automated five axis CNC universal tool measuring machine for metrological and geometric inspection: (a) Five-axis CNC tool measuring machine; (b) the camera, lens and the LED incident light

The image processing software is enhanced, allowing a range of complex tool geometries and profile forms to be evaluated. To gain an understanding of this tool geometry complexity, some of ground tool forms are depicted in Figure 6.9 where 'programming routines' based upon an optical tool presetting machine are shown, for profile assessments. Typically, these universal tool measuring machines (Figure 6.7) have image processing software, allowing for the following tooling-based metrological assessments:

- Incident light image processing – with automatic illumination control, offering 'search-and-run' and auto-focus enhancements.

NB For manual measurement of radial, or axial tool geometries, this is achieved at x200 magnification, having facilities for both image memory and log output.

- Contour-tracking tool/workpiece measurement – without the need to write complex programs which can be readily undertaken.

NB Thousands of tool geometry data points can be measured in just seconds, backed-up with nominal/actual comparison for 'best-fit' which can be speedily and efficiently achieved. This data can then be either printed out – in a 'test log', or saved on a disk – for future reference.

- Fully-automatic measurement of contour radii – giving vertically exaggerated graphical display of tool's profile, with the specified tolerance range, allowing checking for 'transitions' on both the cutter's end and along the tool's shanks.

When a new tool requires measurement, it involves entering only the most important nominal tooling dimensions, while performing any necessary corrections during the automatic measuring procedure, afterward, this information is permanently stored in the relevant section of a tooling database. From this point, any further inspection procedure on the tool geometry, will be undertaken automatically – at the simple touch of a button! Such universal tool measuring machines have tooling-based software measurement programs that permit, inspection of tools, such as: diesinkers, and thread-milling cutters, etc., to be readily inspected. This automated cutter geometry inspection, allows the information to be downloaded back to the CNC multi-axes cutter grinder – for further tool grinding enhancement, or it can be sent to the equipment in the tool presetting area.

Presetting off the Machine Tool

High quality tool measuring equipment has been developed in order to eliminate the disadvantages of tool presetting on the machine tool. Presetting machines (Figure 6.8) are usually designed so that they can accurately and precisely locate the toolholder and its respective cutter, in exactly the same orientation, as it would be situated within the intended machine tool's spindle. Once the tooling assembly has been securely located in the presetter, the tooling's cutting edge(s), can then be measured by a range of means, including: a non-contact optical device, a contacting mechanical indicator, or more 'primitively' using some form of comparator gauges. Hence, by making the necessary tool adjustments whilst the tooling is located in the presetter, the operator can ensure that when this inspected tool is finally located in the machine tool, its respective tool offsets will be confidently known and applied to the cutting operation in hand.

By utilizing a tool presetter to measure and set tools off the machine tool, this has been shown to increase the shop floor productivity by >12% for every machine using preset tooling. Due to the demands for the highest 'up-time' possible in the automotive sector, virtually every production shop employs measured and preset tools. In fact, studies conducted at manufacturing companies using a presetting tooling facility, have noted that by utilizing a presetter, this has been shown to save typical workshops >4.52 minutes every time tools are changed. In the following example on the use of presetters, it was noted that significant productivity time and hence cost-savings can be accrued, these calculations being based upon 20 tool changes per eight hour shift, this gave the following savings:

- Minimum time saved for each tool = 3 minutes.
- Total minutes saved per shift = 60 minutes.
- Calculated productivity increase = 12.5%[33].

Fig. 6.8. Optical tool presetting machine for sophisticated tool management control

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[33] This 12.5% productivity gain, meant that one hour was saved for every eight hours of shift operation. Hence, if the facility was run at the ultimate level of operation, such as in a mass production automotive machining facility, running a continuous three-shift system, seven days per week. Then, a total of three hours per day, or 21 hours per week would be saved, which would mean that the amortization for the capital plant (i.e. the presetter and its presetting environment), would be very short indeed.

Significant tool setting and changing timesavings are only one major advantage from utilizing a sophisticated tool presetter and its associated screen displays in Figure 6.9, other features include: integrated tool measurement and inspection and data-storage facilities. Downloading this tool offset and other important data through a DNC-link to each relevant machine tool, making them a vital part of the overall tool-management system. A high-quality tool presetting machine can set tools to ‘micron-levels’ of accuracy and precision (i.e. typically ± 2 μm), holding these preset levels with confidence as soon as they begin cutting chips – so no ‘trial cuts’ are necessary. Moreover, a range of toolholding ‘backends’ can be accommodated in the machine’s spindle, by using special-purpose adaptors. The tool presetting software guides an operator through the measuring program and other tool management tasks. Within the presetter’s computer memory, an operator can store and retrieve tooling information as necessary, allowing for repeat setups, or replacement tools to be speedily and efficiently measured and set. On the presetter shown in Figure 6.8, this machine allows typical tooling screen displays shown in Figure 6.9, having a photo-realistic input screen, which guides the user through the measurement and setting program in easy-to-follow steps. This data is stored for further use and enables tooling repeatability, with very little variability, allowing each individual set tool to have almost identical offset dimensions. This repeatability ensures that the operator can load the machine tool’s spindle with confidence, allowing for tool-data optimization to be achieved on the machine – when these tools are operating under batch, or mass production runs.

For many of today’s presetting machines, they allow the operator to inspect the tooling with ‘video technology’ (Figure 6.9) to assess for tool wear and its measurement. Flank wear in particular, is often a good guide as to the probable life left in the tooling, prior to a tool change. At a certain level of predetermined wear land, the tool is deemed to need replacing. Not only can a presetter be used for presetting tooling assemblies and for tool wear assessment, it can also be employed to monitor and inspect incoming tooling from suppliers in the ‘as-received condition’ , to ‘Vendor rate’[34] and establish the tooling supplier’s quality levels – in terms of their tool geometry and in certain instances, dimensional tolerances.

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[34] ‘Vendor rating’ (VE), is a basic form of ‘Supply-chain management’ by an organization and is normally used in purchase decision-making. In VE, this evaluation process is formalized to provide a quantitative measurement of ‘Vendor Quality’ (VQ). Therefore, VR is primarily meant to impart an overall rating of a particular vendor for use in: reviewing, comparing and selecting vendors – this procedure being an integral part of a rigorous purchasing process and in some instances is utilized instead of acceptance sampling.

Measuring program
for any parameters

Measuring program
for conical ballnose endmills

Measuring program
for ballnose endmills

Measuring program
for grinding packages

Fig. 6.9. Typical cutter screen displays from an optical tool presetting machine

If a presetting machine's tool set-up and inspection capabilities are combined with sophisticated software, its overall abilities are considerably enhanced. Here, it has the potential to perform both tool and component tracking, together with that of whole tooling assemblies within the production facility, whilst operating as a complete tool management system. With such a computerized-system in place, it can store data on individual components and when required, select the relevant information to assemble a complete tool. This data availability, can include the overall tooling inventory and the operator can monitor the workshop's stock of tools and order replacements, based upon a 'Just-in-Time (JIT)' strategy – by directly ordering from the tooling suppliers computerised-stocklists. In order to obtain maximum efficiency with the tool presetter, this can be achieved by linking it with the in-house computer network. Hence, a fully integrated presetting machine can exchange data with the company's other peripheral-networked computer systems, enabling tool lists and other relevant information for specific production jobs to be down-loaded directly to the presetter.

After the tooling assembly measurements are completed, the presetter can generate the data in a CNC compatible format, then DNC down-load to the designated machine tool, removing the necessity for the machine tool setter/operator to input the tooling and cutting data into the controller, enabling production to begin as soon as the tools are loaded into the tool storage magazine. The latest tool presetting machines equipped with a full suite of tool management features and functions, can play a big role in improving shop: productivity/component quality, tool life, inventory control, whilst minimizing downtime, reducing component cycle times and part scrappage.

Mounting and Adjusting Milling Cutters

Possibly the most crucial cutter body to correctly mount and adjust, for the individual cutting inserts, is that of a side-and-face cutter (Figure 6.10). The reason why it is important to set the cutter assembly up correctly, is that invariably the width of the slot in the machined workpiece is identical to that of the respective rotating face widths of the cutting edges. Moreover, whole cutter assembly must 'run true' as it rotates on its arbor[35] – with no discernible 'wobble' – as this effective 'wobbling' will influence the machined slot geometry. At its most extreme, some of these special-purpose slotting cutters can be > 2 tonnes in weight and larger than 1.5 m in diameter, having segmented car-

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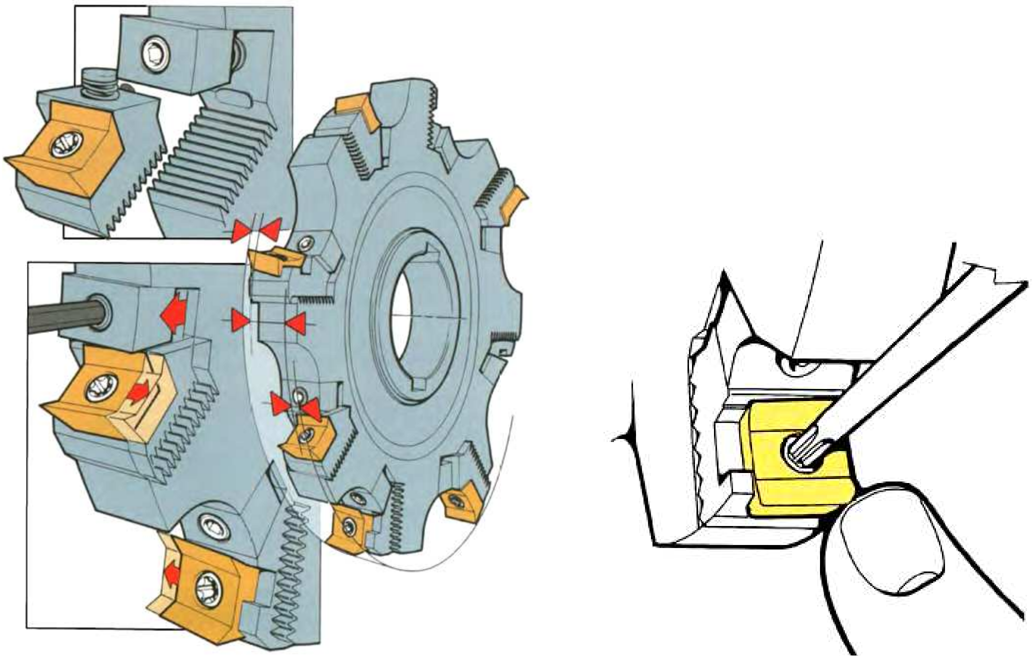
[35] 'Arbor', is the workshop term used for the extension from the machine tool's spindle that the slotting-type cutter is located and driven from. It can be cantilevered – termed a 'stub-arbor', or supported at its free-end, by an arbor-support – normally fitted with adjustable and suitable matched-bearing diameters.

tridges that are precisely and accurately fitted onto the periphery of the cutter body. As a general 'rule of thumb', most of these types of slotting cutters are used to machine component features to a depth of four times their slot width[36]. If a deeper slot is required, then the cutter has to be 'optimized' in some way. Perhaps by using a smaller width cutter than that required for the component's slot width and, if possible, cutting each slot face separately and eventually taking it to the desired width/depth – arbor interference permitting.

Mounting cutting inserts in the case of the staggered-toothed side-and-face cutter body shown in Figure 6.10, is relatively straight forward, due to the lateral adjustment available by the splined cartridge seatings. Here, it is important to ensure that the insert seat is thoroughly cleaned prior to commencing fitment. Moreover, ensuring that the contact against the bottom face of the seat occurs, prior to tightening the set screw – normally to a final torque value of 5 Nm (i.e. illustrated in Figure 6.10 (b)).



(a) (b)

Fig. 6.10. The correct mounting and setting of a cutting inserts
in a staggered-toothed side-and-face cutter body:
(a) mounting & dimensional setting of a staggered-toothed milling cutter;
(b) insert mounting: requires insert seat to be thoroughly cleaned, before commencing
& ensure that contact is achieved between the seat face, prior to tightening the screw,
which has been previously lubricated

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[36] When full slotting, using a side-and-face milling cutter at 40% of the maximum radial cutting depth, a typical feed per tooth would be around 0.25 mm tooth–1.

Each set screw should be lubricated with the recommended lubricant before reuse. In order to ensure that each cutting insert runs true, the slotting cutter, or face mill assembly, should be correctly mounted – in the former case, onto the arbor, the latter into the correct spindle nose taper – being held on a suitable presetting machine.

The whole assembly is then rotated to ensure that each cutting insert is both radially and axially positioned, thereby ensuring that no edges ‘stand-proud’ of each other and at the same time confirming that no discernible ‘wobble’ in the rotating assembly occurs (i.e see the deep-slotting cutter, held in a stub arbor with support, allowing the whole tooling assembly to be rotated and each cutting insert to be inspected/measured, in Figure 6.11).

Although cutter keyways are not strictly-speaking a mounting problem, the subject does need to addressed, as if the cutter’s diameter and its associated driving keys are not considered, this will limit the overall milling performance of the cutter. With most slotting, and side-and-face cutters fitted to arbors, they normally require a keyway/key for rotational driving purposes for the whole cutter assembly. Usually cutters that are <Ø125 mm with insert sizes ranging between 6 to 8 mm, then one key will suffice, but cutters >Ø140 mm with insert sizes of between 11 to 14 mm, they would frequently need two keyways[37].

(a) (b)

Fig. 6.11. Cutting inserts for large diameter cutters require pre-setting to minimize any run-out: (a) a special-purpose deep-sloting cutter utilized for the production of components for the Eurofighter 9 i.e. Typhoon; (b) deep-slotting cutter insert are pre-set to a 10 micrometers run-out tolerance on the tool-presetting machine

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[37] Keyway positioning for two keys – is usually given by the distance between them as: 180° minus half the peripheral pitch of adjacent cutting inserts.

Cutter diameter and driving key limitations, are determined by the cutter's bore and its connected keyway, together with the DOC being limited by several factors: the arbor OD, its mechanical strength, plus any deformation of the driving key(s). For vertical slotting applications, mounting the cutter on an large diameter arbor with the minimum of overhang is desirable. If the feed per tooth can be reduced – assuming component cycle-times will allow – then this will reduce the tendency of key deformation during milling. Milling calculations and key strength, can be obtained from the following expressions and are valid for new cutting inserts:

Torque (T) = P [kW]/n [rpm] × 60,000/2π [Nm]
Force (F) = T/d [mm] × 1,000 [N]
Shear [keyway] stress (τ) = F/area = F/A × E [N mm^{-2}].

NB As the cutting inserts wear, the above values will increase by approximately 30%, therefore, it is usual to add a 'safety factor' to the key(s) material shear strength, by multiplying this value by 1.5.

If special-purpose applications are required, such as when form milling the ubiquitous 'Vee-and-Flat' configuration for an conventional engine-/center-lathe bed, 'gangs'[38] of: side-and-face, angled- and helical-cutters are deployed to form and generate these slideways. Here, it is important to ensure that when presetting the cutters on the tool presetter, that the whole cutter assembly is held in the exact manner that they will be utilised when 'gang-milling'. This 'gang-milling' setup, allows their dimensions and forms to be inspected/measured, while slowly rotating the whole assembly. If two 'helical cutters'[39] are utilized in a 'gang-milling' operation, then their helices should be of the same pitch, but of different 'hands' (i.e. left-ward and right-ward respectively), as this arrangement will balance-out any end-thrust due to opposite cutter helices.

Setting up 'Long-edge milling cutters' – these are sometimes termed 'Porcupine cutters', which are normally required for the heavier and longer cutting applications, is quite a complex presetting process. As the individual cutting inserts must be slowly rotated to ensure that axial and radial run-out values are kept to a minimum. Otherwise those inserts 'standing-proud' of the remainder will suf-

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[38] 'Gang-milling', is a complex forming process utilizing two, or more milling cutters adjacent to one another. So, a side-and-face cutter, located directly together with a helical cutter, represents a 'gang' in its simplest form. This 'gang' of cutters, is normally permanently mounted together for re-grinding and tool presetting – this is assuming that the cutting edges are not made-up from a series of strategically-positions indexable inserts.

[39] 'Helical cutters', are sometimes known as 'Slab-mills', having either a left-, or right-hand helix, which ensures that the length of cut and its shearing mechanism are reduced by a 'quick-helix', which is necessary for the milling of more ductile materials.

fer from greater wear rates, thereby prematurely reducing the cutter's effective life quite significantly while milling an unwanted step into the machined sidewall.

On standard face mills, 'face run-out' can be as high as >50 μm, so when close tolerances and good milled surface texture is mandatory, then extreme care must be taken when presetting such tooling assemblies. In order to assist the presetting of such tooling on some face mills, 'barrel screws' allow fine adjustment to the cutting insert. Such 'barrel screw' designs are quite simply-designed, but surprising effective in both adjusting and retaining the cutting inserts, the following remarks explain how they are designed and their method of operation. 'Barrel screws' (Figure 6.12 (a)), are hardened to resist deformation and have a black oxide finish to minimize corrosion. To prevent them from shifting during a face milling operation, a nylon pellet is embedded in the thread of the 'barrel screw'. Right-hand cutting inserts use left-hand 'barrel screws' and vice versa, as this counter-acting rotation keeps the insert locked firmly in its pocket. The mating surface of a 'barrel screw' is reamed produce a minimum contact of 120° occurs, which ensures accuracy and precision, while minimizing wear. The 'barrel screw' hole is off-set toward the reamed surface, to provide positive contact with the mating surface throughout the range of adjustment of this screw. It should be noted, that these 'barrel screws' cannot adjust the effective 'gauge length' of the tooling, as the amount of adjustment is limited by the position of the cutting insert's clamping screw.

The face-milling cutting inserts are tangentially-mounted, offering considerable support and additional strength to the cutting edge. When presetting the face mill's cutting edges when the cutter body is equipped with 'barrel screws', the following procedure should be adopted:

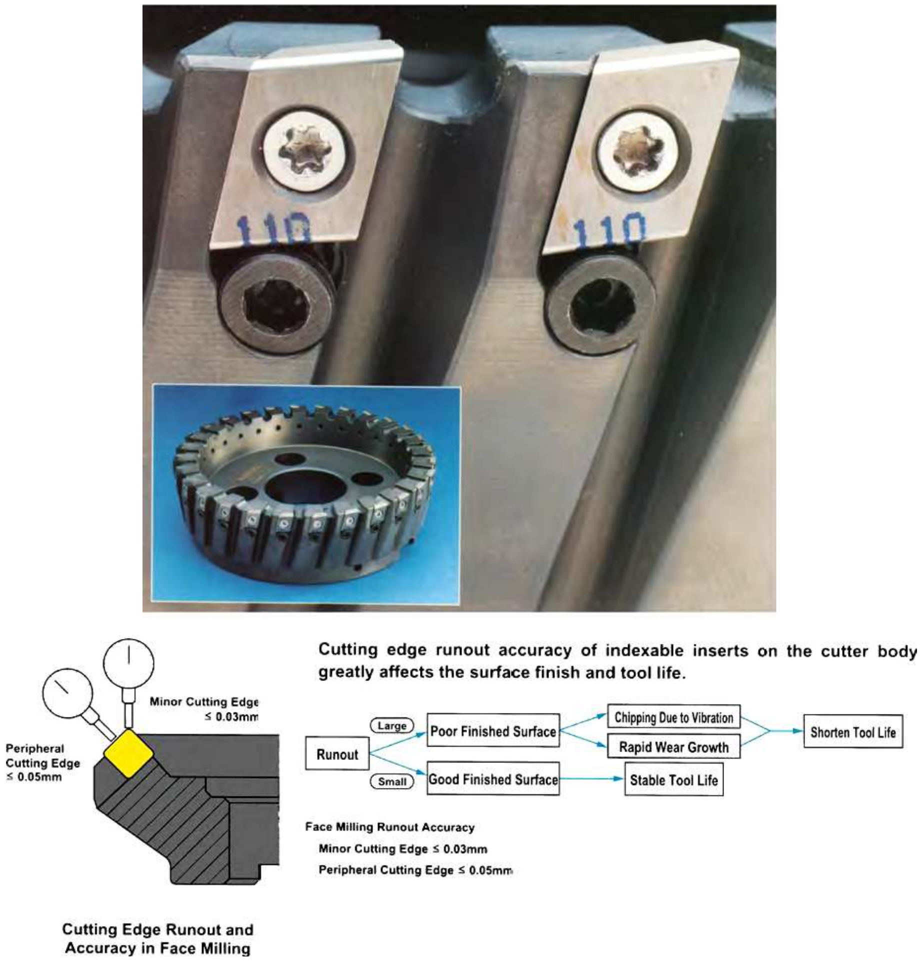
- To adjust the insert outward – leave the cutting insert tight and simply turn the 'barrel screw' to move the insert to the desired setting.

NB Adjustment to the cutting insert's position should only be made in one direction only.

- To adjust the insert inward – loosen both the cutting insert and 'barrel screw', push the insert inward, then tighten the insert's screw and adjust out again to the desired position.

In Figure 6.12 (b), the simple 'flow-chart' highlights why it is important to keep any face milling cutter insert's runout to a minimum. If the run-out of both the minor and peripheral cutting edges is large, then this can create several undesirable problems for the tooling assembly, including:

- Poor surface finish – if a cutting insert 'stands-proud' of the others in the face mill, then it will cut in a similar fashion to that of a fly-cutter, creating a periodically scored surface – after each cutter revolution – degenerating the milled surface texture.



Cutting edge runout accuracy of indexable inserts on the cutter body greatly affects the surface finish and tool life.

Fig. 6.12. Cutting inserts need to be precisely and accurately seated in their respective pockets of the cutter body, to eliminate potential run-out: (a) in order to minimise any milling cutter run-out, barrel screws are situated below the cutting inserts - for fine adjustment and security; (b) insert milling cutter edge run-out accuracy and its affect on tool life

- Chipping due to vibration – as all of the inserts are not set the same, then the most prominent one will take the largest cuts on both the minor and peripheral cutting edges, causing shock loading as the cut is engaged, thereby increasing cutter vibration and potential thermal effects[40] creating the likelihood of chipping here on the most exposed cutting inserts.

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[40] ‘Thermal fatigue’, can be present when cutting is interrupted – as is the case for milling with a prominently exposed cemented carbide cutting insert. Numerous cracks are often observed at 90° to the cutting edge and are often termed: ‘Combcracks’ – due to their visual appearance to that of a typical hair-comb. These cracks, are the result of alternating expansion and contraction of the surface layers as the cutting edge is heated during cutting, then cooled by conduction into its body during intervals between cuts. This very fast alternating heating and cooling cycle, develops the cracks normally from the hottest region of the rake face – this being some distance from the cutting edge, which tends to spread across this edge and down the insert’s flank face. Once these cracks become quite numerous, they can join up and promote partial tool edging to break away – creating cutting edge chipping.

- Rapid growth of wear – because of a prominently set and poorly positioned cutting insert in relation to the others in the cutter body, it will absorb the greatest cutting loads, which will lead to shortened tool life, this being exacerbated by pronounced vibrational tendencies, resulting from unbalanced cutting forces and torque.

NB All of these factors will contribute to a shortened cutter life.

Conversely, if the face milling cutter's insert run-out is small, then a good surface finish and stable and predictable tool life will result.

Mounting and Adjusting Single-Blade Reamers

The replaceable blade is positioned longitudinally by a blade end stop and diametrically adjusted using the front and rear adjusting screws. The blade is micro-adjustable over a limited range of radial movement and can be preset in a special-purpose setting fixture (Figure 6.13 (a) and (c)), to ream the desired diameter that the tool can then consistently produce. This reaming blade normally has a back taper of: between 0.01 to 0.02 mm over a linear distance of between 10 to 25 mm, respectively – when positioned in the pre-setting fixture (Figure 6.13 (b) shows a three-guide pad designed single-blade reamer). A feature of the blade's adjustment, is that it can be reset to compensate for any subsequent blade wear. A clamp, plus two clamping screws securely holds the blade in place, with the wedge-type clamp providing support along the entire blade length. In the case of the single-bladed reamer design, the blade is located and positioned in the reaming head at a 12° positive rake angle. For this type of reamer design, additional standard blades can be fitted, offering both 6° and 0° rake angles.

Taper reaming setting can be achieved by mounting the taper reamer into the special-purpose setting fixture (Figure 6.13 (c)). At least two dial-, or electronic-indicators are positioned along the blade's length, then adjusted so that a very light pressure is applied to the cutting edge of the blade – to prevent it from inadvertently chipping. With the blade 'semi-clamped', adjustment is made so that it is parallel along its length – relative to the tapered guide pads. Once the blade has been 'fully clamped', adjustment occurs to position it higher than its guide pads' diameter, by between 10 to 20 μm – all along the blade's length, which achieves an accurate setting, but this setting will depend on both the workpiece material and the prevailing machining conditions[41].

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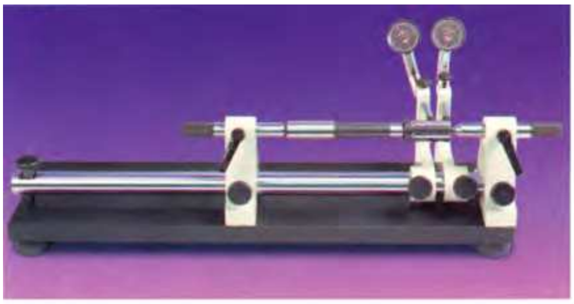
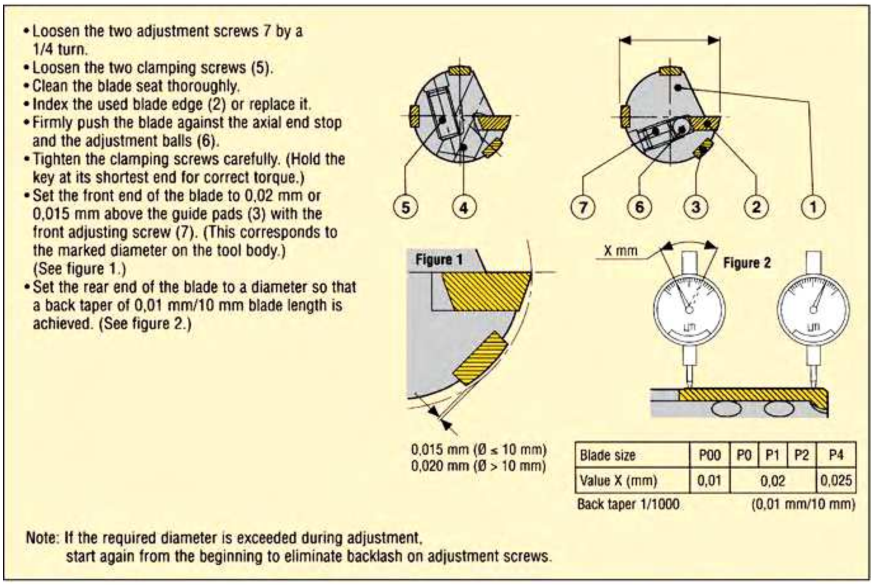
[41] Taper reamers – typical machining details: Cutting speed 4 to 20 m min–1 (Stainless steel 2 to 6 m $\min^{-1}$), Feed 0.2 to 0.8 mm rev–1, machining allowance 0.2 mm and up to 0.5 mm – for large taper reamers, plus Coolant soluble oil 10% dilution.



(a)



- Loosen the two adjustment screws 7 by a 1/4 turn.
- Loosen the two clamping screws (5).
- Clean the blade seat thoroughly.
- Index the used blade edge (2) or replace it.
- Firmly push the blade against the axial end stop and the adjustment balls (6).
- Tighten the clamping screws carefully. (Hold the key at its shortest end for correct torque.)
- Set the front end of the blade to 0,02 mm or 0,015 mm above the guide pads (3) with the front adjusting screw (7). (This corresponds to the marked diameter on the tool body.) (See figure 1.)
- Set the rear end of the blade to a diameter so that a back taper of 0,01 mm/10 mm blade length is achieved. (See figure 2.)

0,015 mm (Ø ≤ 10 mm)
0,020 mm (Ø > 10 mm)

Blade size	P00	P0	P1	P2	P4
Value X (mm)	0,01	0,02			0,025

Back taper 1/1000 (0,01 mm/10 mm)

Note: If the required diameter is exceeded during adjustment, start again from the beginning to eliminate backlash on adjustment screws.

(b)

(c)

Fig. 6.13. Presetting equipment and ‘guidelines’ for the setting of single- bladed reamers: (a) reamer blade adjustment – with manual indicators; (b) typical reamer blade indexing and adjustment, for single-blade; (c) reamer blade presetting equipment for adjustment using electronic indicators for extreme accuracy and precision

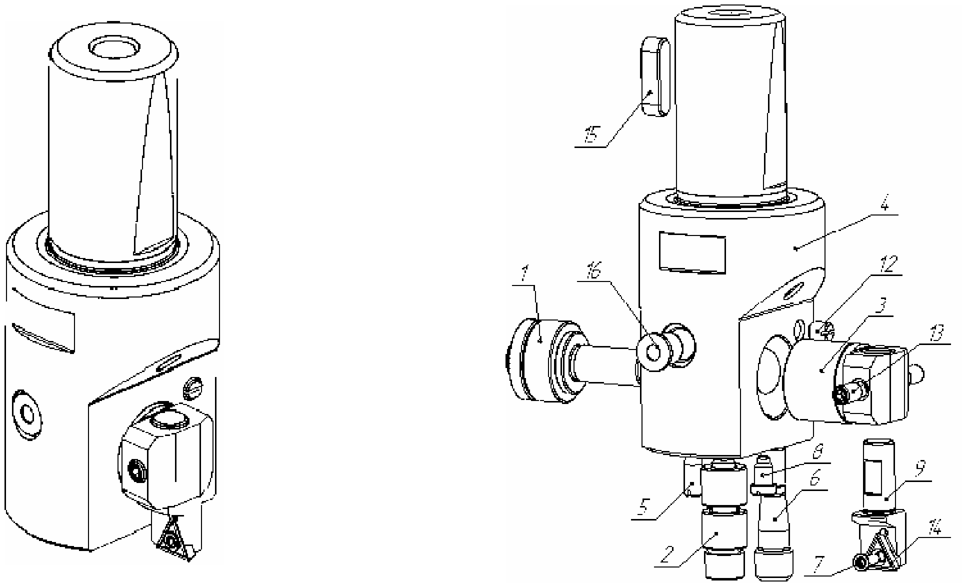
7. BORING HEADS WITH MICROMETRIC ADJUSTMENT OF EDGES

Using the boring tool is especially important solution to improve the accuracy and processing performance and reduce its cost. In addressing these challenges, national and foreign firms use instrumental solutions to improve the designs of boring tools in different directions.

The boring heads have been designed for the whole range of the boring holes with a diameter of 63 – 360 mm. The boring range was divided into the subranges. For each subrange several constructive head variants were designed. Only those variants were selected out of them for the manufacture that meet the technological opportunities of Orsha instrumental plant. It is necessary to note that these constructive variants are the compromise decisions taken by the designers and members of the design department of the plant.

7.1. MODULAR BORING HEAD FOR THE BORES IN THE RANGE OF 63 – 110 MM

In Figure 7.1 (a) shows a general view, and Figure 7.1 (b) – flow sheet of boring head for boring range 63 – 110 mm.



(a) (b)

Fig. 7.1. Boring head for the bores in the range 63 – 1 10 mm: (a) general view, (b) flowsheet

Boring head performed by a modular principle. It includes a cabinet module (bar) 4, which is mounted adjustment module, includes a regulator 1 and slide 3. On a slide 3 is mounted incisal block, consisting of a shank holder 9, which by means of screws 14 is attached plate 7. Shank holder 9 is clamped in the slide with two screws 13.

Controller I is fixed to the bar by screw 5. Slide 3 is fixed to the bar by means of a clamping mechanism 2.

The head is exposed on the size of the movement of the slider 3 by means controller 1. The exact direction of displacement of the slide guide is provided a threaded taper pin 6, the lockable screw 12. To restrict the movement of the slide 3 is used screw 8. For the lubrication of moving parts using oiler 16.

7.2. MODULAR BORING HEAD FOR THE BORES IN THE RANGE OF 110 – 180 MM

In Figure 7.2 shows a general view, and Figure 7.3 – flowsheet of boring head for boring range 110 – 180 mm.

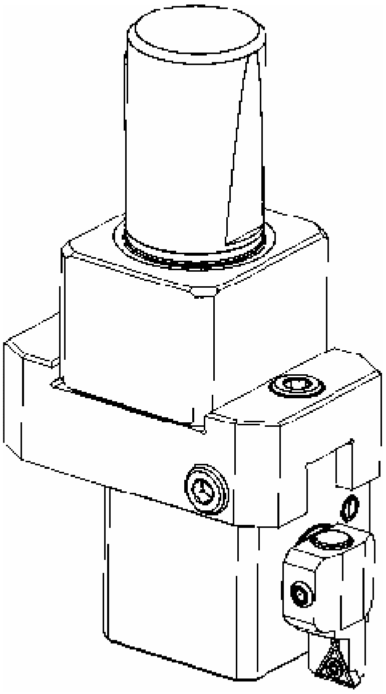


Fig. 7.2. General view of the boring head to the bores in the range of 110 – 180 mm

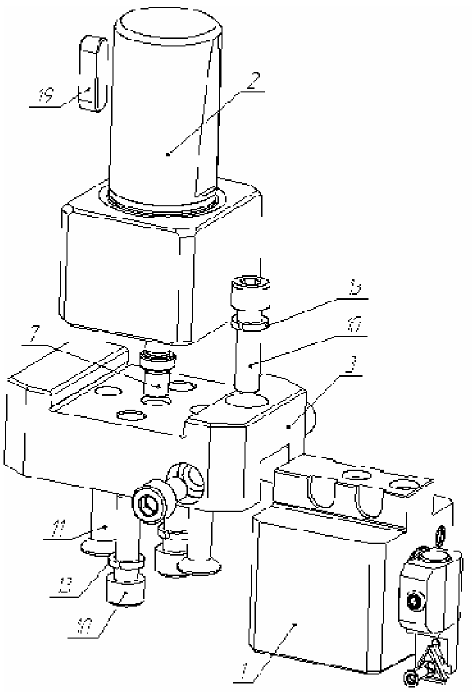


Fig. 7.3. Flowsheet of boring head for boring range 110 – 180 mm

Boring head for the bores holes with a diameter 1 10 – 180 mm performed by a modular principle.

Head design includes a base bar 2 with key 19. The base bar is fixed to the shank that is mounted in the spindle of boring machine.

On the base module bar 2 is installed rod 3 which is centered on the bar with a pin 7 and the screw 10, 11.

In the rectangular guide rods is based moveable boring module 1. Moveable boring module can be fixed in two positions and is attached to the rod by three screws 10. Two positions of a boring module 1 is provided by bores a hole in the two subranges: 110 – 145 mm and 145 – 180 mm (with an overlap of 2 mm). Before processing any range boring module should be exempt from attachment, repositioned, and then clamped by screws 10.

The exact placing the edge on the size of the bore hole is carried out with the control module, mounted in a movable boring unit.]

7.3. MODULAR BORING HEADS FOR THE BORES IN THE RANGE OF 180 – 360 MM

In Figure 7.4 shows a general view, and Figure 7.5 – flowsheet of boring head for boring range 180 – 360 mm.

Boring head for the bores holes with a diameter 180 – 360 mm performed by a modular principle.

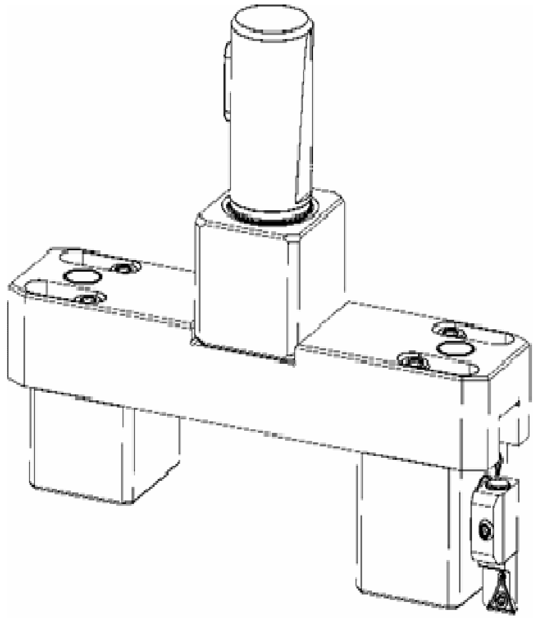


Fig. 7.4. Boring head to the bores in the range of 180 – 360 mm

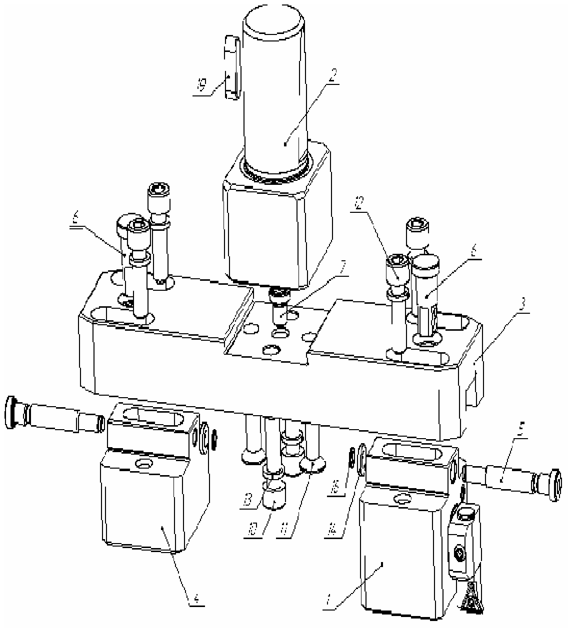


Fig. 7.5. Flowsheet of boring head for boring range 180 – 360 mm

Head design includes a base bar 2 with key 19. The base bar is fixed to the shank whichis mounted in the spindle of boring machine.

On the base module bar 2 is installed rod 3, which is centered on the bar with a pin 7 and the screw 10, 11.

In the rectangular guide rods is based moveable boring module 1. Boring module 1 moves to the guide rod with a means of a regulator and secured with on the rod by two screws 12.

Regulator is a modular unit of construction and is composed of installed in boring module 1 threaded spindle 5, a washer 14 and the ring 16. Regulator's lug 6 is mounted in the hole of rod 3. Coarse adjustment is carried out the size of the bore offset a boring module 1 during the rotation threaded spindle 5 with tempered screws 12.

The exact placing of size of the bore hole is carried out with the control module, mounted in a movable boring module 1.

7.4. THE USE OF MODULAR BORING HEADS IN BORING MACHINE TOOLS MODULES

The boring machine module includes three basic modules: the base adjusting module (for example, a shaft), the intermediate base adjusting module (for example, the extension piece) and actually modular boring head.

In Figure 7.6 the general view boring machine the module without the extension piece for processing of apertures in a range of 240 + 300 mm is represented. Boring machine the module includes a boring head 1, a shaft 2 and elements of fastening 3 heads (screws) in a shaft.

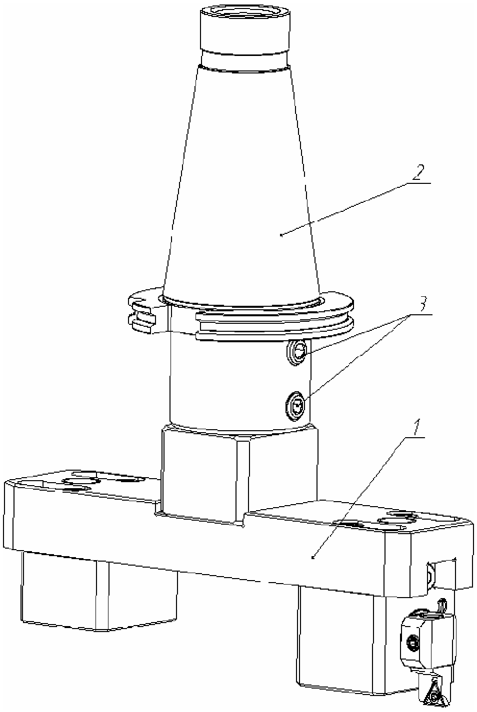


Fig. 7.6. The boring machine module for processing of holes in a range of 240 + 300 mm

7.5. MODULAR MILLS

In practical machining, the included angle of the tool edge varies between 55° and 90°, so that the removed layer, the chip, is diverted through an angle of at least 60° as it moves away from the work, across the rake face of the tool, In this process, the whole volume of metal removed is plastically deformed, and thus a large amount of energy is required to form the chip and to move it across the tool face. In the process, two new surfaces are formed, the new surface of the work piece (OA in Figure 7.7) and the under surface of the chip (BC). The formation of new surfaces requires energy, but in metal cutting, the theoretical minimum energy required to form the new surfaces is an insignificant proportion of that required to deform plastically the whole of the metal removed.

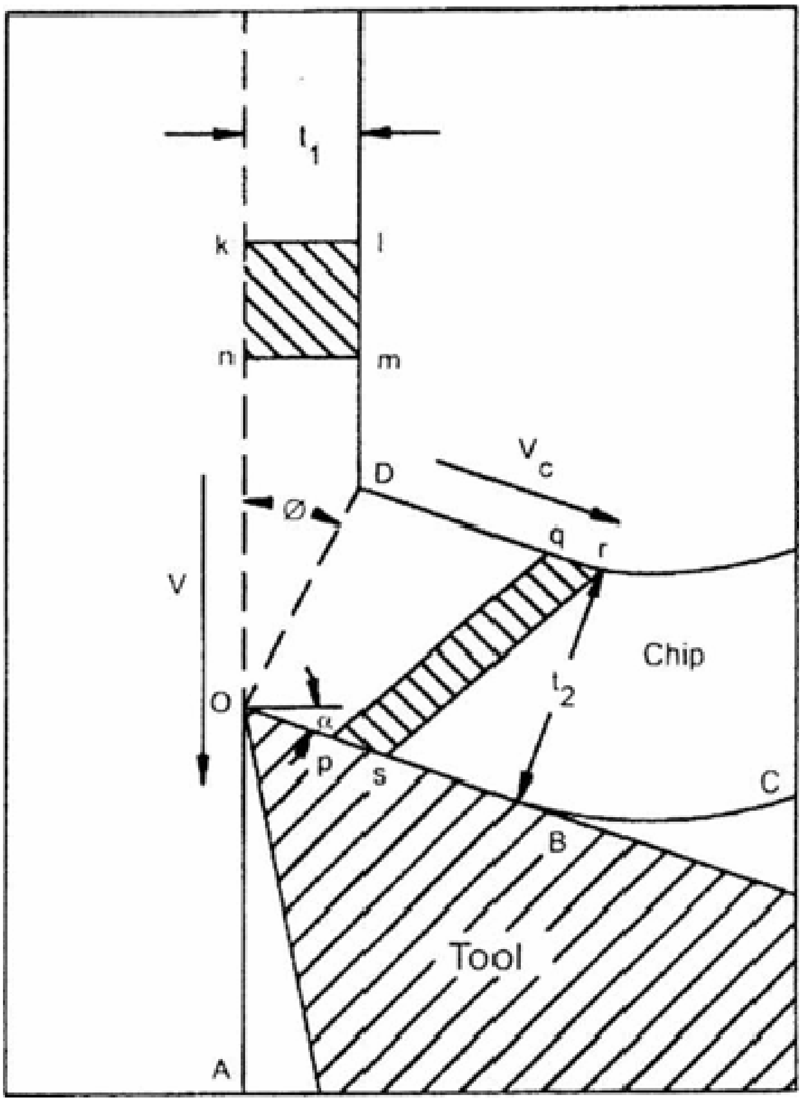
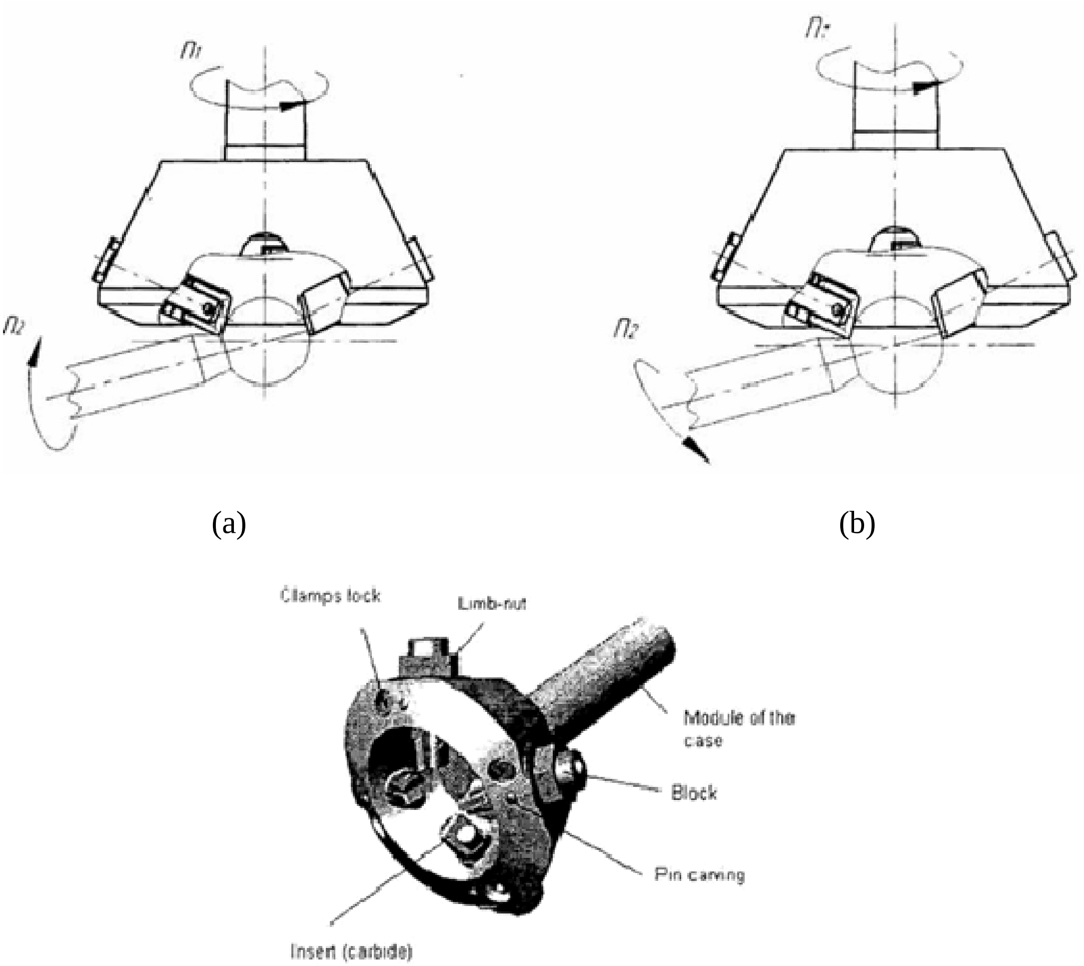


Fig. 7.7. Metal cutting diagram

Both grooves and flat surfaces – for example the faces of a car cylinder block – are generated by milling. In this operation the cutting action is achieved by rotating the tool while the work is clamped on a table and the feed action is obtained by moving it under the cutter, Figure 7.8. There is a very large number of different shapes of milling cutters for different applications. Single toothed cutters are possible but typical milling cutters have a number of teeth (cutting edges) which may vary from three to over one hundred. The new surface is generated as each tooth cuts away an arc-shaped segment, the thickness of which is the feed or tooth load. Feeds are usually light, not often greater than 0.25 mm (0.01 in) per tooth, and frequently less then 0.025 mm (0.001 in) per tooth. However, because of the large number of teeth, the rate of metal removal is often high. The feed often varies through the cutting part of the cycle.



(a)

(b)

(c)

Fig. 7.8. Milling method: (a) Up milling; (b) Climb milling;
(c) Detail of outer sphere surfaces milling with indexable inserts

In the orthodox milling operation shown in Figure 1.2, a, the feed on each tooth is very small at first and reaches a maximum where the tooth breaks contact with the work surface. If the cutter is designed to "climb mill" and rotate in the opposite direction (Figure 7.8 (b)), the feed is greatest at the point of initial contact, outer sphere surfaces milling method may be used either for up mill or for climb mill of worked sphere surface.

An important feature of all milling operations is that the action of each cutting edge is intermittent. Each tooth is cutting during less than half of a revolution of the cutter, and sometimes for only a very small part of the cycle. Each edge is subjected to periodic impacts as it makes contact with the work. Thus, it is stressed and heated during the cutting part of the cycle, followed by a period when it is unstressed and allowed to cool. Frequently cutting times are a small fraction of a second and are repeated several times a second, involving both thermal and mechanical fatigue of the tool. The design of milling cutters is greatly influenced by the problem of getting rid of the chips.

Milling is used also for the production of curved shapes, while end mills, which are larger and more robust versions of the dentist's drill, are employed in the production of hollow shapes such as die cavities. The end mill can be used to machine a feature such as a rectangular pocket with (ideally) vertical walls.

VOCABULARY

A

Adjustable support – регулируемая опора
Allowance for machining – припуск
Arbor – оправка
Assembly – сборка

B

Block-module cutting tool – блочно-модульный режущий инструмент
Boring – растачивание
Boring head – расточная головка
Boring tool – расточной резец
Build-up edge – нарост

C

Carriage – суппорт
Chip – стружка
Chip breaker – стружколоматель
Chip contraction – усадка стружки
Chuck – патрон
Clamping – крепление, Зажим
Climb milling – попутное фрезерование
Collet – цанга
Continuous chip – сливная стружка
Continuous feed – непрерывная подача
Coolant – смазочно-охлаждающая жидкость
Core drilling – зенкерование
Counterbore – цилиндрическая зенковка
Countersinking – зенкование
Countuoring NC system – контурная система ЧПУ
Cross-feed – поперечная подача
Cuttind speed – скорость резания
Cutting – резание
Cutting conditions – режим резания
Cutting edge – режущая кромка

Cutting force – сила резания
Cutting motion – движение резания
Cutting plate – режущая пластина
Cutting tool – режущий инструмент

D

Depth of cut – глубина резания
Discontinuous breaking segment chip – стружка надлома
Drill – сверло
Drilling – сверление

E

Eccentric clamp – эксцентриковый зажим
End mill – концевая фреза

F

Face – передняя поверхность
Face milling head – торцовая фрезерная головка
Facing tool – проходной резец
Feed – подача
Feed motion – движение подачи
Finishing – отделочная обработка
Finishing turning tool – чистовой проходной резец
Fixed support – постоянная опора
Fixture – зажимное приспособление
Flank – задняя поверхность
Flute – канавка
Form tool – фасонный резец

H

Hand loading – ручная загрузка
Hand unloading – ручная разгрузка
Holder – державка

I

Indexable insert – сменная пластина
Inserted-blade milling cutter – фреза со вставными ножами
Intermittent feed – прерывистая подача

L

Lather – токарный станок
Lead screw – ходовой винт
Longitudinal feed – продольная подача

M

Machine centre – обрабатывающий центр
Machine tool – металлорежущий станок
Machined surface – обработанная поверхность
Magazine – магазин
Major cutting edge – главная режущая кромка
Milling – фрезерование
Minor cutting edge – вспомогательная режущая кромка
Modular design – модульная конструкция

N

Nose – вершина режущей кромки
Numerical control (NC) – числовое программное управление (ЧПУ)

P

Positioning NC system – позиционная система с ЧПУ
Primary motion – главное движение
Program – программа
Reaming – развертывание

S

Saddle – продольная каретка
Semi-automatic machine – станок полуавтомат

Single-flute drill – однолезвийное сверло
Single-point tool – резец
Special machine – специальный станок
Spindle – шпиндель
Spot-facing – цекование
Spotted washer – разрезная шайба
Step drill – ступенчатое сверло
Step motor – шаговый двигатель
Straight shank – цилиндрический хвостовик
Strap clamp – прихват

T

Taper shank – конический хвостовик
Thread cutting – нарезание резьбы
Tool angels – углы режущей кромки
Tool life – стойкость инструмента
Tool wear – износ инструмента
Toorning tool – проходной резец
Turning – обточка
Turret lather – револьверный станок
Twist drill – спиральное сверло

U

Universal machine – универсальный станок
Up milling – встречное фрезерование

W

Wedge – клин
Work surface – обрабатываемая поверхность
Workpiece – обрабатываемая деталь
Wrench – гаечный ключ

REFERENCES

1. Yoshimi, Ito. Modular Design for Machine Tools / Ito Yoshimi. – 1nd ed. – Tokyo : McGraw-Hill Professional, 2008. – 504 p.
2. Smith, Graham T. Cutting tool technology: industrial handbook / Graham Smith. – London : Springer; 2008. – 599 p.
3. Gerasimov, A. System of block-module cutting tools / A. Gerasimov, V. Spektor, N. Popok // Materials of II Junior Researchers’ Conference, Novopolotsk / Polotsk State University. – Novopolotsk, 2010. – P. 86–87.
4. Kudelco, A. The Theoretical Fundamentals Of High-Speed Milling / A. Kudelco [et al] // Materials of II Junior Researchers’ Conference, Novopolotsk / Polotsk State University. – Novopolotsk, 2010. – P. 88–91.
5. Gerasimov, A. Manufacturing process of the hub with use of block-module cutting tools / A. Gerasimov, A. Tsubanov, N. Popok // Materials of III Junior Researchers’ Conference, Novopolotsk / Polotsk State University. – Novopolotsk, 2011. – P. 11–13.
6. Maksimchuk, A. Design Of Boring Heads With Micrometric Adjustment Of Edges / A. Maksimchuk, N. Popok // Materials of IV Junior Researchers’ Conference, Novopolotsk / Polotsk State University. – Novopolotsk, 2012. – P. 110–113.
7. Gerasimov, A. Tendencies in the development of boring tool systems / A. Gerasimov, N. Popok // Materials of V Junior Researchers’ Conference, Novopolotsk / Polotsk State University. – Novopolotsk, 2013. – P. 112–116.
8. Gerasimov, A. Cartridge Tool-Holders and boring heads for high-precision holes treatment / A. Gerasimov, N. Popok // Materials of VI Junior Researchers’ Conference, Novopolotsk / Polotsk State University. – Novopolotsk, 2013. – P. 68–71.
9. Шварц, В Иллюстрированный словарь по машиностроению (англо-немецко-французско-русский): 3614 терминов / В. Шварц. – 2-е изд., стереотип. – М. : Русский язык, 1986. – 428 с.

CONTENT

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ГЕРАСИМОВ Андрей Алексеевич

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Пособие для студентов и магистрантов
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