WHITEPAPER

5-AXIS MACHINING CENTERS:

FASTER, HIGHER QUALITY AND LOWER COST MACHINING

DMG MORI

5 axis CHAMPION

WHITEPAPER 1

1. Management Summary 3

Full order books and fewer skilled workers: ways out of the dilemma 4

2. A look at the industries 6

Bright future for 5-axis machining centers 6

2.1 How the industries benefit 6

2.2 Nothing remains as it once was: machining in the automotive environment 8

3. Technology in use 9

3-axis versus 5-axis: similarities and differences 9

3.1 Where 3-axis reaches limits and 5-axis opens up opportunities 10

3.2 5-axis machining centers: technically not new territory for experienced machinists . 11

3.3 Getting things moving 14

3.4 Focus on working space: maximum utilization through process integration 14

3.5 All in one: This is what practical mill-turn and turn-mill centers can do 14

3.6 High component accuracy and surface quality via integrated grinding technology . . . 14

3.7 Now standard: Realizing gear manufacturing 16

3.8 ULTRASONIC: powerful oscillations for really tough materials 16

3.9 Cleverly combined: 5-axis machining and additive manufacturing 18

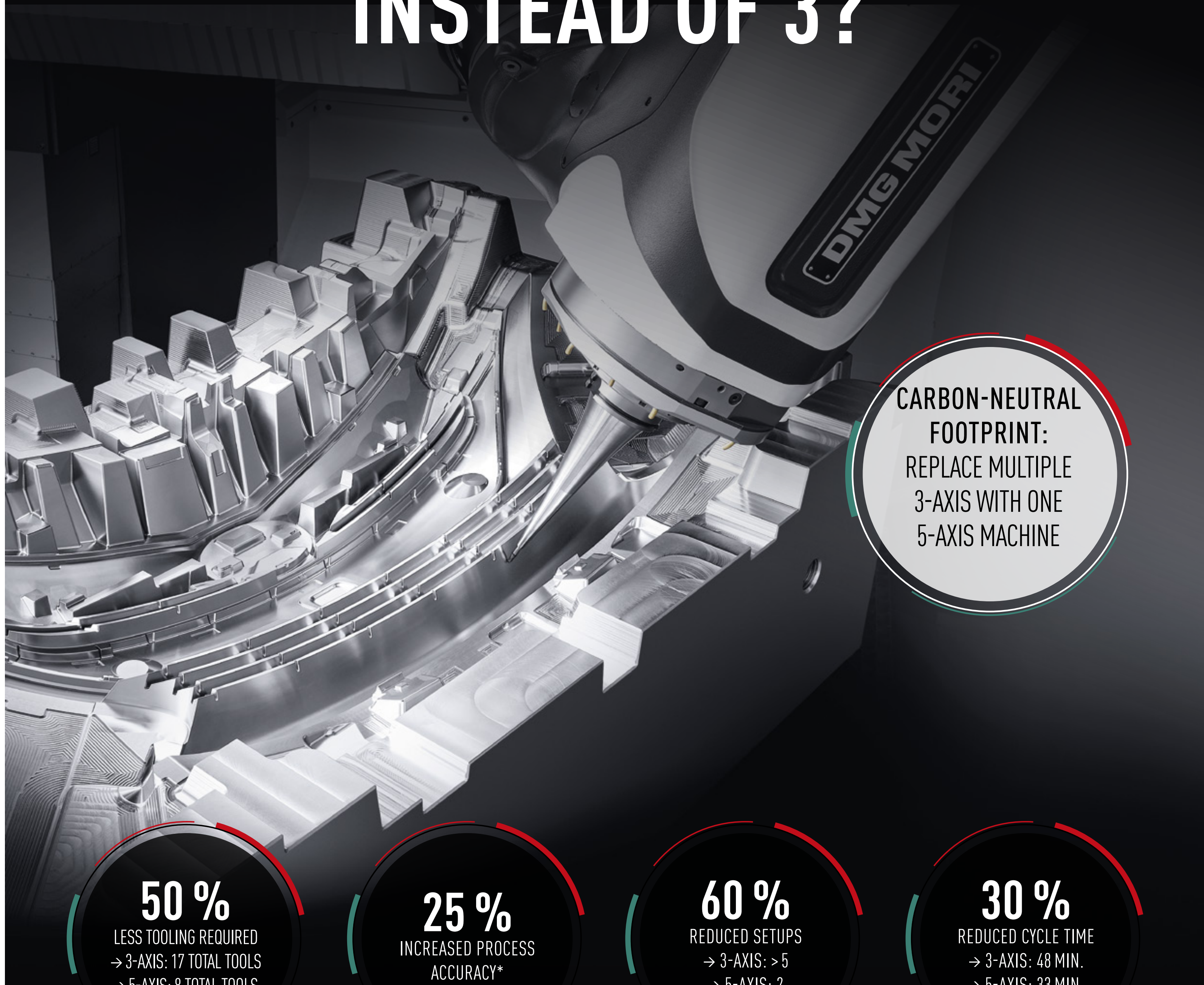
3.10 Additive manufacturing using a powder nozzle: (*DED*) Directed Energy Deposition 18

4. Conclusion and outlook 19

Technological leap: Why now is the right time for a rethink 19

IT'S TIME TO CHANGE!

WHY 5-AXIS INSTEAD OF 3?



CARBON-NEUTRAL FOOTPRINT:
REPLACE MULTIPLE 3-AXIS WITH ONE 5-AXIS MACHINE

50 %
LESS TOOLING REQUIRED
→ 3-AXIS: 17 TOTAL TOOLS
→ 5-AXIS: 8 TOTAL TOOLS

25 %
INCREASED PROCESS ACCURACY*

60 %
REDUCED SETUPS
→ 3-AXIS: > 5
→ 5-AXIS: 2

30 %
REDUCED CYCLE TIME
→ 3-AXIS: 48 MIN.
→ 5-AXIS: 33 MIN.

* Calculation is based on a specific example, using selected products and procedures. Deviations are positive and depend on numerous variables.

1. MANAGEMENT SUMMARY

FULL ORDER BOOKS AND FEWER SKILLED WORKERS: WAYS OUT OF THE DILEMMA

The shortage of skilled workers, the aging workforce in machining technology, the dynamics in supply chains, competitive and cost pressures – these are all issues that are at the top of the agenda for industrial manufacturers. 5-axis machining centers do not fully solve these problems, but they help to drastically reduce their consequences. The highly dynamic machine systems now established on the market are highly dynamic and have high axis speeds. Due to their design, they enable complete machining of components, which saves even more time than rapid acceleration and fast axis movements can.

The significant reduction of many different work steps on different machine types and the resulting elimination of costly repeated set-ups are, from a quantitative and qualitative point of view, the new gold standard for the complete machining of complex component shapes and structures. This trend is underlined above all by developments in machine tool design that are resulting in increasingly sophisticated process integrations for turning-milling or milling-turning, grinding, gear cutting or texturing.

This white paper focuses on 5-axis machining as the contemporary way to integrate and thus accelerate processes. It shows examples of how 5-axis machining is used differently in various industries. It also compares 3-axis and 5-axis machining as processes and illustrates how similar the two technologies are in terms of process chain and operation. The white paper concludes with a presentation of the most important process integrations that leave all options open for industrial production within a 5-axis machining center and thus also set the direction for future developments.

Machining technology then and now

CNC machining can be described as a manufacturing technology that began as early as the 18th century with the invention of the first metal cutting lathes. In the following decades, there were further machine developments with which increasingly precise mechanical work processes could be realized. This technical development also marked the beginning of industrialization. The predecessor of CNC control was numerical control, on which the first NC machine tools were based and which was used, among other things, to meet the manufacturing challenges of the U.S. military faster and better during the Cold War. The well-known U.S. MIT (Massachusetts Institute of Technology) also further developed the technology and applied for a patent for the so-called "Numerical Control Servo system" (NC) at the beginning of the 1950s. From this, in the course of the coming decades, with the development of the first computers, computer-aided – CNC – machining emerged, which is still being further developed to the present day.

Understanding technology: Why 5-axis machining is relevant for control and management

From the recent past to the present, it can be observed that – due to geopolitical and economic changes – the demand for industrially manufactured goods is increasing. Companies have long been producing outside an economically strong Europe and competitive pressure is increasing. Industrial companies in all sectors worldwide are therefore working on the development of high-performance processes that can cope with the increasing market dynamics and, at the same time, the growing shortage of skilled workers.

5-axis machining is a strategy for the complete machining of components that takes both of these issues into account and at the same time helps companies to increase their level of automation. Compared with conventional machining processes, in which various operations on a component are carried out on different machines, machining centers combine different processes in one machine that can be operated by a single person. It is true that in an estimated 95 percent of cases, even components on a 5-axis machine must be reclamped for processing on the sixth side, which results in a first and second clamping. However, the ability to drill at compound angles helps enormously to reduce the number of set-ups. In summary, eliminating handling and set-up times for raw material and tools can generate measurable economic benefits.

2. A LOOK AT THE INDUSTRIES

BRIGHT FUTURE FOR 5-AXIS MACHINING CENTERS

There is hardly an industry in which 5-axis machining cannot be used to accelerate processes in the manufacture of individual components or in series production. Regardless of geometries or free-form surfaces, complex, integral components can be manufactured more cost-effectively by this manufacturing process, as the following examples illustrate.

2.1 How the industries benefit

For example, manufacturers of **medical products** use 5-axis simultaneous machining to mill small instruments from the solid, in addition to orthopedic products such as bone plates. With regard to the choice of materials, such as stainless steels and titanium alloys, it is important to be flexible in the highly regulated area of medical device manufacturing and always be able to ensure extremely high accuracy of even the smallest components during the entire manufacturing process. If we consider the example of a spoon forceps component measuring just 0.8 mm used in an instrument for endoscopic procedures, it becomes clear how important consistent, absolute precision is. This is further emphasized in this example by the machining of a bore measuring only 0.2 mm. Similarly, increasing productivity in a growing industry is a key argument for 5-axis machining.

Accuracy requirements in the **semiconductor industry** go down to microns. Here, 5-axis machining centers are used when, for example, in component production a volumetric accuracy of better than 30 µm is expected together with a positioning accuracy of 4 µm.

In addition, form and positional tolerances of <3 µm are required, which can only be achieved by 5-sided machining in one clamping. Wherever hard-brittle materials such as technical glasses or ceramics are processed due to the exacting requirements for the workpieces, the integration of ULTRASONIC technology opens up additional machining advantages. Components in the aerospace industry, which are often difficult to machine, are much more complex and diversified. They also require suitable technical manufacturing approaches to produce turbine or structural components for aircraft, from small to large. What makes **aerospace manufacturing** special is the wide variety of workpiece materials and geometries, some of which are complex, as well as the value of the components. In most cases, 5-axis machining is the prerequisite for reliable machining. The many possibilities offered by process integration make it easier to achieve quality requirements at acceptable costs.

Companies in the **energy sector** or the supply chain are also focusing more and more on 5-axis machining, as can be seen from the example of water turbines. Originally made of cast iron, forged steel is now used to make turbines reliable, durable and, above all, efficient. In contrast to machining cast-iron turbines, which are mainly used for flushing abrasive substances such as sand or chemicals, the production of steel turbines from the solid is much more complex. Here, too, 5-axis machining centers make milling more efficient.

A much larger market can be seen in mechanical engineering. For example, 5-axis machining centers are used in the production of bearing and steering components and are important for suppliers' high productivity. In **mechanical engineering**, the universal use of machines and the ability to configure a desired range of options are particularly important. Central also are stability and precision as well as the option of matching the spindle to the material being cut. If machine and system builders want to automate their 5-axis machining center, they can do this, for example, with a large tool magazine. In addition to the precision of the systems, their stability is also particularly important, since materials that are difficult to machine often have to be processed. In addition, especially in view of the enormously high production quantities, there is a focus on the service life of the tools in order to lower costs.

Aerospace
1: Compressor Disk
2: Integral Component

Die & Mold
3: Mold insert
4: Segment for Tire Shape

Machinery
5: Planet Carrier
6: Tool Turret

Power Engineering
7: Pelton Bucket
8: Impeller

2.2 Nothing remains as it once was: machining in the automotive environment

The **automotive industry** has always strived for greater efficiency across all tiers, the central requirement being stable production processes. In addition, developments in the field of e-mobility are bringing about changes in materials. For example, significantly more components are now being manufactured from aluminum. Using 5-axis machining centers, it is now possible for example to drill oblique holes in this light material, which reduces the number of set-ups of aluminum components in the automotive sector.

In addition, parameters such as chip evacuation make individually configured 5-axis machining centers the preferred technology - for instance with a horizontal spindle and in combination with a swiveling rotary table for housing production. Contract manufacturers often opt for 5-axis machining centers because they allow flexible production of small batch sizes. Pallet handling systems significantly increase the efficiency and cost-effectiveness of the machine. Autonomous production overnight or at weekends significantly increases spindle hours. In addition, aspects such as ergonomics and accessibility to the work area or the possibility of retrofitting automation via existing interfaces play a role in the choice of technology.

As different as the practical examples listed here are, the motivation behind them is very similar. Companies with 5-axis machining centers have always been looking for machine solutions that, in an ideal case, ensure component production entirely without reclamping and reduce tool changes through new machining strategies. The goals behind this are a reduction in errors, the associated quality improvement, increased utilization of the machine, a reduction in labor costs and accelerated production.

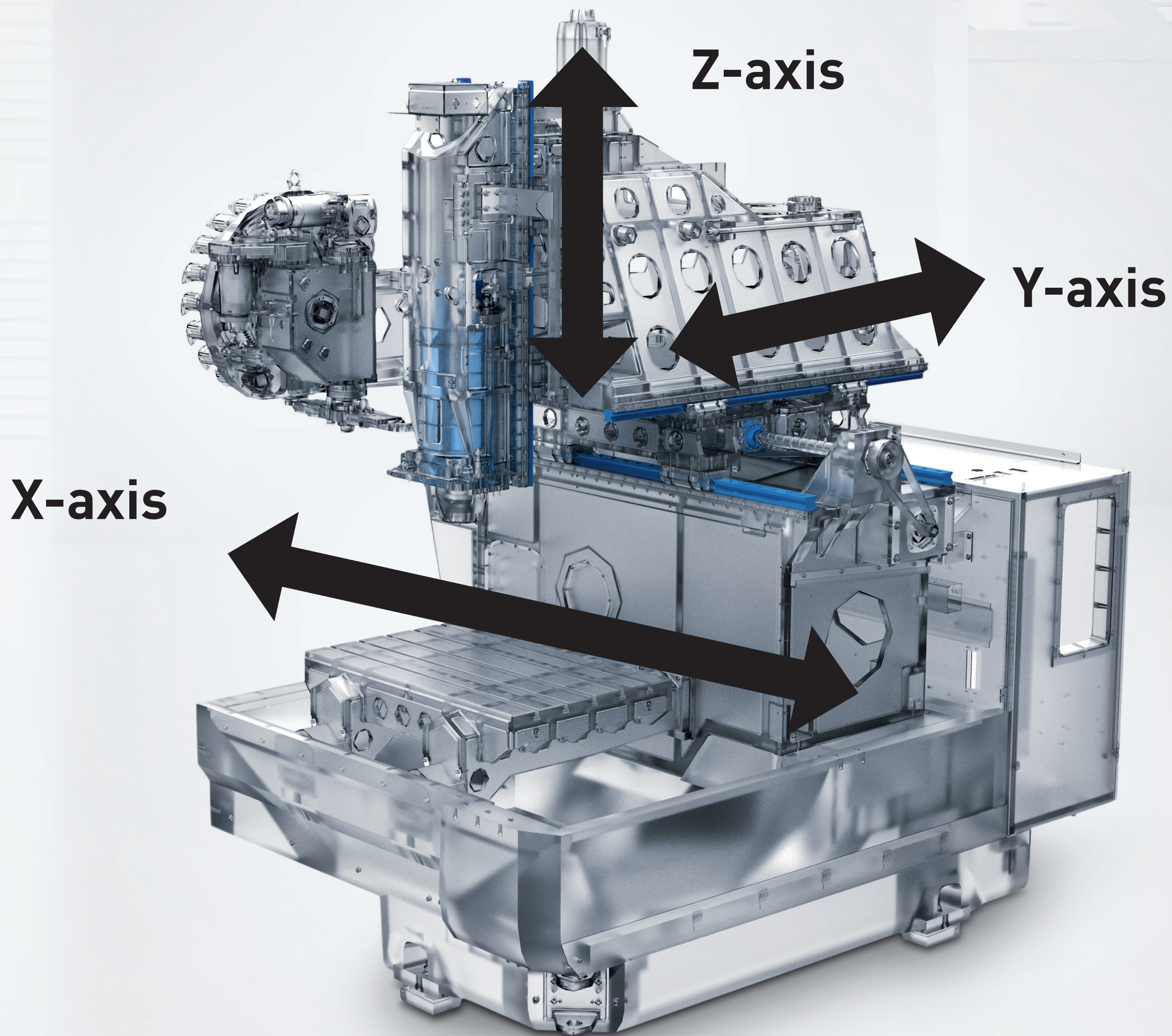
All in all, these are issues that have a positive impact on the total cost of ownership of any machine.

3-AXIS VERSUS 5-AXIS: SIMILARITIES AND DIFFERENCES

The name 3-axis or 5-axis machining center, whether it is a vertical-spindle model (VMC) or a horizontal-spindle machine (HMC), also emphasizes the decisive differentiating factor between the technologies, i.e. the directions in which a tool and workpiece can move.

By definition, a machining center is a machine tool – numerically controlled in at least three axes – with an automatic tool changing device and a tool magazine.

TIP: DIN 66025 DEFINES THE MACHINE AXES::
- The Z axis is always parallel to the spindle.
- The X axis is the main traverse axis.
- The Y axis is perpendicular to the X-Z plane.



Conventional milling is (still) dominated by machining with only three linear machine axes.

3. TECHNOLOGY IN USE

3.1 Where 3-axis reaches its limits and 5-axis opens up opportunities

In 3-axis machining, the cutting tool moves in the three linear X, Y and Z axes. If manufacturing companies use 5-axis machining centers, the machining tasks are usually much more complex, which makes additional rotary axes (A, B or C) necessary.

Compared to the 3-axis configuration, however, the component can be machined from many angles and even simultaneously in five axes. This illustrates why, for example, 5-axis is the favored machining center in many cases in the medical sector for the production of endoprosthetics. Here, one does not only mill more precisely, but also faster and more accurately.

A special case is milling-turning centers, which - as the name suggests - combine the advantages of both technologies and have their origins in milling technology. They enable 5-sided machining of components where, for example, high quantities on the one hand and a wide variety of machining operations on the other have to be taken into account when planning a suitable machining strategy.

Advantages and disadvantages of axis configurations

	3-axis	3+2-axis	5-axis
Constant process parameters in all areas	– –	–	+ +
Use of short and stable tools	– –	+	+ +
Avoidance of multiple setups	– –	+ +	+ +
Large path width due to the use of torus or barrel milling tools	– –	–	+ +
Short processing times	–	o	+
Geometrical flexibility	– –	+	+ +
Danger of collision	+ +	–	– –
Reduced accuracy due to high number of machine axes	+	–	–
Programming effort	+ +	o	– –

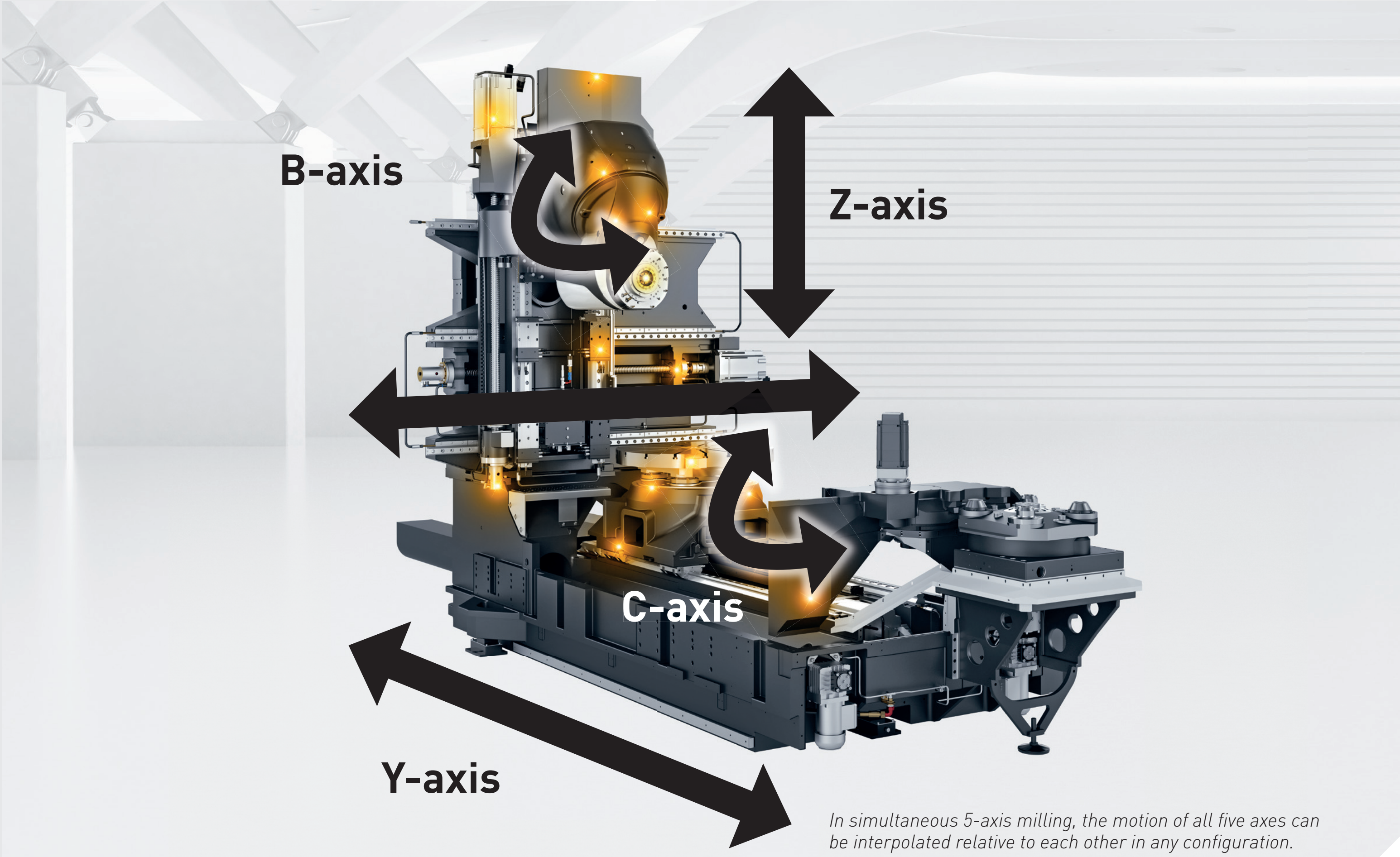
+ + very good + good o average – bad – – very bad

Advantages and disadvantages of different axis configurations (Graphic: DMG MORI | Source: "Successful Milling in Toolmaking", Study Fraunhofer IPT 2018, p. 15)

3.2 5-axis machining centers: technically not new territory for experienced machinists

5-axis machining centers, consisting of three linear and two rotary axes, enable machining in which the tool can be moved in any direction relative to the component, making it possible to mill surfaces anywhere in 3D space. In addition, it is possible to machine inclined bores. Depending on the arrangement of the milling spindle, a distinction is made between horizontal machining centers (HMC) and vertical machining centers (VMC). Since both rotary axes can be allocated as desired to the workpiece and the spindle, these 5-axis machining centers are available in a wide variety of designs.

The combination of CNC control, programming, process chain, 5-axis machining center and tool storage ensures maximum performance by massively reducing component-set-ups and time-consuming tool changes between, for example, face milling, drilling or boring. Only the capacity of the tool storage and the implementation of the axis motions differ from manufacturer to manufacturer. The technical implementation of the tool magazines and the design of automated workpiece changing devices such as pallet changers also vary.



In simultaneous 5-axis milling, the motion of all five axes can be interpolated relative to each other in any configuration.

3. TECHNOLOGY IN USE

3.3 Getting things moving

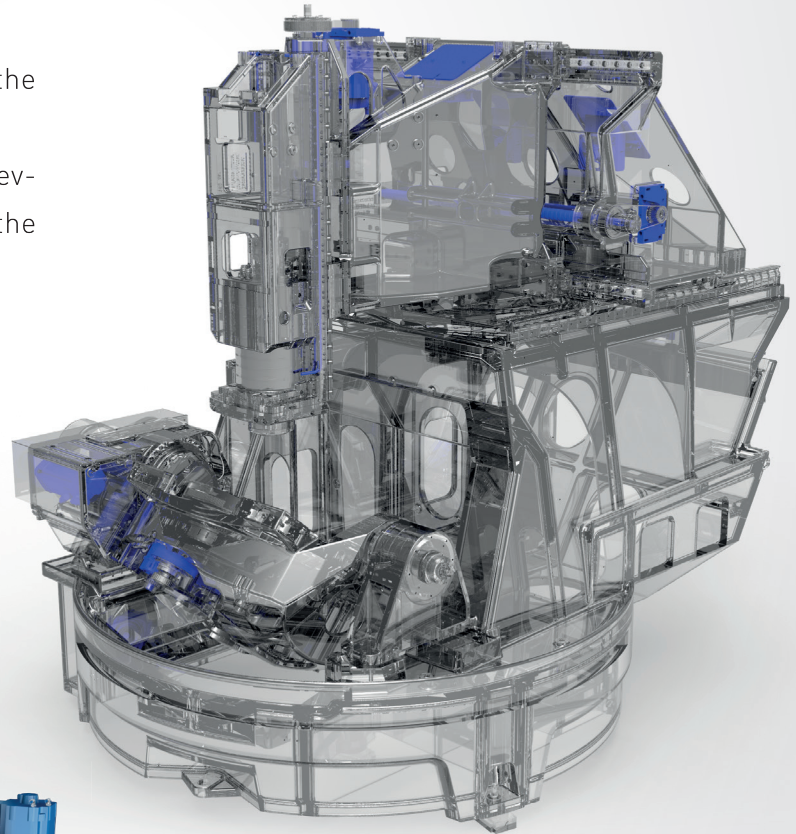
Machining centers with five numerically controlled axes, three linear axes and two rotary axes, can

+ position the tool to engage at any point on the workpiece,
+ move along the surface and
+ maintain any desired angle relative to the workpiece surface.

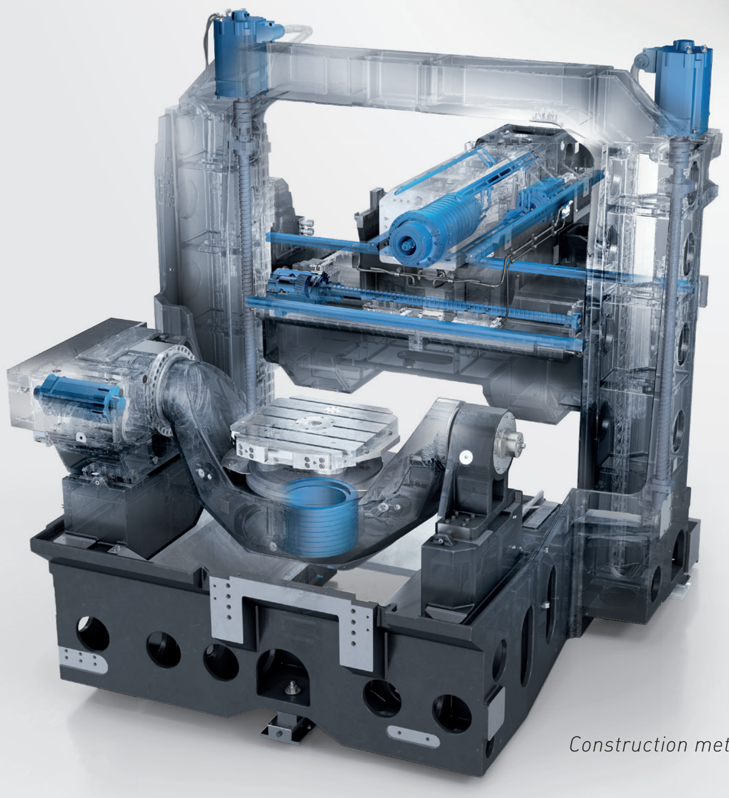
Three different kinematic solutions are prevalent for moving the three linear axes and the two additional rotary axes:

1) Swiveling trunnion, rotary table kinematics:

Workpiece (with table) performs rotating and swiveling motion,
Loads: up to approx. 2,500 kg



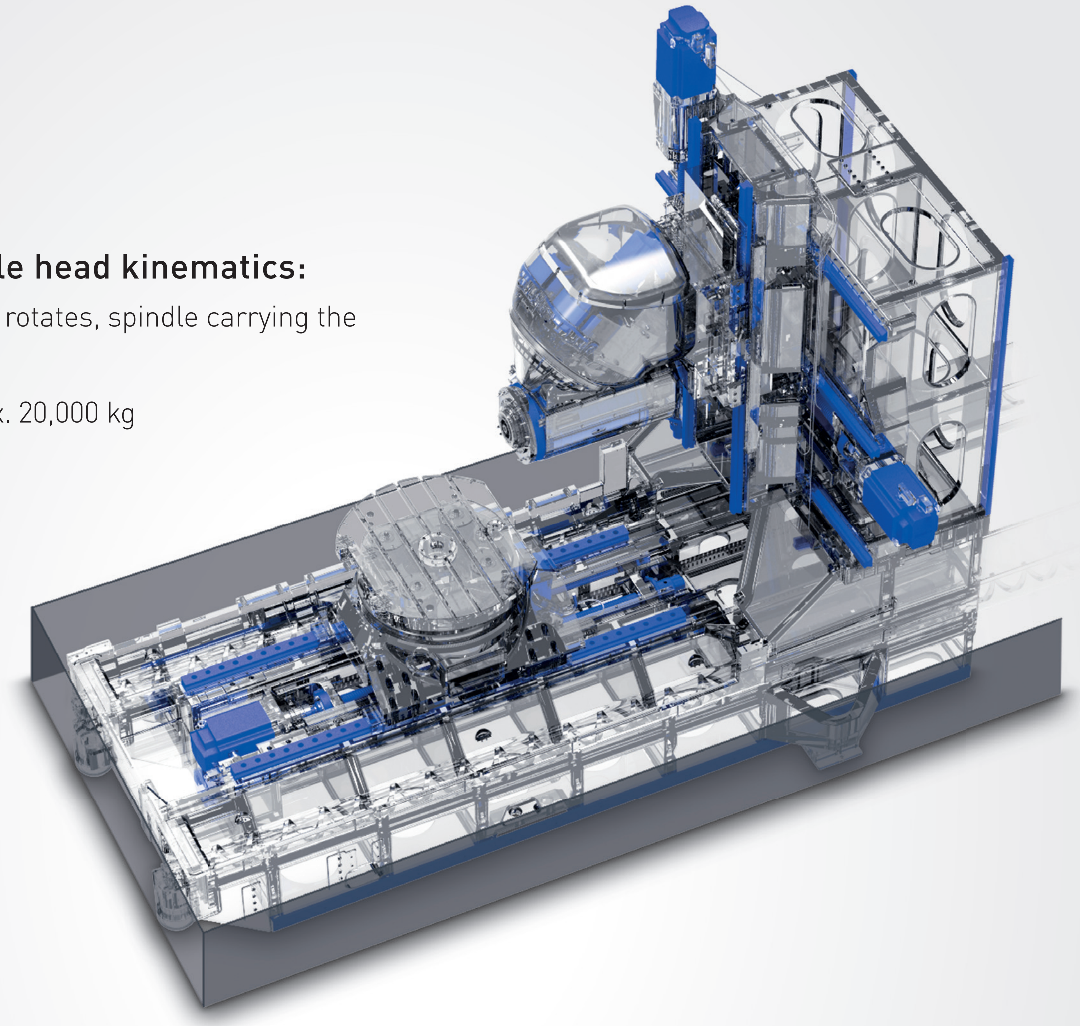
Construction method: VMC with vertical spindle position



Construction method: HMC with horizontal spindle position

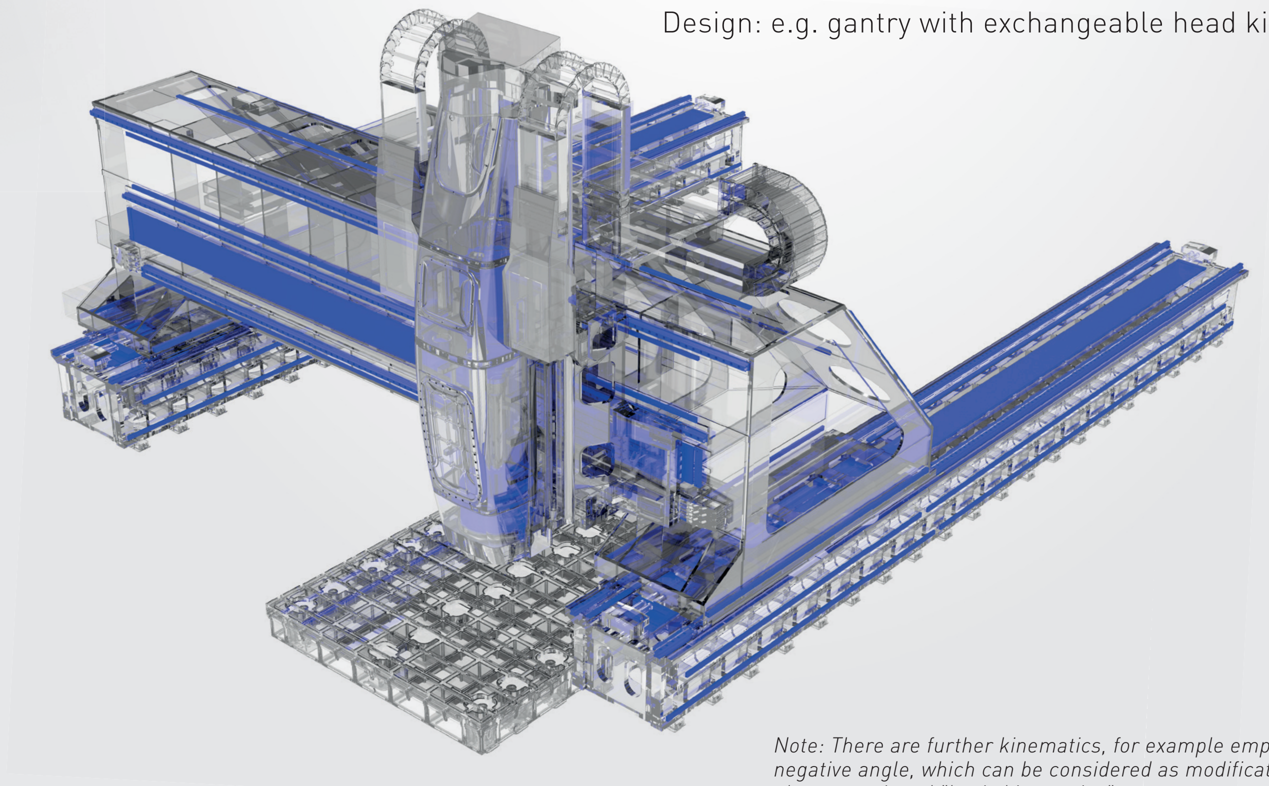
2) B-axis spindle head kinematics:

Workpiece on table rotates, spindle carrying the tool swivels
Loads: up to approx. 20,000 kg
Design: e.g. portal



3) 2-axis spindle head kinematics:

head carrying the tool rotates and swivels
Loads: > 20,000 kg (theoretically unlimited)
Design: e.g. gantry with exchangeable head kinematics



Note: There are further kinematics, for example employing a negative angle, which can be considered as modifications of the above mentioned “basic kinematics”.

3.4 Focus on working space: maximum utilization through process integration

The technical developments of the recent past are increasingly aimed at process integration, with which throughput times can be further reduced. The basic idea: to create a common workspace for many machining technologies. To achieve this, machine builders such as DMG MORI are developing tool solutions or technology cycles that can be used to increase the versatility of machines. For example, 5-axis simultaneous machining can be expanded to include mill-turn and turn-mill technology, grinding applications, gear milling, ULTRASONIC machining of hard-brittle materials and even additive manufacturing processes. Combinations of these are also possible.

3.5 All in one: This is what practical mill-turn and turn-mill centers can do

Industrial manufacturers that have to additionally turn and grind milled components are now no longer forced to reclamp components. This is made possible by integration of turning and grinding processes, which can be regarded as a classical functional extension. Any milling machine with a swiveling rotary table or spindle head kinematics can - to put it simply - also turn, since the table is movable. Instead of a milling cutter, only a turning tool is used. What changes, however, and affects the milling machine design and table, is that the latter rotates at 30 to 40 rpm on a large machine, while with a small table diameter it may well reach up to 1,250 rpm. In addition, mill-turn machines have a direct drive and thus direct power transmission, while traditional milling machines are equipped with a motor and gearbox.

With **Turn & Mill** machines, it is exactly the other way around. Here, it is a fully-fledged lathe that offers one hundred percent milling functionality via a B-axis **milling spindle** in up to 5-axis simultaneous machining. These turning-milling machines are ideal for longer workpieces that can be completely finished on all 6 sides using the lathe's main and counter spindles.

3.6 High component accuracy and surface quality via integrated grinding technology

When turn-mill machines are also used for grinding (FDS), they are technically modified multi-function centers that adopt existing safety measures and also incorporate grinding-specific safety features such as guarding. In grinding, material is usually removed from the wheel during component machining. For this reason, FDS machines are equipped with structure-borne sound sensors, among other things. They detect the first contact between the grinding wheel and the component by continuously probing the increasingly smaller grinding wheel during dressing.
In addition, FDS machines can monitor power consumption to monitor wheel wear, as component contact resistance increases and thus so does the power consumption of the motor.

Both are measures used to meet high quality standards. Furthermore, in addition to the standard coolant tank, mill-turn machines with grinding often have a filtration system that uses centrifugal technology to filter out the smallest particles under 10 µm resulting from the grinding process.

Process integrations such as those mentioned above make it possible, for example, to achieve surface finishes of up to 0.4 Ra during internal, external and surface grinding. In this way, not only can milling, turning and grinding be accelerated in a single clamping, but defects can also be eliminated across all machining and finishing operations by eliminating the need for reclamping.

If cycles for internal, external, surface, polygonal or even oval contour grinding are required in component production, or if dressing cycles are necessary, turning/milling machines with integrated grinding are the production tool of choice. Technologies from DMG MORI, for example, feature in-process measuring during machining. This is made possible by a fully integrated measuring fixture. During the grinding process, the diameter is measured relatively or absolutely - depending on the type of measuring system - and displayed to the operator. The measuring repeatability of DMG MORI systems is 0.8 µm.

In addition to the required balancing technology, turning/milling machines on the market also have a ring-type holder that speeds up grinding wheel replacement and thus production. Another feature of these systems is an internal coolant supply, through the tool holders, leading to the best possible flushing of the contact area. DMG MORI systems also feature centrifugal coolant systems that guarantee minimization of particles. This not only keeps the work area free of chips, but also ensures consistently excellent component quality. Turn-mill machines from DMG MORI also feature structure-borne noise sensor technology.

The sum of the above features forms the basis for achieving first-class surface quality and efficient production on turn-mill machines with integrated grinding.

3. TECHNOLOGY IN USE

3.7 Now standard: Realizing gear cutting

Traditionally, the production of gears has been a labor-intensive and costly process requiring dedicated machines. Instead, combinations of special tools, state-of-the-art machine tools and modern know-how make it possible to produce gears in 5-axis machining centers today. For example, manufacturers such as DMG MORI offer process integration for gear cutting. Using technology cycle software, manufacturers can now easily machine internal gear teeth into components on DMG MORI universal machining centers, for example. The retrofittable software programs enable conversational input of the gear parameters, based on which the NC programs calculate the corresponding cutting cycle. This shortens production times and results in more efficient processes.

In addition to process integration for gear cutting, the machine manufacturer has other technology cycles that can be used to increase efficiency in cutting processes. For example, there are 23 cutting cycles with which new machining processes can be implemented. Furthermore, 15 handling cycles have been developed to support the user in automated machine operation. Measuring cycles enable an improvement in component accuracy and thus more transparency in quality assurance. Eight monitoring cycles ensure greater process and machine safety. These technology cycles implemented at DMG MORI are exemplary initiatives in machine tool manufacturing to increase quality and efficiency in equal measure.

3.8 ULTRASONIC: powerful oscillations for really tough materials

Many current research topics concern materials science. The results are not infrequently novel alloys that are, for example, intermetallic or have shape memory. In addition, developments in electroactive or self-repairing polymers are on the rise, as are composites that are fiber- or particle-reinforced or hybrid materials, to name just a few examples. Looking at the target industries, these materials are widely applicable: carbon components in the automotive industry, for instance, while technical ceramics such as SiC/SiSiC as well as Si3N4 and Zerodur are the main hard-brittle materials in lithography machines for the semiconductor industry. Zirconium oxide is used to form implants in the medical sector or in high-quality luxury watches made by many renowned manufacturers. Hard-brittle materials are used because they exhibit both low wear and are very thermally stable. What these materials have in common is that they are all difficult to machine.

This means that no general statements can be made about either machine requirements or machining scenarios. As an example, we will present a technology for machining such advanced materials that is based on powerful ultrasonics with wear-free inductive transmission. It can reduce the usual process forces by up to 50 percent, which protects the structure of the material being machined. This is made possible by superimposing oscillation in the longitudinal direction onto the rotation of the tool. The advantage: surface feed rates and infeeds can be increased, finishes are further improved and tool life is extended at the same time. In addition, it is possible to minimize microcracks, which can occur when machining hard-brittle materials. Downstream processes such as polishing of optical components are drastically reduced, significantly impacting throughput times and, of course, manufacturing costs. The technology is based on the piezoelectric effect, which is created by superimposing an additional oscillation in the axial direction on cutter rotation via an interface on the tool holder.

In addition to a series of flawless ULTRASONIC-only offerings, most 5-axis milling machines in the DMG MORI portfolio can now be upgraded with impressive ULTRASONIC capability.

3.9 Cleverly combined: 5-axis machining and additive manufacturing

In addition to subtractive machining, additive processes can also be integrated. The *DED hybrid* machines (LASERTEC 65 / 125 / 3000 / 6600 *DED hybrid*), based on the monoBLOCK 5-axis milling machines and NTX Turn & Mill machines, enable additive manufacturing and 5-axis milling on one machine.

3.10 Additive manufacturing using a powder nozzle: (*DED*) Directed Energy Deposition

Laser deposition welding - known as Directed Energy Deposition - takes place via a powder nozzle. The powder is introduced into a molten pool - generated by a laser beam - using argon as the transport and shielding gas. Laser deposition welding with a powder nozzle is characterized by a very high build rates. The component is built up layer by layer and multi-material applications are also possible. This means that different metals can be applied not only alternately, but also in any mixing ratio, giving the component desired properties such as higher thermal conductivity or different degrees of hardness in certain areas. The machine's 5-axis kinematics allow material to be applied exactly where it is needed.

Hybrid concepts minimize the effort of post-processing additively manufactured components by combining laser deposition welding using a powder nozzle with conventional milling or turning in one workspace. Flexible switchover between laser processing and machining processes enables the processing of component parts and the integration of the complete production chain in one machine. Users of laser deposition welding also benefit from the 5-axis or 6-sided complete machining that modern milling machines and mill-turn centers allow. Such an approach enables efficient finish machining to within microns, even in locations that may no longer be accessible after the complete assembly of the component. In this way, the most complex geometries can be realized in finished part quality.

Laser deposition welding and 5-axis machining in one set-up: The LASERTEC 125 DED hybrid is perfect for repairing large components.

TECHNOLOGICAL LEAP: WHY NOW IS THE RIGHT TIME FOR A RETHINK

The examples mentioned make it clear that 5-axis machining centers are already, almost without exception, suitable platforms on which industrial manufacturers can address the increasing market and quality requirements, the dynamics within the supply chains, the shortage of skilled workers and their own demands for vertical integration and complete machining of components. Know-how learned on 3-axis machining centers can be easily transferred by the companies to 5-axis machining. The relevant parameters such as machine coordinates, spindle speed and feed rate, as well as reference point, workpiece zero point and machine zero point, are familiar to machine operators and programmers. It is the sum of an infinite number of small and large advances and innovations in mechanics, materials technology and design theory that make the 5-axis machining center the new standard in production, automatically increasing efficiency and improving quality.

At the same time, modern 5-axis machining centers, thanks to the above-mentioned process integration and various additional functionalities, mitigate the problem of an increasingly aging workforce and create a framework for counteracting the shortage of skilled workers. The fact that 5-axis machining centers are more than just a trend, but are advancing to become the new gold standard in industry, is demonstrated by the many developments that renowned machine manufacturers such as DMG MORI have on their agenda. For example, the company is planning the second generation of the DMU 40, monoBLOCK and INH 5-axis machining centers, while hardly any information on innovations in 3-axis machining can be found in the technical literature.

5-AXIS MACHINING CENTERS

Manufacturing industry – like all other industries – is currently undergoing a transformation. Issues such as the shortage of skilled workers, changes in supply chains, and the increasing competitive and cost pressures must be viewed holistically with the aim of developing solutions that give companies (more) stability again. The use of 5-axis machining centers is an option that can reduce the aforementioned problems and optimize processes. It also shows ways in which 5-axis machining centers can be set up even more economically by means of process integration. The goal: a holistic view of the process chain and thus the inclusion of automation, digitalization and sustainability in industrial manufacturing. DMG MORI will be looking at the elements of this triad in more detail in the near future via various white papers.

Contact:
info@dmgmori.com