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This series presents lecture notes, monographs, edited works and proceedings in the field of the Mechanics, Engineering, Computer Science and Applied Mathematics. Purpose of the series is to make known in the international scientific and technical community results obtained in some of the activities organized by CISM, the International Centre for Mechanical Sciences.
MATERIALS SCIENCE AND THE SCIENCE OF MANUFACTURING, INCREASING PRODUCTIVITY MAKING PRODUCTS MORE RELIABLE AND LESS EXPENSIVE
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Manufacturing a product is not difficult, the difficulty consists in manufacturing a product of high quality, at a low cost and rapidly.

Drastic technological advances are changing global markets very rapidly. In such conditions the ability to compete successfully must be based on innovative ideas and new products which has to be of high quality yet low in price. One way to achieve these objectives would be through massive investments in research of computer based technology and by applying the approaches presented in this book.

The First International Conference on Advanced Manufacturing Systems and Technology AMST’87 was held in Opatija (Croatia) in October 1987. The Second International Conference on Advanced Manufacturing Systems and Technology AMST’90 was held in Trento (Italy) in June 1990. The Third, Fourth, Fifth and Sixth Conferences on Advanced Manufacturing Systems and Technology were all held in Udine (Italy) as follows: AMST’93 in April 1993, AMST’96 in September 1996, AMST’99 in June 1999 and AMST’02 in June 2002.

The Seventh International Conference on Advanced Manufacturing Systems and Technology - AMST’05, which was held in Udine in June 2005, aimed at presenting up-to-date information on the latest developments – generated by research activities as well as industrial experience – in the field of machining of conventional and advanced materials, high speed machining, hard and dry machining, CIM, forming, modelling, simulation, non-conventional machining processes, new tool materials, tool systems, tool condition and process monitoring, rapid prototyping, rapid tooling and rapid manufacturing, ecodesign - assembly and disassembly, and quality assurance, thus providing an international forum for a beneficial exchange of ideas and the furthering of favorable and productive cooperation between research and industry.

Elso Kuljanic
FOREWORD

It is the duty of men of science and institutions who work at fostering development, to promote those territorial aspects which – for their intrinsic interest, but also for indications of a general nature that can be drawn – deserve careful consideration.

Working in this direction has reaffirmed the strength of a concept whose affirmation dates back to Charles Bally and as far as 1909: the existence of a homogeneous European civilization, of a true “European mentality”, fruit of a century-long process of cultural convergence, where powerful elements have come together, such as our Greek-Latin heritage, the spread of Christianity, the role of the languages of culture, and a civilization which over time has spread even beyond Europe.

A case in point is the 1987 establishment of the “Work Group for the study of multilingualism in the territory of Alpe-Adria”, under the patronage of The Conference of University Rectors of Alpe-Adria. As a result of the work in this direction, “The International Centre on Multilingualism” (CIP) was established at the University of Udine, which is similar to different Centres in Europe in this field such as the Brussels Research Centre on Multilingualism (Centre de Recherche sur le Plurilinguisme), the Uppsala University’s Centre for Multi-ethnic Research (Centre for Multiethnic Research), and the Mannheim University’s Eurolinguistischer Arbeitskreis Mannheim.

The International Conference on Advanced Manufacturing Systems and Technology has an important role within this process, in that they allow knowledge to converge on Udine where theory and practice continually confront.

The social world we live in has become more and more complex, thus requiring pluralistic, targeted and serious action. This action requires to develop constant innovation and to promote an integration among professions in order to be able to build, design and develop together. With this aim in mind and hoping in a future where exact science and the science of man will be able to work together more closely – in a wider and further reaching concept of universitas and in conformity with institutional expectations whose hearts are set on promoting this Conference – the Proceedings of the AMST’05 Conference will certainly help in spreading this knowledge locally, across the territory of Alpe Adria and globally.

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SCIENCE, TECHNOLOGY AND SOCIAL INNOVATION

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KEYWORDS: Paradigms of Manufacturing, Fractal Factory, Leadership.

ABSTRACT. In the last twenty years the increased international competition in the wake of globalization has changed the methods of manufacturing, especially the structure and organization of a factory. More self-similarity among the enterprise, the groups and the employees, self-organization and self-optimization have arisen. For this structure the name Fractal Company has been used. Many companies are following this perception, but it is a long and difficult way to go which needs vision and leadership. Some examples are given here.

1 MANUFACTURING IN A TURBULENT MARKET

Around 1990 a study was published which was performed by the Massachusetts Institute for Technology (MIT) and ordered by the automotive industry comparing European, US-American and Japanese plants. The outcome of this study named "The Machine That Changed the World" was terrible, especially for the investigated plants in Germany. Roughly speaking one could say: the Japanese engineers produce with half time consumed, half space and half number of employees. The German plant was said to use one third of manpower in order to repair what two thirds used to produce in poor quality before. There was still the attitude quality costs money. This shock initiated the change of organization, responsibilities and processes. The known rules of manufacturing were questioned. It was realized: manufacturing is service to the market, to the customer. Rather simultaneously arose another impact: markets and competition became global and turbulent. Planning and foresight have become more and more uncertain. Monthly quantities of production and a lot of different sizes were kept stable, and surplus over the market demand was put in store binding capital. That is no longer the right way: manufacturing must follow the market demand. Especially larger companies with their hierarchical and bureaucratic structures became too slow and lost competitiveness. The paradigms of manufacturing changed. In the last fifteen years many developments in technology and organization have appeared to increase the learning and adaptive capabilities of the manufacturing processes.

Whereas a few decades ago the survival of a company was seen in diversification, what we see now is focusing on using better the limited resources of qualified, competent employees and more targeted and efficient capital, communicating and networking with other specialists.

2 THE FRACTAL COMPANY

In 1992 I personally contributed to a proposal for a Fractal Company which was published in the book "The Fractal Company" to raise the speed of reaction and show that it is structured out of many small control loops with high autonomy and responsibility for their range of work. The
main feature of a fractal structure in mathematics is self-similarity, self-organization and self-optimizing. The name fractal was introduced by Mandelbrot in the U.S.A. in the 1960s, because in describing algorithms broken (fractal) orders, like $x^{2.8}$, are eminent, as there are many structures between an exact geometrical plain and a cube. Self-similar means that the total structure is repeated down to the smallest unit. In a company that means, that you will find the company in the thinking and acting of the smallest element, i.e. the human being, the employee. With this aim the enterprise is organized in small, fast, partly autonomous control loops. This fundamental idea was taken by many enterprises that formed autonomous and responsible groups with budgets and targets. Each company according to its situation must find its own solution and adapt continuously. The leading management must realize that qualified and motivated co-workers are the most valuable asset of a company.

The other, already mentioned feature of a fractal structure is its ability of self-organization and self-optimization. It is a must for interdisciplinary project teams of today. Only they themselves can reorganize a company, when and how long a specialist should be integrated to solve a complex task. This flexibility is also expressed in the design of new buildings. Therefore, the new project house (Projekthaus) of BMW in Munich is very transparent and of high flexibility in its inner layout.

3 FUTURE DEVELOPMENT OF A FRACTAL STRUCTURE

In my opinion these ideas need further development to increase social innovation in society and enterprises. We would like that the citizen identifies himself with his state and the employee with his enterprise. But why would he do that when he knows that politicians are not fair and do not tell the truth and the enterprise will fire him very fast when the situation requires that and the management has no feeling of responsibility for him.

We must find a new design of working contracts, which must lead to a higher flexibility, adaptability and survival of the enterprise and accordingly to a higher motivation of the employees, when they are more dependent on the success and misfortune of their company in their income. The gap between independent and dependent employment is too big. Even if more and more young people are willing to take the risk of independent activity, we must realize, that in the future many qualified persons will also be dependent employed, think alone of the capital-intensive business. These employees must and can be given more autonomy, responsibility and risk. We must begin to think about possible ways not only of new working contracts, but also about new working culture and mentality. It will be a long and difficult way.

4 MANAGEMENT AND LEADERSHIP

This requires politicians and leaders in the economy who have visions. In Germany a politician said several years ago: who has visions should go to a medical doctor but not to government. I think vision makes the difference between politicians and a statesman, between a manager and leadership. A leader must incorporate values and give an example.

Each organization must define its values and aims. That must be internally communicated in a simple, clear and understandable way, periodically confirmed and complemented. It is strange
that in an organization you can only have a very limited number of values and aims to communicate and follow up. The quality of an organization can only be seen by the results outward, internally there are only costs. A leader has always the dilemma to follow the set targets stubbornly and with reliability, on the other hand he has to correct the target in time when it is becoming illusory without getting the image of being opportunistic and unreliable. To lead a group or company means also to give the employees freedom and to take risks. People who act make failures, but they must be sure to have the back-up of their leader. In such a culture innovations will take place. We know that only about 10% of all innovation-processes become a success. It is not worthwhile and poisonous to look for the guilty. Innovation-processes are uncertain and unplannable in the result.

5 THE NEW WORLD OF WORKING

Back to the new world of work and here is an example of a company where I am a member of the supervisory board: it is the Brose, an automotive supplier in Germany, Coburg. Thanks to the leading owner, they have created new working conditions: high flexibility in the design and layout of the offices, your work place, your working hours and your income depend strongly on your efficiency, while the company offers many possibilities for recreation, the difference between working and leisure time is no longer sharp. The result is that the Brose has become an appreciated employer, especially for young engineers, it has grown considerably and is one of the leading innovators.

Leadership is different from Management, which is – only – the continuous optimization of the networking of humans, machines and influences. Continuously significant figures are compared and influenced. It is mainly an administration. Whereas leadership develops the strength of the co-works it makes their weaknesses insignificant. The culture in the company is important and it also takes into account the culture of the region.

6 A LEADER: ERNEST SHACKLETON

Therefore, for states and enterprises besides structure and organization, the leadership is decisive. In history there are several examples or guides. One of the most known may be mentioned here: it is the Englishman Ernest Shackleton (1874-1922). Shortly before the outbreak of the First World War he and 28 men started on an expedition to the South Pole. The ice enclosed their ship, the Endurance, before reaching the shore of the Antarctic. The ship did not stand the pressure of the ice and sank. The crew, dogs, provision, tents and life saving boats were rescued on a large ice floe. In this hopeless situation Shackleton became an eminent leader, a guide who demanded more from himself than from his men. He was hard, consequent, reliable and foreseeable in his attitudes, but simultaneously motivating and human. A team-leader. This interesting and teaching story cannot be told here in detail. After many months he sailed in one of the open boats to the Falkland Islands to ask for help. Most men waited in the icy cold. The happy end is that the dogs had to die to give food to the crew and all men, without any loss, arrived in England in 1917. Shackleton was awarded "Sir" because of his outstanding leadership.

Today many politicians and managers are far from this example and are not appreciated by society or employees. On the other hand I am sure that there are many people in a leading position but
they are not recognized in public regardless of their fulfilling tasks and excellent duties, results. The success of a company will come when further development of its technology is embedded in a culture created by good leadership.
CHARACTERISTICS OF MODERN MANUFACTURING TECHNIQUES

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KEYWORDS: Manufacturing, Machining Technologies, Future Trends.

ABSTRACT: Today 5 production paradigms can be identified as actual and with future potential. The advanced machining technologies and the developments of machine tools and tools are already initiated, but must be implemented to a growing extend.

1 INTRODUCTION

Today, the manufacturing industry is on the threshold to the 5th manufacturing revolution.

- Substitution of hand work by machines
- Automation of the factory
- Integration of computers into the production process
- Integration of information and communication techniques enables globalization
- New production techniques by penetration of nano- and bio-technologies and application of new materials

Every revolutionary step demands for new production paradigms.

Today, technology doesn't dominate anymore because the new mind of thinking also demands for the consideration of nature, economy, society and technology (NEST).

However, in every period of paradigm changing, the production technology has been subject to a fundamental and continuous change. This process of steady changing will persist without important leaps in innovation having to be expected, but certain developments, such as the application of linear motors or parallel kinematics on machine tools, undoubtedly will speed up the overall progress in manufacturing.

In general, it will be a reduction of process chains and an increased safe performance of processes, for instance by increased use of simulation technologies.

Manufacturing becomes faster and more flexible but only when the corresponding production techniques, the manufacturing technologies and digital manufacturing etc. are available.

Therefore, to be faster and more flexible are the fundamentals of advanced manufacturing today.

2 TODAY’S AND FUTURE PRODUCTION OBJECTIVES

Significant drivers of innovation are actually the ability of innovation to follow the requests of the market:
- lower prices

- high quality
- large variety
- short delivery times, i.e. immediate availability
- innovative products
- environment friendly products

Today, 5 production paradigms can be identified in the consumer goods manufacturing (Figure 1).

<table>
<thead>
<tr>
<th>Paradigm-Start</th>
<th>Craft and Small Batch Production</th>
<th>Mass Production</th>
<th>Flexible Production</th>
<th>Customized Production</th>
<th>Sustainable Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 1850</td>
<td>small volume per product</td>
<td>~ 1910</td>
<td>~ 1980</td>
<td>~ 2000</td>
<td>~ 2020</td>
</tr>
<tr>
<td>Market Characteristic</td>
<td>electricity</td>
<td>steady demand</td>
<td>small and medium volume per product</td>
<td>globalization, fluctuating demand</td>
<td>environment</td>
</tr>
<tr>
<td>Technology Enabler</td>
<td>interchangeable parts</td>
<td>computer</td>
<td>information technology</td>
<td>nano-, bio-, material technology</td>
<td></td>
</tr>
<tr>
<td>Process Enabler</td>
<td>machine tools</td>
<td>moving assembly, linked production lines</td>
<td>flexible manufacturing systems, robots</td>
<td>reconstructable machining systems</td>
<td>new manufacturing processes to add atom to atom</td>
</tr>
</tbody>
</table>

FIGURE 1. Paradigms of Production Technology

- Small Production or Craft Production
This means to make exactly the product that the customer asks for, usually one product at a time. Highly skilled workers and the use of very flexible machines are the characteristics.

- Mass Production
The products are manufactured in big series and produced with extremely high quantities, e.g. cars, telephones, photo equipment etc. Because of the large quantities, products can be produced at lower costs which, in turn, enable a number of people to buy the products.

- Flexible Production
This was introduced in the late 1970s in order to respond to the change of the market, that started to be saturated by mass produced goods and the request for more diversified products.

- Customized Production
The goal is to produce a variety of almost-customized products at mass production prices. It is a society-driven paradigm, as customers are asking for a larger variety in consumer products. This mass-customization and personalization paradigm is driven by globalization, intended as the creation of a single worldwide market. Globalization creates a huge excess of global production capacity of high quality products that can be produced in several countries.
- Sustainable Production
Based on society's needs for a better environment and therefore "clean products".

The new emerging technologies of nano, bio and material technology alone or combined with each other will provide the possibility to achieve this future requirements and the goals of society in 2020 and later.

3 ADVANCED MACHINING TECHNOLOGIES

Considering the significant drivers of innovation and the mentioned general trends in innovative production technologies there are the following general trends of manufacturing technologies, machine tools and tools:
- Reduction of manufacturing time
- Reduction of planning and manufacturing costs
- Realization of high accuracy standards
- Miniaturization of products
- Application of new high performance materials, e.g. metal matrix composites, ceramics, fiber-reinforced material etc.
- Ultra-precise surfaces

3.1 MANUFACTURING TECHNOLOGIES

- High Speed Machining (HSC/HSM)
Today, HSM technology has established itself in the industrial countries as state of the art. This is also due to the fact that standard machine tools have become faster and thus allow application of machining processes at higher speeds. HSC means an increase of the cutting speed by a factor of 5 to 8 (Figure 2)
This results in a reduction of the manufacturing time and costs and an improvement of quality.
- Dry and Minimal Lubrication Machining

Economical and ecological reasons and the legislation force to reduce the application of coolants. When dry machining, the most important functions of the coolant, as cooling, lubrication and chip removal must be substituted. The lack of cooling causes a rise of temperature, and as a consequence internal stress within the workpiece as well as dimensional and shape deviations, fringe layer effects, chip melting and chip build-up on tools and workpieces. Possible solutions can be seen in vacuuming the chips or blowing them away by means of compressed air.

Modification of the geometry and special coatings can improve the suitability of tools for dry machining. But a minimum lubrication will often be better. Very small quantities of lubricant (below 100 ml/h) have to be exactly applied to the cutting zone (Figure 3)
- Hard Machining
Highly tempered steels expect a great deal from both the heat hardness as well as the tenacity of the used tools. For hard machining (> 58 HRC) TiAlN-coated finest-grain carbides have especially proved true. In every case hard machining decisively shortens the process chain: Hard turning substitutes all following operations. In die and mold making erosion processes can be substituted by hard milling. So, an optimum combination of hard milling and erosion can lead to a higher efficiency.

- Micro-Cutting
It is a well-known fact that the miniaturization of components keeps persisting. Good examples for this development in particular are high standard products for everyday life such as mobile phones, video recorders etc. An increasing integration of functions in small and miniature components is demanded. These micro-systems are produced by etching, primarily in such cases where injection-moulding or electro-forming dies, etch masks or even miniature components have to be made directly. Micro-cutting of dies normally involves machining of very difficult materials. This means that monocrystalline cutting materials have to be used for tools to ensure cutting edge sharpness and stability. Also only materials having a homogeneous structure can be machined adequately.

3.2 MACHINE TOOLS
- HSC-Machine Tools
The requirements to a hsc machine demand for a close interaction between the manufacturing technological process, the components of the machine and the tools. HSC-machines differ from normal nc-machines by the following essential points:
- high frequency motor spindles
- fast cnc-controls
- highly dynamic feed drives (Figure 4)
- light weight construction
- safety devices

FIGURE 4. Time from 0 to 100 km/h

Higher purchase and operating costs of linear motor machines are compensated by an extreme productivity increase. As an example Figure 5 shows machining of a graphite electrode with machining time having been tremendously reduced.
- Machines for Micro-Cutting
Of course it is also necessary to develop appropriate new machine tools for micro-cutting. The ideal machine tool provides extremely high spindle speeds up to 500,000 rpm for achieving the required cutting speed at very small tool diameters. The moving components all move without friction and must be mechanically uncoupled from each other.

- Parallel Kinematic Structures
Machine tools with parallel kinematics (Figure 6) have aroused much discussion. Their benefits are:
  - inherent stiffness
  - simple frame components
  - reduced moved masses
  - identical feed drives in each axis

![FIGURE 5. Example for the Efficiency of a Linear Motor Machine](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Rapid feed (m/s²)</td>
<td>100</td>
</tr>
<tr>
<td>a (m/s²)</td>
<td>15</td>
</tr>
<tr>
<td>Kₚ (1/s)</td>
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<tr>
<td>Vₚ (m/min)</td>
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</table>

![FIGURE 6. Machines with Parallel Kinematics](image)
Like other innovations, however, these machines will not generally replace the conventional machine tool but will have certain focal points of economic application.

- One setup machines
The integration and combination of different manufacturing technologies lead to a tremendous shortening of the production chain, e.g. pre-machining and finishing, cleaning and measuring processes. Flexible clamping and peripherical components must be applied.

- Reconfigurable machines
New kind of machines with standardized interfaces, reusable applicable mechatronic components, integrated sensors and actors result in a big range of performance.

- Accuracy-Controlled Machines
Accuracy-controlled machines are machines capable of recognizing their current condition and of correction it automatically when required. New kinematic concepts or additional actuator equipment must allow adaptive movements to compensate orientation errors. Current position measuring must be removed from the axes and must be relocated at the real point of process action. This means that the measuring system must be capable of making three-dimensional tool position and orientation identification. For this reason, speed and position determination of the machine must permit transmission directly at the point of machining (Figure 7).

- Lifecycle oriented machines
The simulation of the production process enables to recognize the virtual life time of the machine, beginning at development and design, regarding the manufacturing use and ending in the recycling phase (Figure 8). The best selection of economical production based on specific application parameters will be possible.
3.3 INTELLIGENT TOOLS

Today’s tools will be replaced by intelligent tools equipped with sensors for recognition of accuracy-relevant factors (such as wear, process forces, chatter) located as near as possible to the point of machining, as well as with integrated actuator devices, based on small and fast elements for error compensation (displacement, vibration, edge wear) (Figure 9).
4 CONCLUSIONS

Figure 10 shows that the demands on the accuracy of the products permanently increase. Therefore, the modern manufacturing techniques and machines must be steadily improved. In the new millennium machining technology and machine tools fundamental developments have already been initiated, but now have to be implemented to a growing extent. An important fact is that introduction of these new technologies must be faster than experience has taught us in the past. More courage for entrepreneurial action will be required since in the future the markets show an even more dynamic behaviour than in the past.

![Diagram showing developments of accuracy from 1950 to 2025](image)

**FIGURE 10. Developments of Accuracy**

5 LITERATURE

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COMPETITION AND COLLABORATION IN PRODUCTION SCIENCE

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KEYWORDS: Competition and Collaboration, Process Chain, Gear Production.

ABSTRACT. Competition and collaboration are the driving forces for science in general and for production science in specific. Competition is an appropriate mean to focus rare sources. Collaboration enables a holistic approach to production and can be seen as a new paradigm for production research. An example for the new paradigm of process chain development is given: the decreased process chain for the production of gears for the automotive industry. Material scientists, metal forming engineers, grinding experts and automation specialists work together with industrial partners.

1 TWO SIDES OF A COIN

Competition and collaboration are two sides of one coin. We see that in the national and international economic scale. Globalization means the internationalization of markets, of trade, of capital, of goods and services. What is true in economy is also true in science. As a matter of fact, globalization is not the invention of economists and business executives. Globalization and competition on global scales has existed for decades and centuries in the scientific world – at least in the upper level of scientific communities. So competition seems to be self-evident on the first glimpse – nevertheless, from the point of view of the German university system, there seems to be several deficits, which I would like to speak on.

Competition

♦ sharpens the profile of a university, of a faculty
♦ allocates rare resources to the best groups/labs
♦ overcomes overcapacities
♦ attracts the best students
♦ attracts the best professors
♦ makes potential transparent to industry

FIGURE 1. Why do we need competition in science?

The question is why do we need competition in science (Figure 1)? Actually, the answers are not too far away, as industrialists could give them for their own field. Competition sharpens the profile, makes clear the strong and weak points of an academic unit, of a university, of a faculty or...
even of a smaller unit like a laboratory or a seminar. This profile is the best scale for allocating resources. Resources are always rare. Right now, this is especially true for German universities and research institutes. Although there are many complaints, I think such a situation has some advantages. It gives the chance to give the money, the funds and the personnel to the best groups or to the best laboratories instead of distributing the resources by principle of giving everyone a slice of the cake.

From market economy we know that competition is a very effective means to overcome overcapacities. This steering role is of course especially valuable in times of rare resources. But in the scientific world, brains are the most important currency. Competition provides the necessary basis for attracting the best students, under the condition that students can identify the competition. This calls for university fees. The problem is, that in Germany there are no fees. There is a vivid discussion about this fact, and I am convinced it is only a matter of time before we introduce them. But right now, there are some influential opinion leaders who are against the introduction of fees. We’ll have to wait.

Along the same line, is necessary to attract the best professors to the best faculties. This has to be reached by resources as well as by wages. And here again, there is very little leeway in German universities. This has to be changed.

Finally – and this seems to me especially important – competition makes the potential of a scientific group, of the human and fund resources transparent for customers, i.e. the partners in industry and the partners in society, that are especially the students.

Collaboration

◆ facilitates spezialisation and a broader approach
◆ gives different views on complex processes
◆ offers a better usage of machines and equipment
◆ brings faster results
◆ corresponds to the new paradigm: product instead of function

FIGURE 2. Why do we need collaboration in science?

We come now to the second side of the coin, to collaboration (Figure 2). In the academic world, I would like to distinguish between two types of disciplines or scientists. One type knows everything about nothing. This means that knowledge is extremely deep, but is only spread over a very small domain, almost nothing. The other type knows nothing about everything. They have extremely wide, but also very shallow knowledge. Collaboration between disciplines provides the very valuable opportunity to combine specialization with deep knowledge with a broader approach.

This also means that under the condition of collaboration different views on complex systems and processes are possible. Often, such views provide new ideas and valuable innovations. The use of machines and equipment can be improved, results are gained faster, and finally a new paradigm
may be introduced in science, especially production science, which is already common in industry: If production science with its applied research claims partnership with production industry, it has to see this paradigm change which took place one or two decades ago. The organizational structure in many companies and very often in innovative companies has changed from a functional orientation to a process orientation. The product and its path through the company come into the focus of managing strategies.

My colleagues in Hannover and I have concluded from this deep change in structure and process-oriented organization, that it is not the single and isolated process in research projects that must be looked at, but the manufacturing of a whole product. For our partners, a specific process is not of interest, but the total process chain which a product runs through [1,2].

One example of this approach in production science shall show you how my colleagues and I react to this new challenge. I have chosen an example of new process chains of high performance components from the automotive industry. I’ll speak about the production of gears.

2 PROCESS CHAIN FOR GEARS

Gears belong to the most important machine elements in machines, cars, machine tools and energy transformation systems. Although we live in a century with a wide range of applications in electronics and photonics, with micro-devices like micro-electronic or photonic elements, still, mechanical elements like gears are indispensable for the transformation of speed or torque. The history of gears goes far back, more than 2000 years (Figure 3). The first evidence on the existence of gears was given by Philon 230 B.C. who wrote the μηχανική συνταξίς, the compilation of inventions. Philon shows a water hoisting device in Luxor, an old Egyptian city, where important testimonies of culture were built more than 3000 years ago. The picture also shows a modern, extremely compact power shift transmission for a heavy truck. The development in gears, especially for the automotive industry, is mainly concerned with the transmission of higher power, the reduction of weight and construction volume, an increase in comfort and in reliability. These achievements have been reached through materials of higher strength, through higher macro and micro-geometric accuracy and through a considerable improvement in surface integrity. Besides that, of course, productivity is a main criterion of gear manufacturing.

My group works in this field together with other groups of material science, metal forming and automation, in cooperation with the automotive industry and with machine tool manufacturers. The approach of our project is an entirely new process chain, as can be seen in Figure 4[3]. Conventional production comprises of at least 14 steps, starting with a sawing or shearing process from bar stock. After storage, the steel block has to be heated, then forged and deblurred by shearing. Cooling and temporary storage again follows until the forged part is intermediately machined in the soft state by turning and hobbing. Since heat treatment is done in batch operation, storage is necessary again. Finally, the hardened and tempered part is finished by abrasive processing.
The integrated production chain is drastically shorter, and takes place mainly in a flow line, so that only one storage step is necessary. Production starts again by shearing from tubing or a rod. Heating, forging and heat treating stations are integrated into the production line. Forming is done by a so-called precision forging process, which takes place in a closed die. Therefore, the forging result has no burr, and thus does not need deblurring by shearing. The main point is, that the teeth of the gear are already shaped with a tolerance in the range of 0.2 mm to 0.4 mm. In Figure 5 precision-forged helical gears can be seen. It is especially interesting that additional form elements can be formed, which do not need further machining operations. Heat treatment is done using the forging heat, with integrated, controlled cooling by gas, or with a two-phase fluid. Integration of the hardening and tempering process into the forging line saves a considerable amount of energy, because the material is heated only once.
The precision forging is of a quality that needs only hard machining by grinding. The part is finished in two clippings, in a universal grinding machine, and in a gear grinding process. There are several possibilities, as shown in Figure 6. Principally, generating (cinematic) and profile grinding can be distinguished. In profile grinding, the gear tooth geometry is determined by the shape of the grinding wheel, whereas in cinematic grinding, tooth geometry is generated by cinematic coupling of the tool and the work piece movement [4, 5]. Each group of processes can be further subdivided into discontinuous and continuous processes. Because of quality and productivity reasons, in our project we concentrated on discontinuous profile grinding and on continuous grinding with a cylindrical warm-threaded wheel or involutes screw.

FIGURE 5. Precision forging process with integrated heat treatment

FIGURE 6. Gear grinding processes according to German DIN 3960 classification

Discontinuous profile grinding means that each tooth space is ground in a single path. The grinding wheel has to be shaped according to the profile of the two adjacent teeth. The process is
highly productive, although the shaping of the grinding wheel is not a trivial geometric problem. I’ll report on some of our approaches and the results achieved [6,7].

The machine which was developed in collaboration with a German machine tool builder and my research group for our investigations is shown in Figure 7.

FIGURE 7. 6-axes gear grinding center Kapp KX1

The machine is versatile – which is very advantageous for R & D purposes. It was designed for discontinuous profile grinding, for continuous screw grinding and for external tooth honing. It has six numerically-controlled axes. We equipped the machine with an additional dressing unit and, of course, with the necessary force measuring devices. The machine is fully encapsulated, in order to use oil as a coolant. The oil is temperature-controlled, to ensure thermal stability of the machine. The NC-control 840 D was designed so that arbitrary electronically-linked gear trains could be defined. This was essential for the cinematic and profile grinding processes as well as for the dressing of the grinding wheels, i.e. the profile wheel or the screw wheel.

For profile grinding, the main problem was calculation and generation of the tool or wheel profile. It is firstly a three-dimensional geometric problem where the given contact line of the tooth flank has to be transformed into the axial cross-section of the tool, as can be seen in Figure 8. I will not go into the mathematics, which is based on vector algebraic calculations. The theory has been state-of-the-art since the end of the sixties. But since modern gears have been profile-corrected several times, to improve fatigue strength and vibration and noise behavior, the involute equations had to be extended, to provide for arbitrary mathematically describable modifications. This was not trivial. Besides that, for precision forged blanks, the tooth foot and the tooth head roundness had to be incorporated into the wheel profile. Especially the latter is important for the fatigue life of the gear, because in forgings, in comparison to pre-machining by milling, a protuberance cannot be generated. Thus in profile grinding, the foot of the tooth is ground, too.
The quality of the manufactured gear is dependent on several geometric deviations of the machine and the tool. This might be due to thermal effects as well as to elastic deformations or deviations of the theoretical machine positions and movements. Because we set the goal to achieve at least quality 5 according to ISO standards, we developed a system to reconsider different deviations of the geometric system. The Figure 9 shows six influences, displacements of the tool in $x_s$ and $y_s$ direction, tilting of the tool around the $y_s$ and the $z_s$ axis, and of the workpiece around $x_w$, and finally the rotation of the workpiece around $z_w$. The effects for these erroneous influences can be calculated, so that preventive correction is possible, or reasoning backwards, the influences can be determined by the different effects. The Figure 10 shows how this correction model works. The profile lines for the left and right flanks are improved by two corrections from the initial state, where the quality was in the range of quality 9 to 10. The quality value of 5 to 4 could only be reached by applying the correction model. Quality 4 and 5 is beyond the superior industrial demands which are now in the range of 6.
Let us assume that the tool profile has been correctly determined. It then has to be achieved at the real grinding wheel. For the wheel made of sintered alumina, which was used, we developed a special dressing procedure, working together with a dressing wheel manufacturer. The rotating dressing tool is equipped with hand-set diamonds of a special strength [8]. The simplest possibility to generate the right and left half of the profile is to dress it in one path. But that would implicate that one side is dressed by push and the other by pull. This would lead to different loads, and thus to different elastic deformations of the grinding wheel. This is the reason that a twin edged dressing wheel was developed (Figure 11).

This example of developing a new process chain for gear manufacturing shows the essential collaboration of different disciplines, and of research institutes and industrial companies (Figure 12).
Integrated heating, forging, hardening and tempering made it necessary to think about the material. Material scientists had to enter the project. Because in precision forging, die wear resistance is of crucial importance, the material scientists also had to give their advice on how to improve this feature. Presently, thick coating of dies at the critical parts of the surface seems to be the best solution.

![Material Forming Grinding Component Industry Research Institutes](image.png)

**FIGURE 12. Project consortium**

For the development of the precision forging process itself, metal forming engineers were responsible. The optimal design of the die, the material flow considerations and the definition of the process parameters was their task. Together with the material scientists, they developed the hardening and tempering process which was integrated into the forging process. The Institute for Transport Systems and Automation had to be consulted to ensure the time-critical material flow from the shearing device via heating and forging to heat treating.

My group, together with the metal forming engineers, investigated the optimal shape of the forged blank. If the forged blank is too near to the final geometry the forging process is complicated, pressure in the die increases and adds to the wear of the forging tool. On the other hand, the allowance of the forged blank must not be too high, so the flanks can be ground in only two paths. The optimal geometric and technological interface between the size and the shape of the forging and the subsequent finishing operation had to be determined. The strong and weak points of the adjacent processes had to be investigated.

Besides that, the industrial partners played an essential role in the project. The forging press manufacturer developed a machine with sufficient power and press force and an extremely short pressure contact time, since the duration of contact while the pressure is held in the die dominantly determines the heat flux from the heated workpiece, approximately 1200°C, to the die. If the die is overheated, the die material looses strength, and due to this, wear increases.

Cooperation with the gear grinding machine manufacturer enabled my group to obtain a specific grinding machine for the given purpose. Development of the dressing system and its integration
into the gear grinder was the result of collaboration with a small, but innovative dressing roll manufacturer. Finally, demands were made and input given by the automotive parts supplier, in connection with the car manufacturer.

The process-chain-approach needs inevitably collaboration between partners. Several academic groups as well as industrial partners have to cooperate simultaneously and in an open mind manner. As a matter of fact the new paradigm brings industry and academia closer together. Thus the other customer of academia, the students gain also to a great extent. In any case the participating worlds, industry – research groups – students need driving forces: These are competition and collaboration.

REFERENCES

A NEW STRUCTURE OF AN ADAPTABLE MANUFACTURING SYSTEM BASED ON ELEMENTARY WORK UNITS AND NETWORK INTEGRATION

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KEYWORDS: Elementary Work System (EWS), Adaptation, Network, Integration, Information, Logistics.

ABSTRACT. The existing industrial production structures for various products are based on A.W. Taylor principles of the division of work and operations, developed almost a hundred years ago. The previous century introduced into manufacturing technology, systems and their control a large number of innovations, based on fundamental and applied research in various fields of interest. The contribution presents a new approach to the structuring of an Adaptable Network Manufacturing System (ANMS) for the production of various HT-products. The ANMS is based on a competent selection of Elementary Work Systems (EWS). Some structures and characteristics of their elements and units are explained in detail. The second part of the contribution presents the procedure for the structuring of an optimal ANMS. The role of innovation management and marketing research is analyzed. The active cooperation with a team of researchers, dealing with advanced investigations related to the new product, and the team of product designers is explained. Special attention is focused on the subjects S and their competence, as well as on the methods of how to increase the necessary knowledge, needed by the subjects operating an ANMS.

1 A BRIEF HISTORY OF THE DEVELOPMENT OF MANUFACTURING SYSTEMS

At the beginning of the second half of the previous century, the manufacturing technology became a field of significant changes. In 1952, the CINCINNATI – MILACRON [1] developed the first computer-controlled machine tool, an NC-milling machine, creating a revolution in the development of production technologies.

The computer capacity and the physical size of the process computers were being improved fast. These achievements enabled more flexible, faster and reliable production activities. The introduction of NC into manufacturing technologies became very intensive, indicating significant changes of the philosophy of manufacturing industrial products.

About fifteen years later, in 1967, a second revolutionary step changed significantly the technology of new products. The first manufacturing system »MOLINS 24« was developed in England, by the physicist Williamson [2]. The M-System consisted of six NC-machine tools with loading units, a transportation system Molac, connecting the individual MT with the pallet rack and the work setting station, Figure 1. A process computer for integration and coordination of various activities on six MT controlled various machining and other processes, necessary for manufacturing geometrically and technologically similar parts, based on the group technology principles.
A year later, two important developments of manufacturing systems were realized: the Cincinnati Variable Mission [3] and the IKEGAI Turning System COMPTURN [4]. In the next four decades, the principle of integration of NC machine tools and other computer controlled equipment into the manufacturing systems was widely applied in the production of HT-products.

2 THE WORKABILITY AND CAPACITY OF A MANUFACTURING SYSTEM

The development of the first manufacturing system »MOLINS 24« focused on two types of integration:
- the mechanical integration of classical work units, work setting stations and storage places by means of various transportations and handling devices, and
- the computer integration of the functions for running, control and supervision of the manufacturing system.

The manufacturing of parts in a MS with various processes is, however, limited in terms of:
- dimensions of parts to be produced,
- accuracy and surface requirements,
- number of available processes and tools,
- ability of the process to form a required shape in a given material, etc.

These limitations cannot be changed if the parts to be produced have different requirements (dimensions, processes etc.), which the available MS does not cover. This means that a new M-system must become available and put in operation. The limited flexibility of the MS becomes an important cost problem, affecting the competition of the firm. This situation can be solved effectively by large companies which have sufficient financial means and intellectual capacities to meet the manufacturing requirements. When the dimensions of parts, technological processes,
accuracy etc. require a new manufacturing system, a new investment will be necessary. The SME (Small and Medium Size Enterprises) cannot easily solve this type of problems.

Another observation, related to the percentage of time employed by the MS, is of great importance since it affects the production costs. A full day employment is 100%. Let us assume that the normal production time is 8 hours or 33% of the full day. Active employment of the MS might be perhaps 4 hours or 16.5%. This means that the time in which a MS generates parts is only ~ 1/6 of the full day. The low usefulness of this distribution is not desirable.

These are the reasons why it is necessary to search for a new solution related to manufacturing, which may provide better results and much lower production costs.

In order to explain the proposed solution, let us consider the following topics in the development of a new approach to form the future structure of manufacturing systems with the existing SMEs:
- the structure and properties of the EWS,
- the selection of the necessary EWS for manufacturing an innovative HT product,
- the network integration of EWS by information communication and logistics in order to structure an ANMS for the production of a HT-product.

3 MOTIVATION FOR THE DEVELOPMENT OF A NEW SOLUTION

The last decade brought a number of new ideas and solutions into the field of industrial production. The most important among them is, perhaps, the application of the communication networks into the manufacturing activities.

FIGURE 2. Factory as a large complex multilevel adaptive system
The classical production system, (or factory), represents a fixed structure of various working units on 1. the cooperative level (for business policy formulations and strategic decisions), 2. the management level (management, marketing, research and development, sales etc.), and 3. the manufacturing level (design, technology planning, manufacturing cells & systems, assembly, etc.). Figure 2 [7] These units are located in various buildings, forming a fixed structure of the factory. Any changes in the production programme usually involve considerable expenses.

To improve this situation, Large Manufacturing Corporations (LMC) introduced a new approach when organizing an enlargement of their production capabilities. Based on the principle of "Manufacturing in Networks", developed by researchers in the USA, Germany, Japan, UK etc., they introduced the Network Structures. Selected Small and Medium Size Enterprises (SME) are integrated into an information communication network with the major LMC directing, managing, controlling and also selling the products on the global markets. The individual SME-members of the clusters usually produce various components of the products which have been developed and designed by the LMC. This type of production is still based on F.W. Taylor principles which, today, may be questionable [9]. The SMEs working in this type of networks are limited in their development, decision making, independence and financial means.

In the EU, the SME employ about 66 % of the workforce and generate ca. 56 % GNP. [10] For this reason, it is important to find new ways of significantly increasing the innovativeness, productivity and production output of the SMEs in order to decisively increase the GNP of nations.

4 THE MORPHOLOGY OF AN ELEMENTARY WORK SYSTEM (EWS)

The basic unit (BU) for the implementation of an arbitrary process related to the manufacturing of a product or to perform a service function, is its structure as an Elementary Work System (EWS) [7] Figure 3. It consists of a process P, process implementation device PID and a subject S. These three elements P, PID and S, are interconnected to form a closed feedback work system. The correlation between these elements and their behavior is very important for its proper and effective functioning. Table 1 reveals the elements of EWS for various functions and activities in manufacturing.
Let us identify these three elements:
- what are their characteristics,
- how can they be described analytically,
- what are the possibilities to determine the functioning of the EWS under selected conditions.

In order to structure properly an EWS for a certain process in the development, design, production, assembly etc. of a product, it is necessary not only to describe these three elements of the EWS in words, but to define these elements by analytical methods.

A manufacturing process, for instance, turning, grinding, assembling etc. must be described analytically in such a way that the structure of the description indicates the factors, affecting the output in terms of process performance and quality. The analytical tools for process and PID description are the transfer functions or the describing functions. These functions define the relation between the output and input, which expresses the conditions affecting the process, dynamics, costs and quality. The describing function is used for the description of nonlinear systems. Tools and methods have been developed for the estimation of various influences related to the conditions, materials and dynamics, affecting the process output. Research into the identification and control of manufacturing processes, machine tools and other devices brought a number of descriptions of

<table>
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<tr>
<td>MARKETING</td>
<td>COMPUTER</td>
<td>MARKETING MANAGER</td>
<td>Software System</td>
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<td>TRANSPORTATION</td>
<td>TRANSPORTATION DEVICE</td>
<td>DRIVER</td>
<td>LOGISTICS</td>
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<tr>
<td>DEVELOPMENT</td>
<td>(COMPUTER)</td>
<td>RESEARCHER</td>
<td>SUPPORTING DEVICE</td>
</tr>
</tbody>
</table>
P and PID by transfer and describing functions. Our future task will be to collect and standardize this information for future use.

\[ C = K + E \]  

5 THE INTEGRATION OF THE EWS INTO AN ADAPTABLE NETWORK MANUFACTURING SYSTEM (ANMS)

An analysis of the capabilities of SMEs to create new innovative HT-products and to manufacture it for global markets shows that the available knowledge and financial means of these enterprises usually cannot meet these problems [5]. On the other hand, the SMEs employ a number of creative and intelligent subjects who would be capable of generating new ideas, leading to new innovative HT-products. However, the present structures and organization of the factories and the transfer of knowledge, research and advanced working methods, are not the best solutions for the improvements of production activities.

Several years ago the author proposed a new structure of an Adaptable Network Manufacturing System which was developed and successfully tested, [6].
5.1 THE ORGANISATIONAL STRUCTURE OF AN INNOVATIVE HT-PRODUCT SPECIFICATION

An unidentified subject, employed perhaps in an SME, research institute or university gets an innovative idea about a new product. Let us assume that this idea is presented to a clever manager of an SME. He becomes enthusiastic and decides that the idea should be tried out, Figure 4. For this reason the manager organizes a small group of selected product developers or designers with creative ideas, who start to search for various solutions, together with the originator of the innovative idea. The aim of this effort is a well developed HT-product specification, considering the functions, performance, loading, quality and reliability, price, delivery time, etc.

However, the knowledge of these subjects in various fields is usually not sufficient. They are, for instance, not informed about the research accomplishments in the areas which can contribute a great deal to the innovation of the product.

For this reason, a carefully selected research team should be employed in order to provide the newest and most relevant knowledge for the solution. This integration of two teams working together is highly important and the only way to transfer effectively the scientific research results into new products.

An important question to which the innovation management must get a reliable answer is »whether the new product has the chance to be sold on the global markets.« The specification of the HT-product enables the marketing research to obtain an appropriate answer. The decision whether detailed design and manufacturing should be initiated and financially supported, depends on the marketing research results, making expectation assessments more real.

FIGURE 4. Process of high-tech product specification
5.2 DEVELOPMENT AND DESIGN OF AN HT-PRODUCT RESULTING IN THE PROTOTYPE

Figure 5 reveals a corresponding work structure to accomplish this task.

The product specification \( \{X_i\} \) describes the input data which the D & D team has to consider. The intellectual structure of the team must be carefully selected. The competence of the individual D & D subjects, the ability to create innovative design solutions, to cooperate and communicate in the team, to trust and to adapt at an appropriate level of knowledge and the ability for self-organization are the decisive criteria in this respect.

However, the newest knowledge and research results are usually not known to the D & D team. For this very reason a research team should be selected carefully, considering their previous investigation in the field, covering broadly the interests and the aims of the active D & D team. This means that the role of the researchers financed by the science policy must be changed to support the transfer of applied research directly into application, related to the HT-product development. The organization of research activities on the state level, however, does not allow this type of approach. Science and technology research policy is focused on fundamental and applied research within universities and institutes only. The results of this work are the published papers. The SMEs therefore cannot use the newest and most advanced research results for their development work. This is not only a financial problem, but also a question of the designers' knowledge. While the LMC are able to keep the appropriate level of competence and active cooperation with the researchers, this is not the case with the SME.

The second necessity which must be considered and solved are the additional training courses for the D & D. The volume and quality of knowledge in various fields of working technologies have grown tremendously. Information and communication knowledge, design methodology, control
and systems theory, materials, etc., in particular, are spheres that subjects working in various fields are often not familiar with. For this reason their work productivity and quality are rather limited. With selected training courses on various topics, the subjects will get a lot of useful knowledge which will significantly contribute to the improvement of their work performance and productivity.

The next step in the process is the manufacturing of the prototype of the HT-product, Figure 5. A manufacturing team develops the technology for the prototype, entering into this process by the information \( Y_D \). The activities of the team, their knowledge of the most advanced technologies, etc. can be specified in the same way as for the D & D team. The role of the manufacturing research team and the importance of the additional training courses have the same objectives and procedures as earlier discussed.

The output \( Y_P \) of these activities is the prototype of the developed HT-product, which will be tested and improved before the final decision is made, which means that this product will be planned for production on an appropriate large scale for global markets.

The role of the Virtual Coordination Unit (VCU). The organizational structuring of working teams, as well as the responsible decision making concerning their activities, are in the hands of the innovation management. For this type of activities, the manager must have a large amount of well-organized and quickly accessible information at his disposal.

The solution of this requirement was developed and realized as Virtual Coordination Unit (VCU) shown in Figure 6 and Table 2 [6]. This new working unit provides all the information needed for the activities: from the decision making to the manufacturing of the prototype.
The VCU is connected via Internet and various local networks with the data and knowledge bases worldwide. The problem of obtaining systematically organized information, that the production needs, from the data and knowledge bases, was realized by many research institutions and industries. This was the reason for the organization of the European Network of Excellence, with the objective to solve these important problems within the EU-project VRL-CiP (Virtual Research Laboratory – Communication in Production) [7]. It will take quite a long time for this problem to be solved successfully.

TABLE 2. Data and knowledge bases of the VCU

<table>
<thead>
<tr>
<th>Data Bases</th>
<th>Products, available on the markets</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>components, elements</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Bases on Production Capacities</td>
<td>Enterprise A</td>
<td>(mechanical</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>electrical</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>biotechnical</td>
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<tr>
<td></td>
<td></td>
<td>hydraulic</td>
</tr>
<tr>
<td>Knowledge Bases</td>
<td>Research, focused in certain field</td>
<td>(employer,</td>
</tr>
<tr>
<td></td>
<td>Research institution, individuals</td>
<td>available machinery, EWS's</td>
</tr>
<tr>
<td></td>
<td>Training courses, relevant for work improvement, teachers, etc.</td>
<td>capacities, financial means etc.</td>
</tr>
<tr>
<td></td>
<td>Experts, individuals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Programming systems for various tasks</td>
<td></td>
</tr>
<tr>
<td>Patents</td>
<td>Patents, related to the new HT product, procedures for preparing the patents of newly developed products and technologies</td>
<td></td>
</tr>
</tbody>
</table>

5.3 STRUCTURING THE PROCESSES FOR THE MANUFACTURE OF AN HT-PRODUCT

Each product consists of a number of components, which must be manufactured, measured, sometimes painted, hardened, etc. There are, in general, many hundred processes which must be available in the manufacturing systems in order to create every component on the list.

The fact is that the number of products on the markets varies from small to medium to large. This means that the flexibility of manufacturing systems must be very high and easy to accomplish. The solution of this problem is vital for the competitiveness of national manufacturing industries on global markets.

The innovation management, Figure 5, of an enterprise has to prepare, after the prototype is finished, an accurate and detailed survey of the EWS, needed for manufacturing the HT-product. The VCU, with its data and knowledge bases, provides the necessary information about the EWS in various SMEs. Its structure is shown in Figure 6, and indicates the information about the data and knowledge available on the website.
The manager should select the EWS, situated in various SMEs, which are able to manufacture the proposed product. The interest of the contacted SME will decide about the cooperation between interested firms.

A great advantage of this approach is the structuring of an adaptable network manufacturing system (ANMS) by selecting the appropriate EMS via the local databases with the procedures related to the VCU. This means that a team of experts led by the innovation manager selects the available and proper EMS for the jobs. The selectors must not only take into account the technological properties, but also the daily free-of-work time in which the SMEs can be employed. This type of approach may contribute to higher employment of the SME in comparison with the classical organization of the factory. No new high financial costs are required to implement the production of the HT-product.

6 INTEGRATION OF THE EWSs INTO AN ANMS

The innovation manager S1 of the SME1 selects from various SME2 ... SMEk ... SMEn, via VCU, a set of the EWS1,2,...,t, able to produce the planned HT-product. He invites his colleagues to form a team in order to discuss the production of the proposed product. Figure 7 indicates the basic structure of an Adaptable Network Manufacturing System (ANMS), with the objectives as described above, [6].

The selection of the EWSs and their locations, as well as the VCU, is finally established by a competent team which also solves the logistics, based on the principle of »just in time«. Figure 8 reveals an arbitrary distribution of the EWS, integrated via Internet, LAN and the material transportation logistics (MTL) into an Adaptable Network Manufacturing System (ANMS).

For the implementation of various production functions the SMEs have a number of EWSs working together. For instance, for the manufacture of an axis with two types of gears, the following processes are required: 1 – turning; 2 – milling; 3 – hardening; 4 – grinding. The limitations are the maximal dimensions and the accuracy of the processes. Therefore, a SME, cooperating in the ANMS, employs more than one EWS, called production unit PU, as shown in Figure 9. This type of manufacturing structure represents an optimal solution, related to much better exploitation of the machinery than in the case of a classical factory.

The adaptability of the manufacturing system (ANMS) structure depends upon the innovation team of managers who are determined to achieve as low as possible investment costs in the process implementation devices (PID), by effectively employing the existing PID. This is a very effective way of increasing the competitiveness of the SME on the global markets.
FIGURE 7. Basic structure of an ANMS

FIGURE 8. Network structure of a complex adaptive factory system with distributed EWSs
A New Structure of Manufacturing System

7 CONCLUSIONS

The existing industrial production structure, based on A.W. Taylor principles developed almost a hundred years ago, were analyzed. It was shown that the SMEs, which contribute more than 60% to the GNP and employ more than 50% of the work force, are not in the financial and intellectual position to develop and manufacture innovative HT-products for global markets.

This research paper, supported by experiments, shows how an innovation manager of a SME initiates the development of an innovative HT-product. The procedure of the product specification, the role of the development and research team, as well as the marketing for the decision making of the management, are discussed in detail. The product specification presents a carefully prepared and tested input into the D & D and the manufacturing of prototype activities. In order to accomplish innovative products, active support of research transfer for the design and production technology is necessary. To increase the knowledge for the work improvement of the cooperative subjects, various training courses are planned and executed. A virtual coordination unit (VCU) is established for the selection and control of the information related to the processes involved.

The Elementary Work System (EWS) necessary for the implementation of various processes which are not at the disposal of various SMEs. These elements are integrated by communication and logistic means in order to formulate an Adaptable Network Manufacturing System (ANMS) for manufacturing an HT-product, competitive on global markets.

REFERENCES


SOME APPROACHES IN THE MACHINING RESEARCH

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KEYWORDS: Machining, Modeling, Experiments

ABSTRACT The paper discusses some approaches in machining research. Development of empirical technology, as well as of science-based (predictive) technology, and development of computer-based technology are presented. The application of mathematics of statistics and design of experiments, simulation of machining processes such as analytical simulation, geometrical simulation, finite element simulation, and supervision systems in machining are discussed. Also, the importance of machining research for computer integrated manufacturing enterprise in global market conditions is discussed.

1 INTRODUCTION

Initially, machining was an art. There was no engineering basis for determining proper machining parameters such as cutting speed, feed, depth of cut and cutting tool characteristics for obtaining higher productivity in machining operations. According to E. Merchant [1], basic technology of the machining process began to evolve in the 20th century, going through three main stages in that timeframe. These were:

1. Development of empirical technology, beginning in the early 1900s.
2. Development of science-based (predictive) technology, beginning in the 1940s.

Each of these stages was triggered by a key event and, interestingly enough, all three of these stages today co-exist and synergize each other. The aim of the research in machining is to find a solution which will make a product of high quality, at a low cost and rapidly. These objectives are summarized in the first author’s maxim “Manufacturing a product is not difficult, the difficulty consists in manufacturing a product of high quality at a low cost and in a short time.” [2].

This aim cannot be achieved without a better understanding of machining processes - new approaches, such as stochastic approach, modeling, simulation, supervision systems, new methodologies, etc. The paper will present some approaches in machining research and their related examples.

2 EMPIRICAL RESEARCH

The empirical research for engineering of the machining process was initiated by F.W. Taylor. In 1880 he started a massive, factory-based research program that lasted 26 years without any publication. In 1906 he published the results of his research in his classic book - that is actually a huge paper, with more than 300 pages "On the Art of Cutting Metals" [3], which was presented at the Winter Annual Meeting of the American Society of Mechanical Engineering in New York.

That research produced an empirical understanding of machining process and empirical equations such as Taylor equation:

\[ v_c T^n = C \]  

where: \( v_c \) is the cutting speed, m/min, \( T \) is tool life, min, \( n \) is exponent whose value depends on the specific workpiece material, tool material and some other factors of the particular operation such as machine tool, and \( C \) is empirical constant whose value depends on the specific workpiece material, tool material and some other factors of the particular operation. This relationship is the basic equation for the identification of machining process. The application of Taylor’s results had generated an increase of approximately 200-300 percent in the productivity of the machine tools. After the publication of Taylor’s results a strong effort emerged to continue the research in the same direction. Different tool life equations were developed. An equation which explains tool wear and tool life phenomenon better is for example the "New Tool Life Equation" proposed by E.Kuljanic [4] - the first of this kind,

\[ T = C' v^{k_f} f_z^{k_z} S^{k_s} \left( \frac{v}{f_z} \right)^{k_{vz}/f_z} \left( \frac{S}{f_z} \right)^{k_{sz}/f_z} \left( \frac{v}{S} \right)^{k_{vs}/f_z} \]  

Where: \( C' \) is empirical constant, \( v \) is cutting speed, m/min, \( T \) is tool life, min, \( z \) is number of teeth, \( f_z \) is feed per tooth, mm, \( S \) is stiffness of the machining system, N/mm, \( k_f', k_z', k_s', k_{vz}', k_{sz}', k_{vs}' \) are exponents. This equation includes interactions between different variables. The interaction is present when the effect of one variable depends on the level of the other variable or variables. The exponents \( k_f', k_z', k_s', k_{vz}' \) etc. and the constant \( C' \) given in the equation (2) are obtained from the experiments. New Tool Life Equation includes only statistically significant factors and interactions. Tool life equations are needed for the identification of the machining process and its optimization.

3 SCIENCE BASED RESEARCH

In the late 1930s a new approach to machining began to evolve the science based research. The basic characteristic of science-based technology for engineering of machining is that it draws on the science of physics. Therefore, it is independent of empirical information. Hans Ernst investigated the mechanism by which a cutting tool removes metal from a workpiece, i.e. the process of chip formation. He published his main findings in the paper "Physics of Metal Cutting" [5]. He proposed the concept of the "shear plane" in chip formation, i.e. the very narrow plastic zone "plane" between the body of the workpiece and the body of the chip.

M.E. Merchant applied the science of the mechanics of solids bodies to the "shear plane" concept. This resulted in the model of the equilibrium force system acting in the chip-tool-workpiece system, Figure 1, [6]. The result was a science-based-predictive model of the basic process of chip formation - the first of this kind, i.e. the first science-based predictive model in engineering of the machining process.

With the application of unmanned machining system: machine tool, workpiece, tool, fixture and control unit, chip formation, research has become more important, for example, the form of the chip is more important. The long chip can stop the machining process and damage the tool and the workpiece. Even in milling there can be a long chip. For example, E.Kuljanic, in his research
Some Approaches in the Machining Research

FIGURE 1. Condensed form of the M.E. Merchant orthogonal cutting force system (1944)

for the Ph.D. thesis in milling at the University of Cincinnati (USA), obtained the curled long chip in milling stainless steel, Figure 2.
The width of the workpiece was only 50 mm, and a carbide cutter was used. The chips were more than 500 mm long and welded on each cutting edge. They would brake when hitting the body of the milling machine. Such “impossible” chips were obtained due to the welding joints of many short, approximate 8 mm long, chips, Figure 2. There were two welding joints. First the chip No.1 was welded to the tooth at the exit of the tooth from the workpiece, Figure 3a). At the next entrance of the tooth, the chip formation of the chip No.2 started and at the same time when this chip was welded to the chip No.1. At the exit of the tooth the chip No.2 was welded to the tooth, but the actual chip consisted of chip No.1 and chip No.2, Figure 3b). Since the cutter was rotating, after the third exit of the tooth from the workpiece, the chip was three times longer and so on. In this way a long chip was welded from a number of short chips No.1, No.2, No.3, etc. Each tooth produced a long chip which was welded onto the cutting edge. Therefore, the long chips were rotating with the cutter and would break only after hitting the body of the machine tool.
This phenomenon happened during two hours in milling testing over a period of more than four months. That means that it is very difficult to have the right welding conditions - such as tem-
FIGURE 2. Welded chip in milling a) one side view, b) the other side view of the same chip.

FIGURE 3. Welded chip in milling, a) chip No.1 welded on the cutting edge, b) chip No.1 welded to the chip No.2.
perature, pressure, etc. - at two different places, i.e. at the entrance: chip to chip, and at the exit: chip to cutting edge. Max Kronenberg’s comment was "Such a long chip in milling can be obtained only in Cincinnati".

Merchant’s discovery of the science-based predictive model in engineering of the machining process, based on Ernst’s shear plane, opened a new era in chip formation, i.e. in machining.

4 COMPUTER BASED TECHNOLOGY

The computer based technology has a significant influence on approaches in machining research. The numerical control brought a radical change in the field of machining in the 1950s. We were convinced that the research of numerical control started at Massachusetts Institute of Technology - MIT. However, the inventor of the numerical control of machine tools was John T. Parson [7]. He filed his initial patent on numerical control in 1952. He started to work on the numerical control concept in the latter part of the 1940s. In 1949 he signed a contract with the US Air Force "to design and construct a milling machine using servo-mechanisms actuated by punch cards on tape to produce wing sections" for supersonic air planes. However, he was well aware of the inability of his company to carry out such an undertaking alone. He took as subcontractor the Servomechanism Laboratory at MIT. However, MIT made a prototype of the numerically-controlled servo system and filed a patent on the prototype in 1952. It is interesting to note that the machine tool industry and the manufacturing industry did not want to apply the numerical controlled servo-system for machine tools. The time required to manually prepare the program for NC machining of a part could be, in some cases, more than 50 times the time required to machine that part. MIT solved the problem by automating the programming process which was the beginning of the computer based technology.

The computer technology and the numerical control radically changed the industrial conditions in production. One of the most important strengths of the computer technology, as applied to machining, was its capability to combine both empirical and science-based technology in the engineering of machining operations. In particular, it proved to be able to simulate the actual ingoing performance of such an operation; i.e. it could create "dynamic" models. However, of even broader significance was the fact that it provided power capability to integrate these dynamic models of machining performance with the performance of all the other components of the overall system of manufacturing, as first envisioned by Merchant in 1961 [8].

After more than forty years the industrial conditions in production completely changed. The operator’s precious experience and knowledge cannot be directly used in automated machining operations. This can be compensated with the results obtained from machining research. Furthermore, the facilities and techniques to do the research completely changed as well. For example, in machining research we can use: design of experiments, mathematics of statistics, modeling, computer and new software, new methodologies, etc.

5 MATHEMATICS OF STATISTICS AND DESIGN OF EXPERIMENTS

The application of statistical methods and design of experiments in machining research is very important. It is of such an importance that the mathematics of statistics affects the way of thinking which yields a better understanding of many processes.
Billions of euros are spent for experiments around the world every year. However, it is amazing how little the design of experiments is used. It is obvious that without the application of the design of experiments and mathematics of statistics the experimental results could be poor, less reliable, and the experiment could be time consuming and more expensive. Therefore, the aim of this section is to emphasize the need of the application of mathematics of statistics and design of experiments in machining research.

Some examples of the application of mathematics of statistics and design of experiments in machining research are given as follows: comparison of tools from different manufacturers, regression analysis-effect of tool life data analysis on tool Hfe equation and some examples of design of experiments.

5.1 COMPARISON OF TWO TOOLS FROM DIFFERENT MANUFACTURERS

In manufacturing production there is a need to find out which tool is better for machining a given material. This can be done by tool wear testing and by applying statistical analysis [9]. Different tool wear data in turning were obtained for two different tools. Table 1.

<table>
<thead>
<tr>
<th>Test</th>
<th>VB Tool A [mm]</th>
<th>VB Tool B [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.43</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>0.39</td>
<td>0.43</td>
</tr>
<tr>
<td>3</td>
<td>0.40</td>
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<tr>
<td>4</td>
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<td>5</td>
<td>0.34</td>
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<tr>
<td>6</td>
<td>0.45</td>
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<tr>
<td>7</td>
<td>0.36</td>
<td>0.31</td>
</tr>
<tr>
<td>8</td>
<td>0.35</td>
<td>0.37</td>
</tr>
<tr>
<td>Mean</td>
<td>0.40</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The arithmetical mean of tool wear for the tool A was \( V_{BA} = 0.40 \) mm and for the tool B was \( V_{BB} = 0.35 \) mm. From the t-test, we obtain:

\[
|t| = 1.72 \text{ and } t_{\alpha=0.05} = 2.145.
\]

We may conclude that the arithmetical means of the tool A and the tool B are not significantly different since \(|t| < t_{\alpha=0.05}\).

More reliable comparison can be done by testing at different cutting speeds and with the application of regression analysis to determine tool life equations. These equations are then compared statistically by using the methodology given in [10].

5.2 APPLICATION OF REGRESSION ANALYSIS

Regression analysis is, for example, used to determine the association between two variables in experiments, where one of the variables is a non-stochastic variable, the values of which are predetermined when the experiment is designed-planned.

Regression analysis is a useful mathematical tool which can be used in research particularly for identification of machining process needed for optimization of the process. To show how
important it is to determine which variable is non-stochastic variable an example in machining is presented. One of the reasons, why the so called Taylor exponents in (1) are usually different when the tool life experiments and the regression analysis are done at the same conditions in USA and in Europe, is the wrong determination of the non-stochastic variable. Hundred years ago F.W. Taylor (USA) proposed the tool life equation (1). To determine the exponents and the constant $C$, Taylor plotted cutting speed $v_c$ against tool life $T$ without applying regression analysis.

Mostly the way, cutting speed $v_c$ versus tool life $T$ is used in USA today when regression analysis is applied. In Europe the tool data analysis is done in opposite way, i.e. tool life $T$ versus cutting speed $v_c$. In order to convince Max Kronenberg that it was possible to obtain different tool life equations from the same data, when the analysis of data was done $v_c$ versus $T$ and $T$ versus $v_c$ the first author made the following statistical analysis in 1976 [11].

The tool life data for turning steel with HSS tool from the PhD thesis [12] were used for regression analysis done in two different ways: $v_c$ versus $T$ and $T$ versus $v_c$. In Figure 4, two different tool life equations determined from the same tool life data are given. The equations a) are obtained with the regression analysis $T$ versus $v_c$, and equations b) are obtained with regression analysis $v_c$ versus $T$. It can be seen that the Taylor exponent $m = 0.108$ ($T$ versus $v_c$) is approximately 40% greater than the $m = 0.077$ obtained with the regression analysis $v_c$ versus $T$. The reason why the exponent $m$ is different can be seen from Figure 4. In this case, $T$ versus $v_c$, the regression analysis is done with the values $y$ for each point, and in the case of $v_c$ versus $T$ the analysis is done with values $x$.

The difference of the exponent $m$ affects the optimal tool life very strongly

$$T_e = \left(\frac{1}{m} - 1\right)(c_c + \frac{C_g}{C_1 + C_o})$$

For the criterion of optimization-minimum machining cost, where $T_e$ is tool life for minimum machining cost, $c_c$ is tool change time, $C_g$ is the tool cost between two resharpening, euro/cutting period, $C_1$ is direct labor cost on the machining system, euro/min, $C_o$ is overhead cost (rate) of the machining system, euro/min.

For example, for turning steel with HSS tool the tool life for minimum machining cost is $T_e = 100$ min for $m = 0.077$, and $T_e = 69$ min for $m = 0.108$ [11][13] due to and respectively. The tool life $T_e$ for identical turning operation is 45% greater when regression analysis is done $v_c$ versus $T$ in comparison to $T$ versus $v_c$.

According to these results E. Kuljanic proposed to ISO (International Standard Organization), in 1979, to standardize the testing procedure in which the regression analysis should be done - tool life versus cutting speed, since the tool life physically depends on the cutting speed. The ISO accepted the proposal in the ISO standards 8688/1 and 8688/2.

5.3 DESIGN OF EXPERIMENTS

The design of experiments is a very useful technique to increase the reliability of experimental results and to decrease test time, experimental expenses and required time. The best results are obtained when the design of experiments is combined with appropriate statistical analysis and with good understanding of the process examined.
FIGURE 4. Different tool life curves obtained from the same data

DESIGN OF EXPERIMENTS AND REGRESSION ANALYSIS - SURFACE ROUGHNESS
This is an example where a complete $3^4$ design of experiments was used to determine the relationship between the surface roughness $R_a$ in turning and the following non-stochastic variables: cutting speed $v_c$, depth of cut $a_p$, feed $f$ and radius of the insert $r_e$. Regression analysis was used, and the Student’s t-test was applied to determine the significant effect of the variables. The experiment was turning a brass bar: cutting speed $v_c = 99-196-393$ m/min; feed $f = 0,040 - 0,125 - 0,315$ mm; depth of cut $a_p = 0,2 - 1,0 - 2,0$ mm; radius of the insert $r_e = 0,4 - 0,8 - 1,2$ mm. After dropping the non-significant variables: cutting speed and depth of cut, we obtain:

$$R_a = \frac{1,533 f^{0.444}}{r_e^{0.66}}$$  \hspace{1cm} (4)
It can be seen that the Equation (4) is highly significant according to the analysis of variance of the regression:

$$ F = 393 > F_0 = 4.92 $$

This is an example when testing procedure is short, that is not very usual in this area. Therefore, it was possible to use a complete $3^4$ design of experiments.

**DESIGN OF EXPERIMENTS - ANALYSIS OF VARIANCE AND EFFECT OF SIGNIFICANT FACTORS**

In order to find out the effect of four variables: number of teeth in the cutter $z$, stiffness of the machining system $S$, cutting speed $v_c$ and feed per tooth $f_z$ on tool life $T$ in face milling, a $2^4$ design of experiments was applied, milling tests were carried out and analysis of variance and effects of significant factors were determined. The result of the research was the proposed new tool life equation (2), for face milling stainless steel with carbide cutter E. Kuljanic [2],[4]

$$ T = 211.79 \cdot 10^5 v_c^{-4.023} f_z^{-1.454} z^{-10.267} S^{-1.329} . $$

$$ \cdot (v_c z)^{2.3913} (v_c S)^{0.3880} (z S)^{0.8384} (v_c f_z S)^{0.0190} (v_c z S)^{-0.1972} \quad (5) $$

It was proved, for the first time, that the number of teeth in the cutter, stiffness of the machining system and some interactions have a significant effect on tool life in milling stainless steel with carbide cutter.

The application of mathematics of statistics in manufacturing was very inadequate 25 years ago. Only a few researchers in CIRP (College International pour la Recherche en Productique - Paris) such as R. Levi, G. Lorenz, E. Kuljanic and J. Peklenik were using and promoting the statistical methods and design of experiments.

**6 SIMULATION OF MACHINING PROCESSES**

Simulation of machining process is becoming more and more useful in machining research. The main advantage provided by machining simulators is to enhance the comprehension of the machining results, forecast the machining outputs to an acceptable degree and thus reduce the cost and the number of machining experiments. Obviously, simulation of machining is a very complex task. It can be performed at different levels. The main procedures of a machining simulation are given in table 2.

<table>
<thead>
<tr>
<th>TABLE 2. Classification of simulation systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMULATION TASK</td>
</tr>
<tr>
<td>Workpiece / tool interaction - Uncut chip thickness estimation</td>
</tr>
<tr>
<td>Cutting forces estimation</td>
</tr>
<tr>
<td>Temperatures estimation</td>
</tr>
<tr>
<td>Workpiece surface characteristics estimation</td>
</tr>
</tbody>
</table>
6.1 ANALYTICAL SIMULATION OF MACHINING

Analytical simulation is the simplest approach of machining simulation. It can be used to estimate the uncut chip thickness when the geometry of the operation is very simple. For example, an analytical simulation of machining was used together with experimental data to evaluate the influence of tilt angle on cutting forces and surface finish in ball-nose end milling by Schulz et al. [14]. The cutting forces can be estimated from the uncut chip thickness by using an empirical approach such as the Kienzle force model, equation (6), or by shearing and ploughing force model, equation (7), as follows:

\[
F_c = k_{s0} h(t)^{1-a_h} L
\]  
\[
F_c = k_{sc} h(t)L + k_{pc} Lg(t)
\]

Where \( k_{s0} \) is the unit cutting force, \( N/mm^2 \), \( h(t) \) is the instantaneous uncut chip thickness, \( a_h \) is the uncut chip thickness exponent, \( L \) is the width of cut, \( k_{sc} \) is the shearing coefficient, \( k_{pc} \) is the ploughing coefficient and \( g(t) \) is the contact function, whose value is 1 when the cutter is in contact with the workpiece and 0 elsewhere. Usually, cutting temperatures are not estimated by applying this approach. The main advantage of this approach is its simplicity. Also, it is not time consuming method. The main disadvantage is that it can not be applied for complex geometries such as hobbing. A common use of this approach is to provide quick data for cutting force coefficient estimation in very simple machining cases, such as turning and milling.

6.2 GEOMETRICAL SIMULATION OF MACHINING

In geometrical simulation of machining the volume removed from the workpiece is determined numerically by geometrical intersection of the tool and the workpiece.

In this approach the tool is represented by a set of basic solids such as tetrahedrons, while the workpiece can be represented in several ways. The most common workpiece models are Z-map models, first developed by Anderson in 1978 [15], sliced-sections models [16] and solid models. In 2003, a new approach was presented by E.Kuljanic and M.Sortino, where the workpiece is represented by an octree [17]. Different machining operations can be simulated with the same model of the workpiece without modification. This is the most important characteristic of this methodology. An example of simulation of hobbing, turning and drilling of a gear is given in Figure 5. Also, this method is suitable for simulation of complex machined parts and tools.

The cutting forces can be estimated in the same way as they are estimated in the analytical simulation of machining.

The geometrical simulation of machining can be useful in several applications such as development of new tools, simulation of complex machining operations, both for supervision and experimental data analysis - for example cutting forces, simulation of machining very expensive workpieces, etc. The main disadvantage of this approach is that it is based on empirical equations. Therefore, there is a need to have reliable equations.

6.3 FINITE ELEMENT SIMULATION OF MACHINING

The finite element simulation of machining is mostly used by researchers in this field. The aim is to predict all variables quantitatively with acceptable accuracy such as flow of the chip, the stress
To accomplish this task, a relationship between forces, friction, strain, strain rate and temperature is needed. This equation is, in general, quite complex and its reliability depends on the parameters that are difficult to determine since the conditions of workpiece material tests are different from the real cutting conditions.

The Johnson-Cook constitutive equation [18],[19] is widely used to model the workpiece material behavior under high strain, high strain rate and at high temperatures:

$$
\sigma = (C_1 + C_2 \varepsilon_{pl}^n)[1 + C_3 \log\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)][1 - \left(\frac{T - 20}{T_m - 20}\right)^m]
$$

Where $\sigma$ is the stress, $\varepsilon_{pl}$ is the plastic strain, $n$ is the strain index, $\dot{\varepsilon}$ is the strain rate, $\varepsilon_0$ is the reference strain rate, $T$ is the temperature, $T_m$ is the reference temperature, $m$ is the temperature sensitivity index and $C_1, C_2$ and $C_3$ are the material constants, see Table 3.

In 2002, Hamann et al. presented a paper on the determination of constitutive equation by direct methods such as the split Hopkinson’s pressure bar bench - SHPB test. The paper provided guidelines for the application of experimentally determined constitutive equations by using the finite element approach [20].

Another approach to determine the stress response of workpieces in orthogonal machining was presented by Batzer et al. [21]. Two commercial steels, AISI L6 and AISI O1 were analyzed by using quasi-static tensile, split Hopkinson’s bar and orthogonal machining testing. The coefficients of Johnson-Cook model were determined by using test data. The predictions of machining
The simulation were high correlated to real dry-cutting machining tests.

**TABLE 3. Johnson-Cook equation parameters for AISI4340 [19]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>950 MPa</td>
</tr>
<tr>
<td>$C_2$</td>
<td>725 MPa</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0.015</td>
</tr>
<tr>
<td>$n$</td>
<td>0.375</td>
</tr>
<tr>
<td>$m$</td>
<td>0.625</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>3.500s$^{-1}$</td>
</tr>
</tbody>
</table>

The most common way to determine the workpiece material properties at high strain rates is the Hopkinson’s bar test.

Finite element theory relies on the hypothesis of linearity, therefore, it applies to small displacements. This theory has been extended to large displacements by introducing iterative methods instead of linear methods. The most common non-linear iterative method is the updated Lagrangean method with Euler’s stress-strain relation, where the change of shape is taken into account and incompressibility constraint in the deformation zone is relaxed.

$$\{ \dot{F} \} + \{ F_t \} = \{ [K_M] + [K_G] + [K_F] \} \{ v \}$$  

Where $\{ \dot{F} \}$ is the nodal force rate, $\{ v \}$ is the velocity of nodes, $[K_M]$ is the stiffness matrix, $[K_G]$ is the geometrical stiffness matrix, $[K_F]$ is the correction matrix for load, $\{ F_t \}$ is the thermal force load caused by volumetric change.

The simulation of chip formation using finite element is quite difficult. A parting criterion should be introduced such as maximum stress/strain or a geometrical criterion. A geometrical separation method that is considered to be the most effective for ductile materials was presented by Obikawa in 1996 [22]. Obviously, the parting process changes the stiffness matrix of the workpiece, thus it adds a non-linearity in the iterative method. A common way to include it in the model is to add fake elements to the workpiece mesh. The behavior of the fake elements is non-linear, and when the plastic strain reaches a critical value, the element is deleted. This process is very complex and time-consuming. Therefore, the application of finite-element method to practical cases is rare. In 1996, CIRP proposed a round-robin on FEM simulation. The aim of the round robin was to simulate the cutting forces, the chip contact length and the shear plane angle, the temperatures and friction of a turning operation of a low-carbon steel. Several research groups participated in this work, in which each group proposed a different finite-element approach. The results obtained by simulation were compared to the experimental test results. The differences between the obtained simulation results where from 50% to 400%.

The simulation of high speed machining by applying a physics base modeling technology which includes the change in the constitutive equation and friction characterization at cutting speeds up to 400 m/min, was presented in 2002 by Ng et al.[19]. 3D finite element modeling of orthogonal and oblique cutting operations with both continuous and segmental chip formations was also part of this work.

Modeling of machining operations of a low machinability material TiAl6V4 was presented by F. Klocke et al.[23], in which a 5-axes milling operation of a turbine blade was modeled. The simulation results helped find the influence of cutting parameters on the process. The estimated results obtained by simulation were in good accordance to the test results.
7 SUPERVISION SYSTEMS

In machining, direct and indirect supervision systems could be used [24]. Direct system measures, for example, the actual flank wear land $V_B$ or the crater wear. The tool wear, tool breakage and some important process parameters can be determined by applying indirect measuring processes. This methodology is, in general, less accurate than direct methods.

Tool wear is determined by vision systems from a picture. In 2003, an algorithm for automatic measurement of the flank wear land was proposed by M. Sortino and implemented in the Wearmon software (University of Udine) [25]. The algorithm was able to identify the shape of the worn area and measure the average and maximum tool wear in many practical cases. Similar approaches were presented by M. Lanzetta [26], by T. Pfeifer and L. Weigers [27]. The vision system can not be applied during cutting. In order to improve machining, a flow of information about tool condition is necessary. Indirect measuring processes are suitable for on-line tool condition monitoring. They are based on the application of sensors such as dynamometers, acoustic emission sensors, accelerometers, etc.

For tool condition monitoring, it is necessary to obtain the information required from the sensor signal, and the correlation between the signal characteristic and the tool condition. In many cases, there are external disturbances and limited computer power. One approach to solve this problem could be to use faster computers. It would make possible to use the original acoustic emission signal instead of the root mean square acoustic emission signal (AERMS), which is now broadly used.

In 1995, the state of the art on the application of sensors for tool condition monitoring in research and industrial conditions had been presented by Byrne et al. [28]. According to the authors, the tool condition monitoring systems are not applied in industrial conditions due to their limited reliability. A method for estimating the tool wear in milling by applying the cutting forces measured with a rotating dynamometer was presented by the authors in 2005 [29]. This method is based on the ratio between actual cutting forces and the cutting forces when the tool is sharp. A good correlation between the experimental results and the estimated tool wear was found.

Multiple sensor systems are more reliable from an extended research. It is obvious that, the architecture of the system is more complex and requires advanced artificial intelligence techniques to take into consideration all information. In 2003 Scheffer et al. [30] investigated the application of a multiple sensor tool condition monitoring system for hard turning. Their approach was based on the application of dynamometers, acoustic emission, vibrations and temperature sensors. The monitoring system was able to estimate the tool wear with a good reliability. Generally, the question is which combination of sensors will provide the required information at the minimum cost.

8 CONCLUSIONS

The conditions in global market are changing very rapidly. In such conditions the competitiveness has to be based on new ideas and new products. It is important to have computer integrated manufacturing enterprise in which machining systems must be able to autonomously increase the effectiveness of the machining system and avoid or correct machining errors during cutting in order to manufacture a product of high quality at low cost and in a short time. Thus, there is a further need of research in computer based technology by applying the approaches discussed
in the paper such as empirical approach, science based approach, stochastic approach, modeling, simulation and supervision. Also, there is a need to develop new methodologies and suitable decision making strategies.

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NUMERICAL & EXPERIMENTAL METAL CUTTING ANALYSIS: AN APPRAISAL

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KEYWORDS: Metal Cutting, Turning Experiments, Numerical Simulation.

ABSTRACT. Numerical analysis of metal cutting operations is increasingly relied upon in computer experiments, in order to clarify mechanical, thermal and tribological aspects in view of process optimization. The acid question is, however, whether impressive color displays and detailed figures describe what is actually taking place, or if some results might more properly belong to virtual reality. A classic experimental design for second order response surface work, concerning a simple cutting operation on mild steel, was run both in the metal cutting laboratory and on dedicated software, and results compared also in the light of classic models. Agreement concerning responses such as forces, temperature, and cutting ratio, was found to range from definitely fair to quite poor, underlining that reliance on numerical model may not always be fully justified. Analysis of deviations throws some light on a complex situation.

1 INTRODUCTION

Detailed numerical models of metal removal processes, currently implemented in commercial software with a wealth of graphic displays, provide fast, detailed description of mechanical and thermal aspects of operation. Users are expected to assume models and finite element discretization to be adequate, numerical analysis flawless, and therefore provided proper material parameters are fed into the program correct results are invariably obtained. Laboratory tests being expensive and time consuming, numerical results are often taken at face value, and experimental verification is conveniently dispensed with. In a number of instances one may put up with numerical results, even of questionable value, if only because seldom people bothers checking, and some inconsistencies with experimental evidence may be blamed upon scatter in machining tests. However in some cases predictions fly on the face of established facts, and the situation must be addressed squarely. In the case at hand, failure of some predicted results to satisfy elementary checks spilled the beans. Doubts did first arise when some numerical results were found inconsistent with equilibrium conditions in simple, two-dimensional steady state cutting operations, and force components on rake face did not match friction coefficient, an user selected parameter. Failure to find satisfactory explanations prompted a specific investigation involving a set of laboratory tests, covering a comprehensive range of machining parameters. Existing doubts were confirmed by independent, published experimental evidence.

2 LABORATORY TESTS

Free orthogonal cutting tests were performed turning dry C45 (AISI/SAE 1045), BHN 190 steel billets, 190 mm dia. by 350 mm long, using uncoated carbide tool inserts HM NOVATEA MT 6 ISO P30 with a nominal cutting edge radius of 0.02 mm (a fresh tool was used for every treatment combination; individually measured radii ranged from 0.02 to 0.025 mm). Relief angle was 11°, and a constant width of cut of 5 mm was achieved in free orthogonal plunge cutting by previously machining into the workpiece radial grooves 5 mm apart, and using a tool 6 mm wide, see Figure 1. Turning experiments were carried out on a UTITA CNC lathe with a peak power of 30 kW, and reduction in workpiece diameter due to infeed was compensated for automatically by increasing rotational speed, thus keeping cutting speed close to nominal value.

Cutting forces were measured with a KISTLER Type 9263 piezoelectric tool-post dynamometer, and rake face temperatures were read with embedded Chromel/Alumel thermocouples inserted into two 0.5 mm dia. holes, sunk by EDM into tools 3.1 mm apart, with the hot junction 0.8 mm behind cutting edge and 0.2 mm below rake face, see Figure 1. All signals were sampled at 1 kHz rate and fed via an A/D converter into a PC for storage and analysis.

Factors (and levels) were machining parameters, namely cutting speed $V_t$ (50, 125, 200 m/min), rake angle $\gamma$ (-10°, 0, 10°), and feed $f$ (0.05, 0.125, 0.20 mm/rev). Responses were main (tangential) and normal cutting forces $F_t$ and $F_n$, chip thickness $h_c$, (enabling computation of cutting ratio $r_c$), and rake face temperature $T$ at a selected location. A classic RSM second order design was selected, in the shape of a face centered cube in sample space, three replications at central point catering for error estimation; treatment combinations are listed in Table 1. Numerical simulation with a commercial software product was also performed for all treatment combination listed in the above mentioned table, introducing in every instance the cutting edge radius pertaining to the corresponding tool used in actual cutting tests. Material properties were specified for both tool and workpiece in terms of supplied data base; introduction of experimental tool-chip friction coefficient, attempted first, had to be dispensed with later in favour of default values, as it led to inconclusive results. A typical result (temperature distribution, with mesh) is shown in Figure 2.
TABLE 1. Experimental design, showing treatment combinations

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Rake angle $\gamma$</th>
<th>Cutting speed $v_p$, m/min</th>
<th>Feed $f$, mm/rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10</td>
<td>50</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>-10</td>
<td>200</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>-10</td>
<td>125</td>
<td>0.125</td>
</tr>
<tr>
<td>4</td>
<td>-10</td>
<td>50</td>
<td>0.20</td>
</tr>
<tr>
<td>5</td>
<td>-10</td>
<td>200</td>
<td>0.20</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>125</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>50</td>
<td>0.125</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>125</td>
<td>0.125</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>125</td>
<td>0.125</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>125</td>
<td>0.125</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>125</td>
<td>0.125</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>200</td>
<td>0.125</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>125</td>
<td>0.20</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>50</td>
<td>0.05</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>200</td>
<td>0.05</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>125</td>
<td>0.125</td>
</tr>
<tr>
<td>17</td>
<td>10</td>
<td>50</td>
<td>0.20</td>
</tr>
<tr>
<td>18</td>
<td>10</td>
<td>200</td>
<td>0.20</td>
</tr>
</tbody>
</table>

FIGURE 2. Typical temperature pattern over zone of deformation and tool, showing mesh
Experimental and numerical results (computed temperature corresponding to actual thermocouple location) are shown in Table 2. Test results appear rather consistent with predictions based upon classic metal cutting mechanics; thus unit cutting force $k_c$ is found to range between 1.9 and 3.2 GPa, that is $1 \div 1.6$ times BHN according mainly to feed and rake angle. Average coefficient of friction $\mu$ on rake face (estimated in terms of force components and rake angle, according to classic metal cutting mechanics) ranges between 0.5 and 1.2, agreeing with typical representative values reported in classic literature [1, 2]. A second order polynomial equation for unit cutting force $k_c$ is found to explain some 96% of variation, with feed, rake angle, and product of feed by cutting speed accounting for over 85% and a handful of second order terms making up the remainder, residual mean square being consistent with estimate of pure error from replications. Tool temperature and cutting ratio, both within machining parameter volume considered, are also adequately described in terms of parsimonious second order equations.

3 ANALYSIS OF RESULTS

The degree of agreement between experimental and numerical values shown in Table 2 may be appreciated at a glance considering absolute $D = \text{Exp.} - \text{Num.}$ and percent deviations $D\% = \frac{100(\text{Exp.} - \text{Num.})}{\text{Exp.}}$, see Table 3.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Cutting force $F_p$, N</th>
<th>Normal force $F_w$, N</th>
<th>Temperature $T$, °C</th>
<th>Cutting ratio $r_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>805 833</td>
<td>603 467</td>
<td>383 400</td>
<td>0.14 0.41</td>
</tr>
<tr>
<td>2</td>
<td>751 765</td>
<td>724 469</td>
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</tr>
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<td>0.29 0.53</td>
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<td>0.35 0.62</td>
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<td>1205 558</td>
<td>518 550</td>
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<td>595 651</td>
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</tr>
<tr>
<td>15</td>
<td>635 644</td>
<td>532 315</td>
<td>407 540</td>
<td>0.54 0.54</td>
</tr>
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<td>16</td>
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<td>926 316</td>
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<tr>
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<td>2183 2170</td>
<td>1367 381</td>
<td>425 450</td>
<td>0.40 0.54</td>
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<tr>
<td>18</td>
<td>1889 2186</td>
<td>1285 374</td>
<td>566 610</td>
<td>0.56 0.56</td>
</tr>
</tbody>
</table>
TABLE 3. Absolute and percent deviations between experimental and numerical results

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Cutting force $F_t$</th>
<th>Normal force $F_n$</th>
<th>Temp. $T$</th>
<th>Cutting ratio $r_c$</th>
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<tbody>
<tr>
<td></td>
<td>$D$, N</td>
<td>$D$, N</td>
<td>$D$, °C</td>
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Computed main cutting forces appear to match reasonably experimental values, percentage deviation averaging – 8 with a standard deviation of about 10; disregarding however an apparent outlier, these figures would drop respectively to – 6, and 6 (normally distributed), quite compatible with extended uncertainty of experimental estimates.

Lack of agreement between experimental and computed normal force appears on the other hand substantial, relative differences averaging 47%, and ranging between 15 and 72%, experimental values always exceeding computed estimates. Those of cutting ratio $r_c$, on the contrary, are found to exceed experimental values by some 65% on the average, with a maximum over 200%; excluding however the first two treatment combinations, with small uncut chip thickness and negative rake angle, average relative difference would fall to a still substantial - 48%, and lower limit to – 100%.

These findings appear to agree with published results [3] obtained at NIST on the same type of steel in a comprehensive series of experimental tests, and numerical simulations, see the probability plots of Figures 3 and 4, showing the distributions of percentage deviations between experimental and computed values for normal force and cutting ratio in both
instances. But for two instances in the latter case, either corresponding to a feed substantially lower than those tested at NIST, both sets of data appear to belong to the same distributions, definitely suggesting existence of sizeable, systematic deviations in both instances between predicted and computed responses. The agreement among both sets of experimental results appears remarkable, also in view of substantial differences in cutting edge radius, and of cutting parameter range covered in either test program. Experimental values of cutting ratio $r_c$ too fall far short of computed estimates, also in definite agreement with results referred to above, two out of the three largest deviations at either end corresponding to feed well below the lower limit of the range covered at NIST.

Computed tool temperatures appear on the other hand in reasonable agreement with experimental values, overestimating the latter by an average of some 50 °C, by no means an excessive amount in view of the rather steep gradients near rake face, catering for substantial uncertainties of experimental estimates. A marked association is observed between $DF_F$ and $DT$, with a coefficient of correlation falling just short of 0.7 (highly significant given the relevant degrees of freedom), possibly hinting at some clues towards inherent model shortcomings, see Figure 5.

![Probability plots of $DF_F$ (current data) and $DF_F$ (NIST data)](image)

**FIGURE 3.** Probability plots pertaining to percentage deviations between experimental and computed values of normal force $F_n$, pertaining to data listed in Table 3, $DF_F$, and obtained at NIST, $DF_F$. Distributions are seen to overlap substantially
FIGURE 4. Probability plots pertaining to percentage deviations between experimental and computed values of cutting ratio $r_c$, pertaining to data listed in Table 3, $Dr_c\%$, and obtained at NIST, $Dr_c\%$ 4. But for the case of some tests performed with very small feed, distributions appear to overlap to a substantial extent.

FIGURE 5. Scatterplot of deviations $DF_n$, N, vs. $DT$, °C, showing substantial association.
Experimental estimates of average coefficient of friction \( \mu \) on rake face, computed in terms of force components according to Merchant, appear to exceed substantially the corresponding numerical values both in average and in scatter; no better agreement was obtained either for estimates computed in terms of chip compression ratio [4]. Some differences were observed between the present experimental values of \( \mu \) and those obtained at NIST, where tools with a definitely sharper cutting edge were used. Such differences however almost disappear, see Figure 6, after correction for plowing force components normal and main cutting forces, that is by subtracting estimated forces components acting on rounded surface of cutting edge [5, 6]. Dependence of observed deviations between experimental and numerical estimates from machining parameters were examined, in terms of percentage of total sums of squares accounted for by major contributions, concerning empirical second order models fitted by linear regression. By and large feed accounts for 70% of variation concerning \( DF_n \), cutting speed for about 30% (and feed for 20%) for \( DT \), and rake angle for about 45% for \( DT \), the remainder being accounted for mainly the remaining two parameters, and by the products of cutting speed and rake angle, or feed.

4 DISCUSSION AND CONCLUSIONS

Experimental results obtained were found to be consistent in general with reference literature values, and particularly with data obtained from a comprehensive set of cutting tests performed on the same type of steel at NIST, within the range of relevant extended uncertainties. Results obtained from numerical simulation were in fairly good agreement with experimental data, as