THE FINITE ELEMENT ANALYSIS APPROACH IN METAL CUTTING

Alina Bianca BONŢIU POP[1] and Mircea LOBONŢIU[2]

ABSTRACT: Due to the complexity of metal cutting, numerical techniques were often developed and adopted to replace the experimental approaches - which are expensive and time consuming. In the last two decades, the most widely used numerical technique was the finite element method. The objective of this paper is to carry out a monographic study to identify the finite element analysis approach in the metal cutting process. The result of this study will be a database which can be used as a reference for future research papers.

KEY WORDS: FEA, metal cutting process, monographic study.

1 INTRODUCTION

Based on the words of Wayne Hamman - "The elimination of physical prototypes, through virtual prototyping, is the only way to reduce costs and manufacturing time" (Wayne Hamman – Manufacturing and Production Manager FORD - Computer Integrated Manufacture and Engineering, in December/January 1995), we can say without fail, as also mentioned by (Alexandru, 2002), that the great strides which mankind has achieved in recent decades is mainly due to computer assisted socio-economic activities.

By anticipating and approximating main variables, the finite element analysis method is one of the most important techniques used in metal cutting simulations. Regarding this, many studies were performed in both the research and industrial fields, which were conducted by authors such as (Thepsonthi & Ozel, 2013), (Grzesik et. al, 2009) and (Zouhar & Piska, 2008) - who studied temperature (Adetoro & Wen , 2009)], (Biermann et al, 2010) and (Özel & Ulutan, 2014) – who have studied the cutting forces and other authors such as (Öpöz & Chen, 2010), (Hadi et al, 2011) and (Alexandru, 2002) who studied the stress distribution.

All these variables are an important part of tool geometry design and cutting conditions optimization.

[1] Technical University Cluj Napoca, North University Center Baia Mare, Dr. V. Babeş 62/A, 430083, Baia Mare, România

E-mail: bianca.bontiu@gmail.com; Mircea.Lobontiu@cunbm.ro

Based on the finite element method, one could also perform the geometrical factors analysis studied in the metal cutting process.

Thus, papers such as (Kim & Bono, 2012), (Arrazola et al, 2005), (Roud et al, 2011), (Karpat, 2011) and (Cosma, 2013) were studies on chip formation; (Hadi et al, 2011), (Pramanik et al, 2007), (Biermann et al, 2010) and (Cosma, 2011) analyzed the surface quality, and (Attanasio et al, 2008), (Diciuc, 2013), (Soo & Aspinwall, 2007) and (Yanda et al, 2010) researched the method for the anticipation of tool wear.

The making of this monographic study led me to initiate a statistical analysis and synthesis of major issues researched in technical literature.

2 DESIGN OF RESEARCH

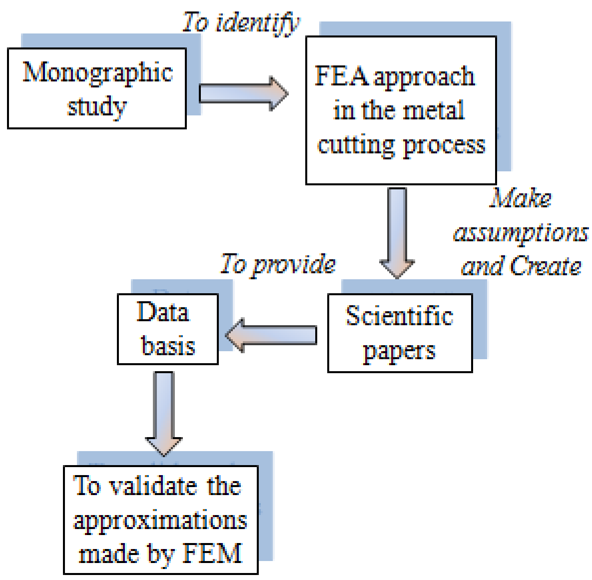

Fig. 1. The paper aim

Specifically, the aim of this paper involves the steps shown in Fig. 1.

Regarding the paper contents, in Figure 2, the planned design of monographic study of FEA of the metal cutting process is presented.

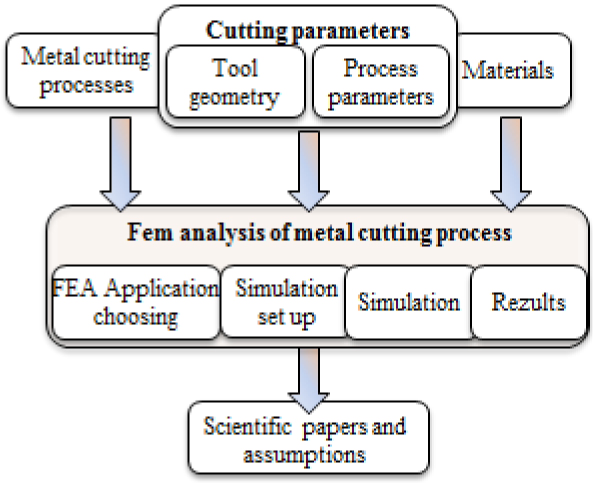

Fig. 2. FEA of metal cutting processes

As shown by the planned design, the FEA approach of metal cutting processes starts with the selection of the cutting process for the study.

Analyzing the references of the research report entitled "Contributions and research on modeling and finite element analysis of metal cutting tribosystem" (Bonțiu, 2011), in which 116 scientific papers published during 2000-2014, I found the most studied cutting processes were (fig. 3):

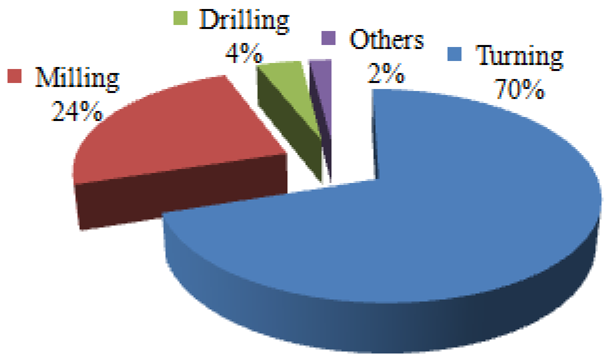

Fig. 3. The most studied cutting processes

During their research, each identified researcher studied at least one machining process using various materials and various cutting parameters.

Their purpose was focused on determining the best tool geometries and the best cutting conditions to increase the process efficiency. Thus, based on my own monographic study of the research project, I found a number of studies.

The first one concerns on the influence of the cutting conditions and tool geometry parameters on metal cutting simulation.

The most studied tool geometry parameters were (fig. 4):

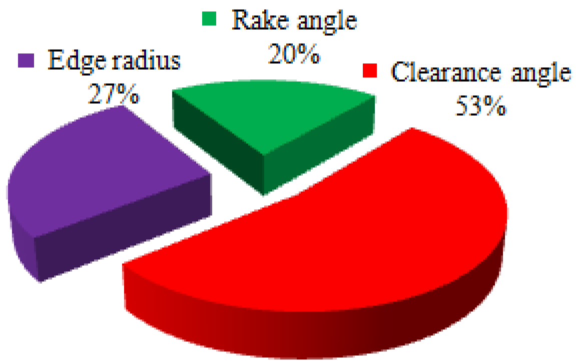

Fig. 4. The most studied tool geometry parameters

Regarding the process parameters, the situation looks as follows (fig 5):

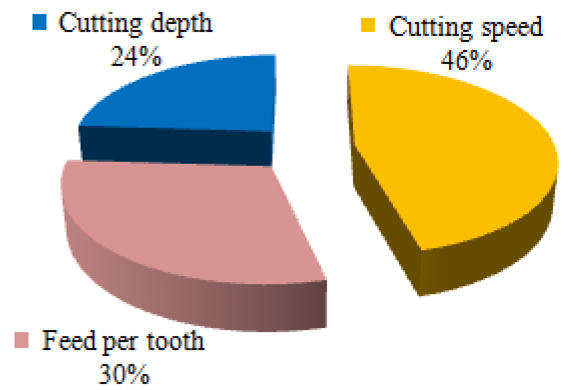

Fig. 5. The most studied process parameters

Another issue arising from my own research involves the most studied materials in FEA of metal cutting processes.

I found that over the last decade, research has focused particularly on steel, as shown below:

Steel	64%
Aluminum	23%
Other materials	11%
Cast iron	1%
Plastic materials	1%

All these studies above were conducted using the finite element analysis method.

The steps in performing this method are to choose an FEA application, followed by the simulation set up, then the carrying out of the simulation, and finally, the interpretation of the obtained results.

Finite element analysis involves dividing a continuum system to small elements, also involves the properties describing of the matrix elements and their assembly to achieve a system of equations whose solutions give the behavior of the whole system.

Thus, researchers usually wrote their own finite element codes for specific processes such as metal cutting analysis until the mid-1990s (Kiliçaslan, 2009).

In the last two decades commercial finite element packages as LS-Dyna, Deform 2D/3D, Advantedge, Abaqus have been widely used throughout the world, in both academic and industrial process analysis.

Choosing the appropriate FEA software for metal cutting simulation is a very important factor in obtaining good quality results due to the capabilities and solver techniques which vary between the FEA applications.

Analyzing the identified and studied references, I found that the most studied FEA applications are DEFORM software, followed by Advant Edge, and then Abaqus.

The percentages are as follows (fig. 6):

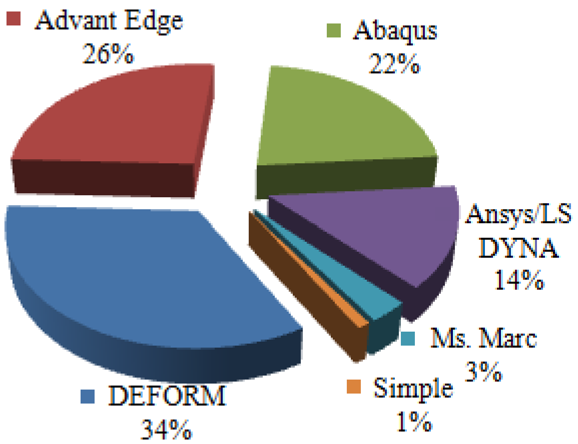

Fig. 6. The most studied FEA applications

DEFORM is the most studied FEA application because is a dedicated system that can be applied to several manufacturing processes such as forging, rolling and machining (Kiliçaslan, 2009).

This software has a specific machining module to quickly set up turning, milling, boring and drilling operations.

Cutting conditions, tools, and workpiece geometry must be defined by the user. Moreover, DEFORM allows the user to adjust specific modeling variables such as mesh size, boundary conditions, and tool workpiece interface conditions.

DEFORM software has a material library which contains various types of steel, super alloys, aluminum, titanium, etc. Additionally, other new materials can be created by using material models.

After the selection of FEA application, the next step is FEA simulation set up, which first of requires establishing the mesh size and to selection of the material model.

Regarding the mesh size in the cutting process simulation, three main approaches were used: Lagrange, Euler and Arbitrary Lagrange-Euler approach (ALE).

The corresponding percentages are as follows in (fig. 7).

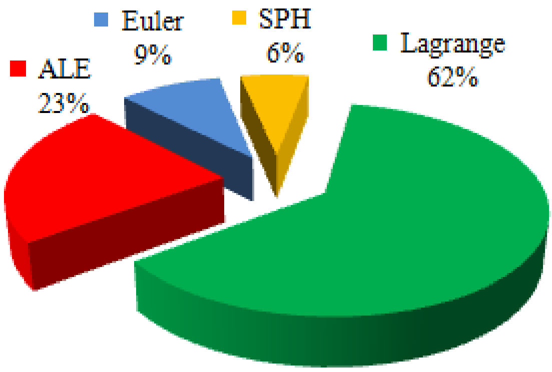

Fig. 7. The most studied Finite Element Methods

The Lagrangian approach is the most utilized because the finite element mesh is attached to the workpiece material, and covers the entire analyzed region. This approach is highly preferable when the unconstrained flow of material is involved.

This formulation is generally used in metal cutting simulations due to its ability to determine the geometry of the chip from incipient stage to steady state.

The chip geometry depends on cutting condition, plastic deformation process, and material properties. Hence boundaries and the chip shape don't have to be known at the beginning.

Chip separation criteria can be defined to simulate discontinuous chips or material fracture in metal cutting models which are based on Lagrangian formulation.

Even though Lagrangian formulation has many advantages, it also has some disadvantages. The chipped material is exposed to severe plastic deformation and its elements are distorted; this is why a remeshing is required.

The chip separation criteria must be provided and this drawback of formulation can be eliminated by using an updated Lagrangian formulation with mesh adaptivity or an automatic re-meshing technique (Kiliçaslan, 2009).

Regarding the material models used in the cutting process simulation based on FEA, I found that in metal cutting simulations one of the most important subjects is represented by the proper modeling of flow stress work piece material in order to obtain true results.

Flow stress is an instantaneous yield stress and it also depends on strain, strain rate, and temperature, and is represented by mathematical forms of constitutive equations (Kiliçaslan, 2009).

Among others, the most widely used metal cutting simulations are Johnson-Cook, which is studied in 89% of the research papers (fig. 8).

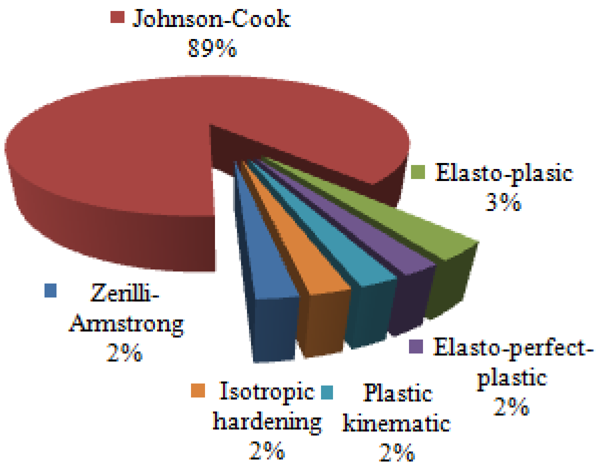

Fig. 8. The most studied constitutive models

Finally, the aim of going through these steps was to anticipate research directions based on the FEA method.

Based on this monographic study I found that various outputs and characteristics of the metal cutting processes such as cutting forces, stresses, temperatures, chip shape, etc. can be predicted by using FEM without doing any experiments.

The percentages are as follows:

Chip formation	62%
Stresses	28%
Temperature	26%
Cutting forces	25%
Tool wear	22%
Strain	19%
Surface quality	16%
Pressure	2%

3 RESULTS AND DISCUSSION

Considering the particular aspects followed in the monographic study on the FEA approach of metal cutting processes, attention will be focused on materials types.

The reason is constituted by the identification of weaknesses in the whole study.

Looking at percentages for each studied material type as shown in Figure 9, aluminum occupies 23% of the material types.

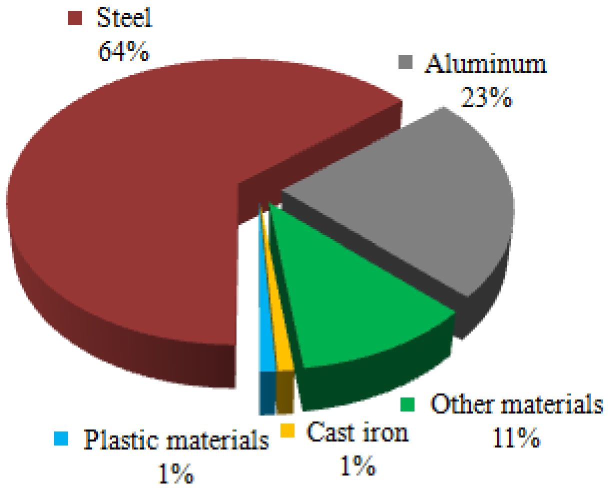

Fig. 9. The frequency percentage comparison of using the workpiece material

Therefore, the researches which I studied were directed on the materials detailed below to identify new alloys used in industry but still unexplored.

As Figure 10 demonstrates, which presents a comparison of the utilization of various aluminum alloys as workpiece materials; it can be observed that the maximum area occupied by AI 6061 alloy is 50% of all identified scientific papers.

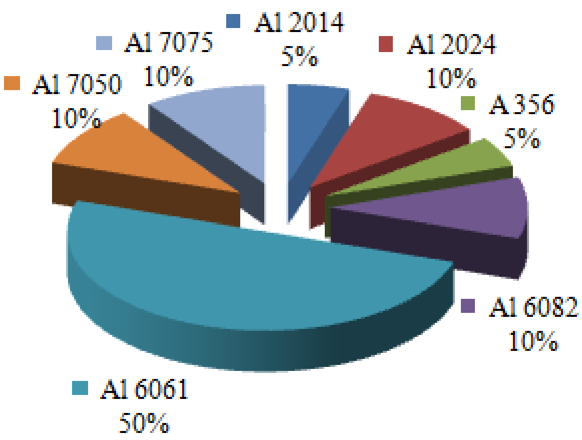

Fig. 10. Comparison of the utilization of various aluminum alloys as workpiece materials

These materials contain different types of alloying elements depending on the series they belong (fig. 11).

Such an aluminum alloy of 7000'series produced by the Universal Alloy Corporation

Company is Al7136. I have not identified this aluminum alloy in the known literature in the field of machining.

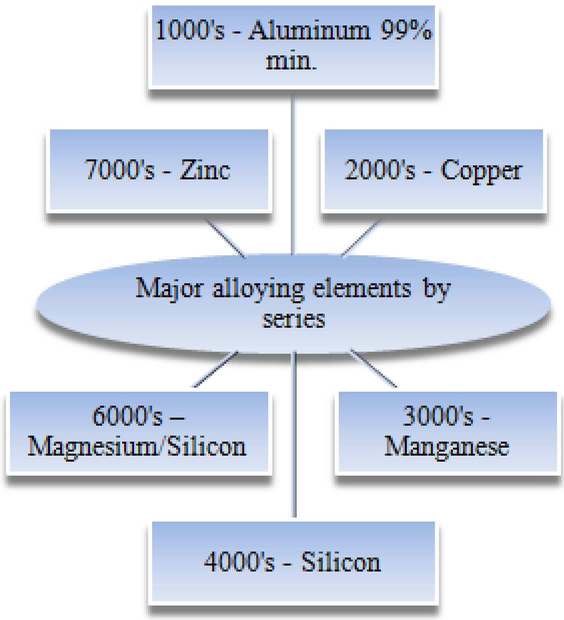

Fig. 11. Aluminum alloying elements

4 CONCLUSIONS

As a result of this monographic study I found that over the past decade, research has focused particularly on steels

As Figure 9 shows, cast irons and plastics each occupy only 1% of all material considered, but their study has now begun to rise in the industry.

The newly identified aluminum alloys - Al7136 and Al7349, have not been studied in terms of processing behavior in any respect.

Most identified research is focused on chip formation studying, at 62%, and on tool wear at 22%, but surface quality covering a range of16%, less than the others.

Cutting depth has been studied in only 24% of scientific papers identified, which is a low percentage compared to feed rate, which covers a range of 30% or cutting speed with 46%.

Considering the significant influence of rake angle on surface quality, base on the multiple studies of tool geometry parameters influences on metal cutting simulation, this parameter was studied only on percentage of 20% compared to clearance angle 53% and edge radius 27%.

5 FUTURE RESEARCHES

Plastics and composite materials required a particular attention due to the fact that these will be used more in the future.

Another research direction drawn from the above mentioned issues is the need of surface quality analysis on machined composite materials.

Also, I found that it is necessary to study the FEA simulation on machining behavior of newly identified materials such Al7136 and Al7349, with the purpose of creating a manufacturing process database.

It is necessary to extend the study of the influence of tool geometry parameters on surface quality as a machining result of composite material and the newly identified alloys.

6 REFERENCES

►Adetoro, O. B. and Wen, P. H., (2009). Prediction of mechanistic cutting force coefficients using ALE formulation, *The International Journal of Advanced Manufacturing Technology*, Vol. 46, Numbers 1-4, 79-90, DOI: 10.1007/s00170-009-2079-7.

►Alexandru, C. (2002). Simularea şi optimizarea sistemelor mecanice utilizând platformă de proiectare virtuală, *PRASIC'02, vol. III - Design de produs*, ISBN 973-635-076-2, 7 - 8 noiembrie, Braşov.

►Arrazola, P.J., Ugarte, D., Montoya, J., Villar, A. and Marya, S. (2005). Finite Element Modeling Of Chip Formation Process With Abaqus/Explicit[tm] 6.3, *VIII International Conference on Computational Plasticity*, COMPLAS VIII, E. Oñate and D. R. J. Owen (Eds), CIMNE, Barcelona.

►Attanasio, A., Ceretti, E., Rizzuti, S., Umbrello, D. and Micari, F. (2008). 3D finite element analysis of tool wear in machining, *CIRP Annals - Manufacturing Technology* Vol.57, Issue 1, Pages 61-64.

►Biermann, D., Höhne, F., Sieben, B. and Zabel, A. (2010). Finite Element Modeling And Three-Dimensional Simulation Of The Turning Process Incorporating The Material Hardness, *International Journal of Material Forming Volume 3, Supplement 1, 459-46. Proceedings of the 13th ESAFORM Conference on Material Forming*, Brescia (Italy), 7–9 April.

►Bonţiu Pop, A., B. (2011). Proiectarea cercetării şi identificarea soluţiilor metodice de proiectare, *Raport de cercetare ştiinţifică,* Baia Mare.

►Cosma, M. (2011). Experimental studies on influence of tool path in 3-axes B.N.E.M. on inclined surfaces at 45 degrees, *Academic Journal Of Manufacturing Engineering,* Vol. 9, issue 4/2011, pp. 6-11.

►Cosma, M. (2013). Study of the Uncut Chip in 5 Axes Ball Nose End Milling for the Third Quadrant of the Tool Inclination, *Applied Mechanics and Materials* Vol. 371, pp 37-4.

►Diciuc, V. (2013). A Comparison between the Wear of the Ball Nose End Mill Generated in 4 Axes Milling and in 5 Axes Milling, *Applied Mechanics and Materials* Vol. 371, pp 106-110.

►Grzesik, W., Niesłony, P. and Bartoszuk, M. (2009). Modelling Of The Cutting Process Analytical And Simulation Methods, *Advances In Manufacturing Science And Technology* Vol. 33, No. 1.

►Hadi, H., Tajul, L., Zailani, Z.A., Hamzas, M.F. and Hussein, M.S. (2011). The Parametric Effect and Optimization On Jis S45c Steel Turning, *International Journal of Engineering Science and Technology* (IJEST), 3(5), 4479 – 4487.

►Karpat, Y. (2011). Temperature dependent flow softening of titanium alloy Ti6Al4V: An investigation using finite element simulation of machining, *Journal of Materials Processing Technology* vol. 211, Issue 4, 1 April, Pages 737-749.

►Kiliçaslan, C. (2009). Modelling And Simulation Of Metal Cutting By Finite Element Method, A Thesis Submitted to the Graduate School of Engineering and Sciences of İzmir Institute of Technology in Partial Fulfilment of the Requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering, December 2009, İZMİR.

►Kim, C. and Bono, M. (2012). Chip Formation and Surface Generation in Micro-milling, 22.03.2012, http://wumrc.engin.umich.edu/research/micro_man/mm.pdf,2012

►Öpöz, T. and Chen, X. (2010). Finite Element Simulation of Chip Formation, School of Computing and Engineering Researchers' Conference, University of Huddersfield.

►Özel, T. and Ulutan, D. (2014). Effects of Machining Parameters and Tool Geometry on Serrated Chip Formation, Specific Forces and Energies in Orthogonal Cutting of Nickel-Based Super Alloy Inconel 100, *Proceedings of the Institution of Mechanical Engineers, Part B:* Journal of Engineering Manufacture, Vol. 228.

►Pramanik, A., Zhang, L.C. and Arsecularatne, J.A. (2007). An FEM investigation into the behavior of metal matrix composites: Tool–particle interaction during orthogonal cutting, *International Journal of Machine Tools and Manufacture*, Vol. 47, no. 10 (Aug 2007), pp. 1497-1506, Elsevier.

►Roud, P. M. Zetek, I. Cesákova, J. Sklenicka, Kozmin P. (2011). Using of Fem for Chip Formation and Cutting Force Prediction Hen Drilling Tool Steel Aisi D3, *Modern Machinery (MM) Science Journal, March 2011, © MM publishing, s.r.o., Pripotocni, 1519/10a, 101 00 Prague 10.*

►Soo, S. L. and Aspinwall, D. K. (2007). Developments in modeling of metal cutting processes, Proceedings of the Institution of Mechanical Engineers, *Part L Journal of Materials Design and Applications,* Vol. 221, Issue: 4, Pages: 197-211, ISSN: 14644207, DOI: 10.1243/14644207JMDA163.

►Thepsonthi, T. and Özel, T. (2013). 3-D Finite Element Simulation of Micro-Milling Ti-6Al-4V Titanium Alloy, *Proceedings of 7th International Conference and Exhibition on Design and Production of Machines and Dies/Molds, Antalya, Turkey, June 20-23.*

►Yanda, H., Ghani, J. A. and Che Haron, C.H. (2010). Effect of Rake Angle on Stress, Strain and Temperature on the Edge of Carbide Cutting Tool in Orthogonal Cutting Using FEM Simulation, *ITB Journal of Engineering Science,* Vol. 42, No. 2, 179-194.

►Zouhar, J. and Piska, M. (2008). Modelling the orthogonal machining process using cutting tools with different geometry, *Modern Machinery (MM) Science Journal.*

7 NOTATION

The following symbols are used in this paper:
FEA = Finite Element Analysis;
FEM = Finite Element Method