Prediction of High Cutting Speed Parameters for Ti-6Al-4V by Using Finite Element Modeling

Moaz H. Ali, Basim A. Khidhir, Bashir Mohamed, and A. A. Oshkour

***Abstract*—Titanium alloy (Ti-6Al-4V) is lightweight, corrosion resistant and high-temperature materials. It has the highest strength to weight ratio of all commonly used metals up to 550 ^{O}C. Machining of titanium alloy (Ti-6Al-4V) by milling operation is widely used in the aerospace industry. High-speed machining processes are of growing industry interest, especially due to appealing feature of high cutting speed processes. The cutting speed is considered as one of the most important factors in the success or failure of any cutting processes. The main purpose of machining modeling is to predict reaction forces (*RF*), stress components at integration points–Mises, and pressure without need to perform many experimental tests. The tests were performed at various cutting speeds while the depth of cut and feed rate remain constant. The prediction by using finite-element modeling method in machining titanium alloy can contribute in reducing the cost of manufacturing in terms of prolongs the cutting tool life and machining time saving.**

***Index Terms*—High-speed cutting process, finite element modeling, cutting speed, and titanium alloy (Ti-6Al-4V).**

I. Introduction

Titanium alloys are lightweight, corrosion resistant and high temperature materials. They have the highest strength-to weight ratio of all commonly used metals up to 550 ^{O}C. Titanium alloys are used extensively in aerospace because of their excellent combination of high specific strength, which is maintained at elevated temperature, their fracture resistant characteristics, and their exceptional resistance to corrosion. Titanium milling is widely used in the aerospace industry and is used increasingly in other industrial and commercial applications, such as military, racing and medical [1].

High-speed machining processes are of growing industry interest [3], not only because they allow for larger material removal rates, but also because they may positively influence the properties of the finished work-piece [4]. An especially appealing feature of high-speed cutting processes is that the specific cutting force for most materials strongly decreases with increasing cutting speeds and then reaches a plateau [2]-[5].

Numerical models are very important in the machining process comprehension and for the reduction of experimental tests necessary for the optimization of cutting conditions, tools geometries and other parameters like the choice of the tool material and coating [6].

Manuscript received December 24, 2011; revised February 27, 2012.

Moaz H. Ali, Basim A. Khidhir, and Bashir Mohamed are with the Department of Mechanical Engineering, Tenaga Nasional Universiti, Putra Jaya, Malaysia (e-mail: muezhm@hotmail.com).

A. A. Oshkour is with the Department of Mechanical Engineering, University of Malay, Kuala Lumpur, Malaysia.

The Johnson-Cook constitutive model of Ti6Al4V had been established. The cutting process of Ti6Al4V was simulated using the orthogonal cutting finite element model. However, in the simulation process, the Johnson-Cook model considered the adiabatic effect is more accurately [7].

Nowadays, many machining researchers are using modeling and simulation techniques to predict and optimize certain machining parameters such as cutting forces, temperature, roughness and residual stresses. These techniques do not need to perform many experimental tests that will take a long time and cost more money [8].

A correct simulation enables good predictions in terms of temperature, strain and stress distribution. This will contribute to cost reductions for the machining process optimization that is still experimentally done and thus expensive [6].

II. Finite Element Modeling (FEM)

Researchers are usually seeking to use a wide range of tools and techniques to ensure that the designs they are created are safe. However, accidents sometimes could happen when they work in the factories or laboratories. Industries need to know whether a product failed because the design was inadequate or due to another cause such as human error. Nevertheless, they have to ensure that the product works well under a wide range of conditions and try to avoid from failure due to any cause. In this respect, finite element modeling (FEM) could help to avoid the failure. FEM is a very important tool for stress and strain analysis because it can produce very accurate results.

In modeling the plastic material flow there are two basic approaches to assigning elements as follows:

1) Fixing the elements in space and allowing the material to flow through them (Eulerian technique).
2) Dividing the material into elements that move with the flow (Lagrangian technique) [9].

A. Material modeling

A two-dimensional fully thermo-mechanically coupled implicit FEM is used and implemented using ABAQUS/EXPLICIT finite-element software [10]. This material modeling is carried out using a work-piece of (60 x 100) mm^2 with machining parameters; cutting depth (d) = 1 mm, feed rate (f) = 0.1 mm/tooth and various cutting speeds as shown in Table. II. The parameters have been verified with the simulation results. In addition, no failure criterion has been implemented for the material so that chips form solely by shear localization through thermal softening. Damage criteria have frequently been used in the past to investigate chip formation [11–14]. However, reliably establishing damage parameters at extreme strain rates possess the same difficulties as determining the flow stress. It was shown in [16] that using a material law without a damage criterion can adequately describe the effects observed in high-speed machining when different materials are compared, although for a quantitative agreement between simulation and a certain experiment, a damage criterion may be necessary [2, 15]. In this study, Ti-6Al-4V is modeled with the Johnson–Cook plasticity model of Eq. (1) It is below:

$$\sigma = (A + B\,\varepsilon_p^{\,n})\,(1 + C \ln (\varepsilon/\varepsilon_0))\,(1 - (T\text{-}\ Tr/Tm - Tr)\text{^}m) \tag{1}$$

where: σ is flow stress, $\varepsilon\rho$ and ε are strain and strain rate, ε_0 is the reference strain rate (*1/s*), temperature *T*, room temperature *Tr*, melting temperature *Tm* and *n*, *m*, *A*, *B* and *C* are constant parameters for Johnson-Cook material model as shown in Table I.

TABLE I: CONSTANT PARAMETERS FOR JOHNSON-COOK MATERIAL MODEL OF Ti-6Al-4V [17].

Cutting constant	
A (MPa)	987.8
B (MPa)	761.5
n	0.41433
m	1.516
C	0.01516
Young’s modulus (GPa)	113.8
Passion ratio	0.342
Melting temp. ℃	1605
Density (kg/m^3)	4428

TABLE II: MACHINING PARAMETERS MODELING.

Cutting Parameters			
Rake angle γ	6		
Clearance angle α	21		
Feed rate, *f*	0.1 mm/tooth		
Depth of cut, *d*	1 mm		
Cutting speeds	80 m/min	120 m/min	160 m/min

B. Tool Modeling

The tool is modeled with the assumption that it is mechanically rigid. Rake angle (γ) = 6 and clearance angle (α) = 21 used to design the cutting tool geometry as shown in Table. II. Thermo-physical material parameters were used for the cemented carbide inserts. The cutting tool geometry is shown in Fig. 1.

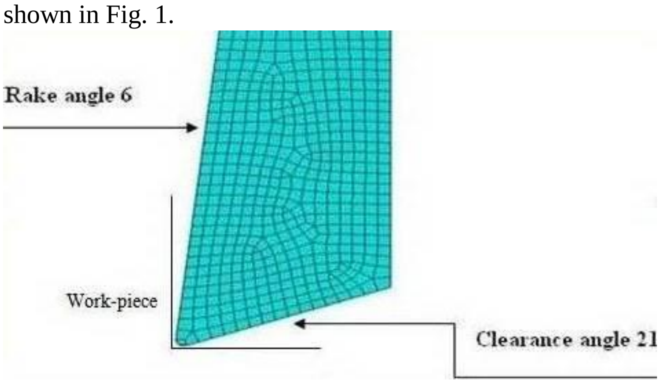

Fig. 1. Cutting tool geometry

C. High-speed Cutting Processes

The difficulty in a machining process of titanium alloy (Ti-6Al-4V) is due to mechanical and physical properties. In this study, orthogonal cutting FEM is carried out. The work-piece and tool have been designed and presented in a two-dimensional and define all the parameters into the ABAQUS/EXPLICIT finite-element software. Then, the cutting processes consist of six frames only which parallel related with time machining process. Each frame is led to provide lots of information about the machining behavior of titanium alloy at different cutting speeds. High stresses and high-pressure loads at the cutting edge through the reduced contact surface are considered the problem faced in the machining of titanium alloy. Therefore, the reaction force (*RF*), stress components at integration points–Mises, and pressure loads those output results from FEM will be discussed later. The increment in total energy and time are very clear with difference cutting speeds such as 80, 120 and 160 m/min as shown in Table. III. These variations have been dependent on the cutting speeds, and this clarifies the importance of the study seriously.

TABLE III: THE CUTTING PROCESS INCREMENT WITH TOTAL ENERGY AND TIME WHEN DIFFERENT CUTTING SPEED.

Cutting speeds	Increment	Total energy	Total time
80 m/min	220475 to 3517750	320674 to 336894	0.00647274 to 0.06
120 m/min	213042 to 3975667	721117 to 748405	0.005809 to 0.06
160 m/min	211681 to 4469800	1.28E+06 to 1.32E+06	0.005441 to 0.06

III. RESULTS AND DISCUSSION

A. Reaction Force

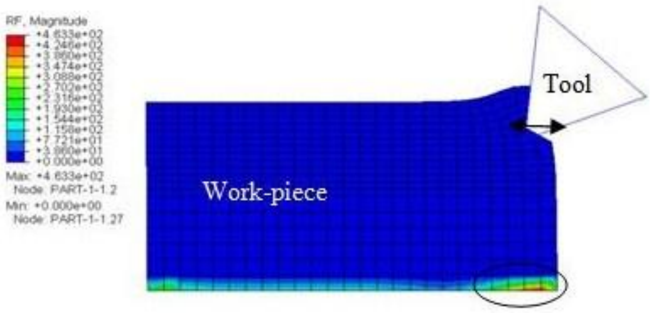

Fig. 2. Reaction force magnitude measured in the first frame at 80 m/min.

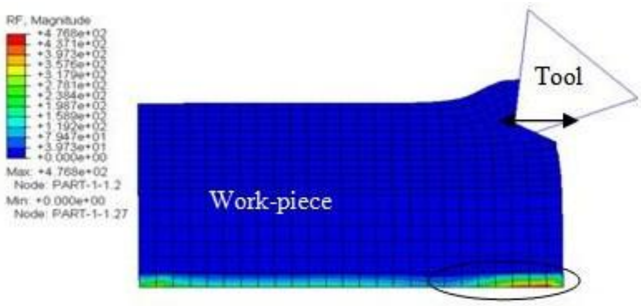

Fig. 3. Reaction force magnitude measured in the first frame at 120 m/min.

Reaction force is basically a force that acts in the opposite direction of an active force. Its value increases when the cutting speed is increased. Red color area as shown in Figs. 2, 3 and 4 are real reaction forces consisted of the impact cutting edge of the contact surface. Each of Figs. 2, 3 and 4 are taken from the first frame, and it shows different configurations of the primary shear deformation.

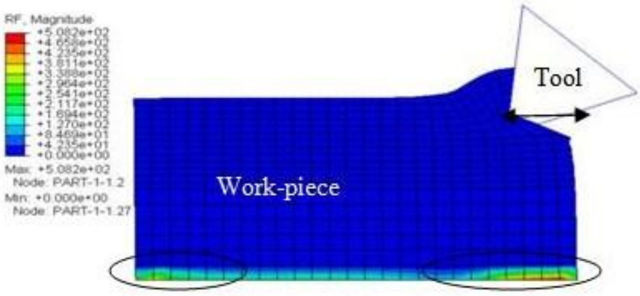

Fig. 4. Reaction force magnitude measured in the first frame at 160 m/min.

The cutting force on the work-piece will be increased when the cutting speed is increased. The reaction force is very small compared to the cutting force, and it is a roughly constant for the cutting speeds of (80, 120 and 160) m/min. Moreover, it could be seen the values of reaction force with the different cutting speeds almost convergent, especially on the frame one and two as well. However, it is possible to note the difference's values after frame three by increasing the cutting speeds. In addition, the reaction force of the cutting speed of 120 m/min is considered a linear motion and increase regularly as shown in Fig. 5.

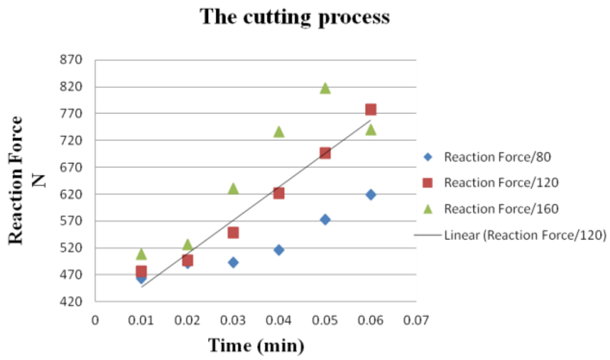

Fig. 5. Reaction force magnitude measured during the cutting process.

B. Stress Components at Integration Points - Mises

This study also shows the stages of changes of high stress at the cutting edge, especially when increasing the cutting speed. It is clearly shown in Figs. 6, 7 and 8 the changes of stress components at integration points – Mises on the contact surface area between cutting edge and the primary shear deformation. The shear deformation zone will be increased when an increment cutting speeds. Each of Figs. 6, 7 and 8 are taken from the first frame and it shows different configurations of the primary shear deformation at various cutting speeds while the depth of cut and feed rate remain constant.

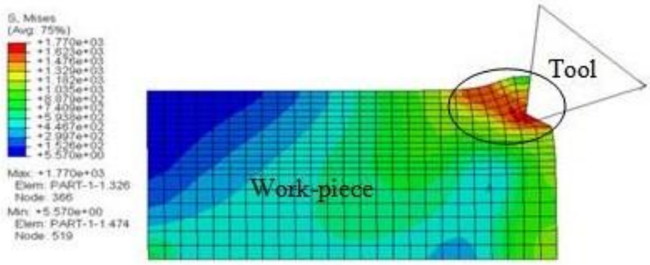

Fig. 6. Stress components at integration points – Mises measured in the first frame at 80 m/min.

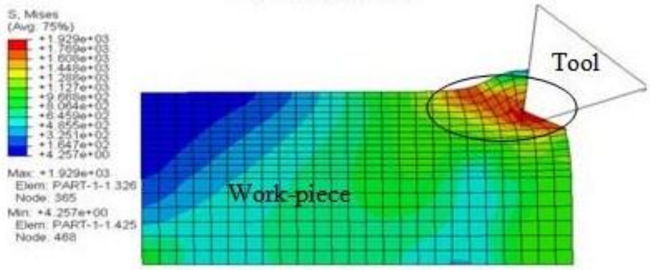

Fig. 7. Stress components at integration points – Mises measured in the first frame at 120 m/min.

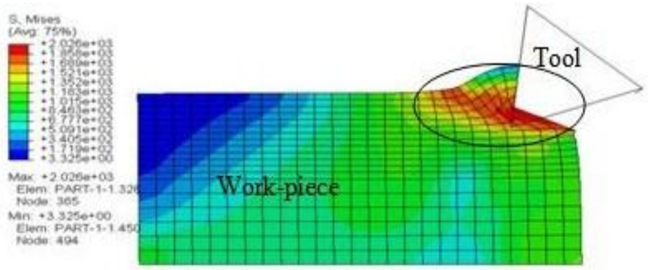

Fig. 8. Stress components at integration points – Mises measured in the first frame at 160 m/min.

Furthermore, the cutting speed of 120 m/min is still a linear motion and increases gradually. However, the cutting speeds at 80 m/min and 160 m/min are unsteady sometimes, especially when 80 m/min in the frame three a slightly higher and 160 m/min in the frame four is a lower as shown in Fig. 9.

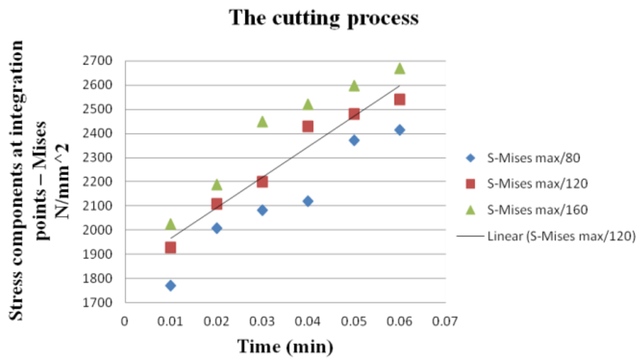

Fig. 9. Stress components at integration points – Mises measured during the cutting process.

C. Stress Components at Integration Points – Pressure

The high-pressure load will appear between the contact surface and the cutting edge. It is increased dramatically while to accelerate cutting speeds. Moreover, it appears at the end bottom of the work-piece as shown in Figs. 10, 11 and 12.

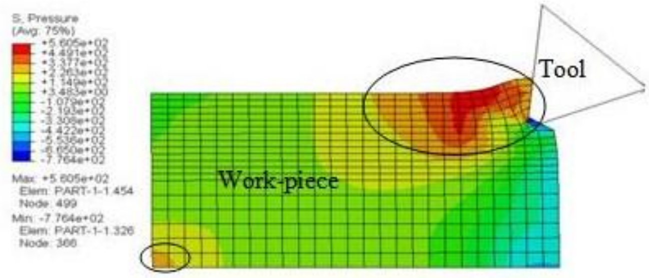

Fig. 10. Stress components at integration points – Pressure measured on the first frame at 80 m/min.

Fig. 11. Stress components at integration points – Pressure measured on the first frame at 120 m/min.

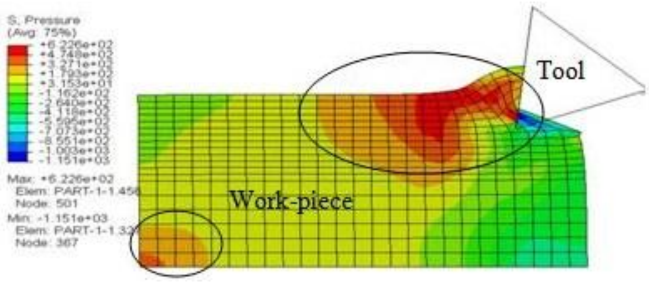

Fig. 12. Stress components at integration points – Pressure measured on the first frame at 160 m/min.

In addition, from the frame one and three, it could be seen the values of pressure load with the different cutting speeds almost convergent. Besides that, the frame two and six are roughly constant for the cutting speeds of 120 m/min and 160 m/min. On the other hand, the frame four is a nearly constant for the cutting speeds of 80 m/min and 120 m/min. This phenomenon proves that the cutting speed of 120 m/min is the speed common among them as shown in Fig. 13.

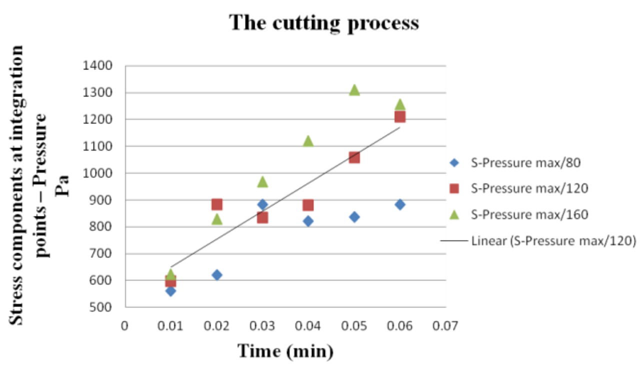

Fig. 13. Stress components at integration points – Pressure measured during the cutting process.

IV. Conclusion

In conclusion, the prediction of high cutting speed is very effective in the machining cutting parameters. In addition, the effect is sometimes positive or negative and this depended on the validity of choice of cutting speed and suitability to the circumstances and conditions in the machining process. Therefore, the cutting speed is considered one of the important factors in the success or failure any cutting processes. Based on the results obtained, the following conclusions can be drawn:

- The reaction force is very small compared to the cutting force, and it is constant for the cutting speeds of 80, 120 and 160 m/min.
- The stress components at integration points – Mises on the cutting process will be increased when the cutting speed is increased.
- The cutting speed is affected directly by the pressure load on the contact surface area.

FEM has been applied to predict the reaction force (*RF*), stress components at integration points–Mises, and pressure. The results were obtained from cutting processes, which confirms that the cutting speed of 120 m/min is recommended more than velocities to cut at 80 m/min or 160 m/min. This is because the velocity of cut at 120 m/min is considered a linear motion, increase regularly and common speed among them.

Acknowledgment

The authors would like to acknowledge the support given by Universiti Tenaga Nasional in carrying out this work.

References

[1] G. M. Pittalà and M. Monno, "A new approach to the prediction of temperature of the work-piece of face milling operations of Ti-6Al-4V," *Applied Thermal Engineering*, vol. 31, pp. 173-180, 2011.
[2] H. Schulz (Ed.), Scientific Fundamentals of HSC, Carl Hanser Verlag, Munchen, 2001.
[3] H.-K. Tonshoff and F. Hollmann (Eds), Spanen Metallischer Werkstoffe bei hohen Geschwindigkeiten, *Deutsche Forschungsgemeinschaft*, Bonn, 2000.
[4] M. Baker, "Finite element simulation of high-speed cutting forces," *Journal of Materials Processing Technology*, vol. 176, pp. 117–126, 2006.
[5] W. Konig, R. Lowin, K. Steffens, and V. Hann, "Aspekte zur Technologie der Hochgeschwindigkeitszerspanung," *Industrieanzeiger*, vol. 103, pp.14–20, 1981.
[6] M. Calamaz, D. Coupard, and F. Girot, "A new material model for 2D numerical simulation of serrated chip formation when machining titanium alloy Ti–6Al–4V," *International Journal of Machine Tools and Manufacture*, vol. 48, pp.275–288, 2008.
[7] H.-b. Wu, C. Xu, and Z.-X. Jia, "Establishment of constitutive model of titanium alloy Ti6Al4V and validation of finite element," *2010 IEEE DOI* 10.1109/ICMTMA, 555, 2010.
[8] H. Sadeghinia, M. R. Razfar, and J. Takabi, "2D finite element modeling of face milling with damage effects, 3rd WSEAS," *International Conference on Applied and Theoretical Mechanics*, Spain, December issue, pp. 14-16, 2007.
[9] G. Boothroyd and W. A. Knight, *Fundamentals of machining and machine tools*, Third Edition, 2005.
[10] HKS Inc, USA ABAQUS/Standard User's Manual, Version 5.8, 1998.
[11] T. D. Marusich and M. Ortiz, "Modeling and simulation of high-speed machining," *Int. J. Numer. Meth. Eng*, vol. 38, pp. 3675–3693, 1995.
[12] E. Ceretti, M. Lucchi, and T. Altan, "FEM simulation of orthogonal cutting: serrated chip formation," *J. Mater. Process. Technol.* vol. 95, pp. 17–26, 1999.
[13] L. Chuzhoy, R. E. DeVor, S. G. Kapoor, A. J. Beaudoin, and D. J. Bamman, Machining simulation of ductile iron and its constituents. Part 1. Estimation of material model parameters and their validation, *J. Eng. Ind*. 125, pp. 181–191, 2003.

[14] L. Chuzhoy, R. E. DeVor, and S. G. Kapoor, Machining simulation of ductile iron and its constituents. Part 2. N*umerical simulation and experimental validation of machining*, J. Eng. Ind. 125, pp. 192–201, 2003.
[15] M. B ̈aker, "Finite element investigation of the flow stress dependence of chip formation," *J. Mater. Process. Technol.* vol. 167, pp.1–13, 2005.
[16] R. Sievert, H.-D. Noack, A. Hamann, P. L ̈owe, K.N. Singh, G. K ̈unecke, R. Clos, U. Schreppel, P. Veit, E. Uhlmann, and R. Zettier, *Simulation der Spansegmentierung beim Hochgeschwindigkeits-Zerspanen unter Berucksichtigung duktiler Schadigung*, Technische Mechanik 23, pp. 216–233, 2003.
[17] T. Ozel and Y. Karpat, "Identification of constitutive material model parameters for high strain rate metal cutting conditions using evolutionary computational algorithms," *Mater. Manuf. Process*, vol.22, pp. 5-6; 659-667, 2007.

Moaz H. Ali was born in Kerbela, Iraq, on November 30, 1978. Graduated from the Al-Rashid School and he received a BS in Mechanical Engineering from the Babylon University. He completed and received a master's degree in manufacturing processes from the University of Donetsk National Technical (DonNTU) Donetsk, Ukraine. Now he is a PHD student at the Tenaga Nasional Universiti (UNITEN) Putra Jaya, Malaysia. His research interests include the finite-element modeling to predict the machining parameters of titanium alloy.

Basim A. Khidhir was a PhD candidate 2008, MSc production engineering (Metal Cutting) 1992; BSc Production engineering (metal cutting) 1985. Senior lecturer in Sulaimanyah Technical College. He has published many papers in different journals in the field of metal cutting.

Bashir Mohamad PhD Mechanical Enginering 1995; BSc Mechanical Engineering 1981. Associate Professor in Universiti Tenaga Nasional, Malaysia. He has published many papers in different journals in the field of manufacturing and metal cutting.

A. A. Oshkour is a PhD student at the Department of Mechanical and Biomedical Engineering, Faculty of Engineering, University of Malaya, Malaysia. He received a Master Degree from the Graduate School of Engineering at University Putra Malaysia, Malaysia in 2009. His research interests Biomechanics, Fatigue and Fracture mechanics. He can be reached at azim_120@yahoo.com.