A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 59 2014 Issue 2
DOI: 10.2478/amm-2014-0077

B. IŞIK*, A. KENTLI**

THE PREDICTION OF SURFACE TEMPERATURE IN DRILLING OF Ti6Al4V

PRZEWIDYWANIE TEMPERATURY POWIERZCHNI PODCZAS WIERCENIA STOPU Ti6Al4V

Titanium and its alloys are attractive materials due to their unique high strength-weight ratio that is maintained at elevated temperatures and their exceptional corrosion resistance. The major application of titanium has been in the aerospace industry. However, the focus shift of market trends from military to commercial and aerospace to industry also been reported. On the other hand, titanium and its alloys are notorious for their poor thermal properties and are classified as difficult-to-machine materials. These properties limit the use of these materials especially in the markets where cost is much more of a factor than in aerospace. Machining is an important manufacturing process because it is almost always involved if precision is required and is the most effective process for small volume production. Due to the low machinability of the alloys under study, selecting the machining conditions and parameters is crucial. The range of feeds and cutting speeds, which provide a satisfactory tool life, is very limited. On the other hand, adequate tool, coating, geometry and cutting flow materials should be used: otherwise, the high wear of the tool, and the possible tolerance errors, would introduce unacceptable flaws in parts that require a high degree of precision.

In this study, heat changes of Ti6Al4V has been examined on the basis of cutting parameters such as depth of cut, feedrate and cutting speed during drilling. Heat changes of the material and tool was monitored by a thermal camera. Maximum temperatures of the experiments were taken to examine optimum cutting parameters. Obtained results have been used to generate a regression analysis and it is seen that regression has given accurate data.

Keywords: Machining, Ti6Al4V, Heat effect, Drilling, Regression analysis

Tytan i jego stopy to atrakcyjne materiały ze względu na ich unikalnie wysoki stosunek wytrzymałości do ciężaru właściwego, utrzymywany w podwyższonej temperaturze i ich wyjątkową odporność na korozję. Głównym zastosowaniem tytanu jest przemysł lotniczy. Jednak zmiana trendów na rynku z wojskowego na cywilny i z przemysłu lotniczego na inne gałęzie przemysłu jest również obserwowana. Z drugiej strony tytan i jego stopy są znane z ich słabych właściwości termicznych i są klasyfikowane jako materiały trudne w obróbce. Właściwości te ograniczają wykorzystywanie tych materiałów zwłaszcza na rynkach, na których koszt jest znacznie większym czynnikiem niż w przemyśle lotniczym. Obróbka mechaniczna jest ważnym procesem wytwarzania, ponieważ prawie zawsze ma miejsce, jeżeli wymagana jest precyzja i jest to najbardziej skuteczny sposób wytwarzania małych objętości. Ze względu na niską obrabialność stopów badanych, dobór warunków obróbki i parametrów jest krytyczny. Zakres posuwów i prędkości skrawania, które zapewniają zadowalającą trwałość narzędzia, jest bardzo ograniczony. Z drugiej strony, należy stosować odpowiedni materiał narzędzia, powłoki, geometrię, w przeciwnym razie wysokie zużycie narzędzia i ewentualne błędy tolerancji wprowadzą niedopuszczalne błędy w częściach które wymagają wysokiego stopnia precyzji.

W pracy badano zmiany cieplne w stopach Ti6Al4V wynikające z parametrów cięcia takich jak głębokość skrawania, posuw i prędkość skrawania podczas wiercenia. Zmiany cieplne materiału i narzędzia monitorowano za pomocą kamery termicznej. Maksymalne wartości temperatury eksperymentów zostały dobrane w celu zbadania optymalnych parametrów skrawania. Otrzymane wyniki wykorzystano do analizy regresji i jest widoczne, że regresja daje dokładne dane.

1. Introduction

Titanium (Ti) alloys due to their unique and excellent combination of strength to weight ratio and their resistance to corrosion is an attractive material in aerospace industries. But titanium and its alloys are difficult to machine materials because of its low thermal conductivity and high chemical reactivity [1-5].

Titanium and its alloys are used extensively in aerospace industry because of their excellent combination of high strength-to-weight ratio, high elevated temperature strength, high fracture toughness, and exceptional resistance to corrosion. On the other hand, titanium and its alloys are classified as difficult-to-machine materials due to their inherent properties such as 1) high chemical reactivity and therefore a tendency to weld to the cutting tool during machining, thus leading to

---

* KARABÜK UNIVERSITY, FACULTY OF TECHNOLOGY, KARABÜK, TURKEY
** MARMARA UNIVERSITY, FACULTY OF ENGINEERING, İSTANBUL, TURKEY

chipping and premature tool failure; 2) low thermal conductivity that prevents heat transfer in the material, consequently increasing the temperature at the tool/workpiece interface affecting the tool life adversely; 3) high melting temperature and high strength maintained at elevated temperature and its low modulus of elasticity impairing its machinability. Increase in cutting speed usually results in rise of cutting temperature since heat generation per unit time increases. This increase in temperature is deleterious to the tool life, dimensional accuracy of the product or machining efficiency [6].

There are certain characteristics of titanium that poses limitations on its machinability. Some of these are given as follows: [7]

1. Ti6Al4V has low thermal conductivity, so heat does not dissipate easily from the tool-chip interface, the tool gets heated quickly due to the resulting high temperatures, and this leads to lower tool lives.

2. Titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures. This causes welding and smearing along with rapid destruction of the cutting tool.

3. Titanium has a relatively low modulus of elasticity, thereby having more "springiness" than steel. Work has a tendency to move away from the cutting tool unless heavy cuts are maintained or proper backup is employed. Slender parts tend to deflect under tool pressures, causing chatter, tool rubbing and tolerance problems. Rigidity of the entire system is consequently very important, as is the use of sharp, properly shaped cutting tools.

The common practice in aerospace industry is the use of cutting fluids and lubricants when machining titanium alloys. Cemented carbide tools are the most frequently used when machining this kind of material at cutting speeds in the range of 45–60 m/min [8,9]. Lubrication improves machinability of the workpiece material, increases productivity by reducing tool wear and extends the tool life. However, the toxicity of the cutting fluids seriously degrades the quality of the environment. Dry machining becomes then an ideal solution and introduce a greater challenge to manufacturing engineers due to the high temperatures generated during machining [10].

Until now dry machining of titanium alloys was not widely investigated. This is probably due to the fact that these materials are still considered as difficult-to-cut materials. In 1986, Dearnley and Grearson [11] performed dry machining (turning configuration) of titanium alloy and investigated wear mechanisms of some tool materials. Their results show that the cemented carbide tool (P grade of ISO codes) is not recommended for machining titanium alloys because of high crater and flank wear rates. They reported that flank wear is due to the low thermal conductivity of the tool material and to the fact that attrition mechanism acts preferentially on the mixed carbide grains: TiC and TaC. Since this study, all machinists seem to agree that cemented carbide tool is not suitable for machining titanium alloys.

Cantero and etc. [12] focused on dry drilling of alloy Ti6Al4V, studying tool wear evolution, quality of machined holes and surface integrity after machining. Two different drilling conditions were analysed in order to observe the effect of heat accumulation in the drill and work-piece. Condition I, machining with a pause between each hole to cool the drill and the work-piece, and condition II, machining series of eight holes without pause. Moderate cutting parameters were selected defined from preliminary tests. Zeilmann and Weingaertner [13] presented a study of the temperature reached during drilling of the titanium alloy Ti6Al4V, employing class K10 carbide drills with and without hard coating (TiAlN, CrCN or TiCN). The main object of this study was to evaluate the temperature for different coated tools under the condition of application of minimal quantity of lubricant (MQL). With MQL applied with an external nozzle, the greatest temperature was measured in the piece drilled with an uncoated drill. For different coatings there are no significant variations of temperature. Reissig [14] presented a post-mortem-method which allows to determine maximum temperatures during machining by measuring the local vanadium concentration in a Ti6Al4V alloy. Based on analytical and experimental test methods, the coated tool performance in milling Ti6Al4V by coated cemented carbide inserts was explained. The PVD coating applied was (Ti,Al,Si)N. Its strength properties at room and elevated temperatures were detected by impact tests [15].

An artificial neural network (ANN) is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems. ANNs learn by example and learning involves adjustments to the synaptic connections that exist between the neurons.

ANNs have found applications in various fields relating to application of Ti6Al4V. Rao et.al. [16] optimized the surface roughness of die sinking electric discharge machining (EDM) by using multiperceptron neural network models and genetic algorithm. Casalino et.al. [17] investigated both CO2 and diode laser welding processes for Ti6Al4V alloy sheet joining and used ANN to generate a model to optimize the process. Yu et.al. [18] applied a fuzzy neural network to acquire the relationships between the mechanical properties and the processing parameters of post-forged Ti-6Al-4V alloy. Reddy et.al. [19] developed a back-propagation neural network model to predict the flow stress of Ti-6Al-4V alloy for any given processing conditions. Sathyanarayanan et.al. [20] utilized a new approach to model the creep feed grinding of superalloys, Ti-6Al-4V and Inconel 718, by using a neural network. All these studies used neural network to model considering process parameters. This study applied ANN to a new area: to predict the surface temperature considering cutting parameters in drilling of Ti-6Al-4V.

2. Experimental Details

2.1. Material

The specifications of Ti6Al4V are shown in Table 1 and Table 2

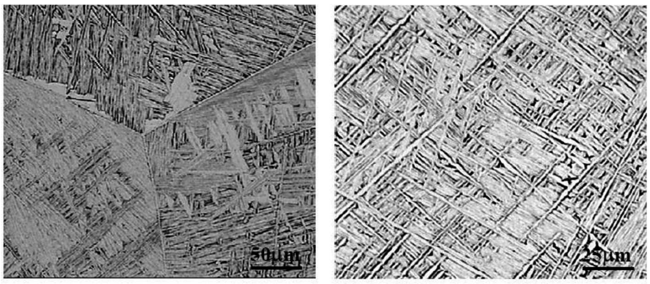
The microstructure of the cast Ti6Al4V model alloy is shown in Fig. 1a and b, showing the two-phase, microstructure consisting of α and β solid solutions. The α phase (shown light) has a lamellar structure which is relatively regular and between these lamellae are thin areas of the β phase (shown dark). Within prior β grains $\alpha + \beta$ colonies are formed, containing α lamellae with similar crystallographic orientation. Growing from the boundaries of the prior β grains α phase is formed which "delimits" these grains (grain boundary α).

TABLE 1
Physical and mechanical properties of Ti6Al4V

Density [g/cm^3]	4.42
Melting Range [°C±15°C]	1649
Specific Heat [J/kg.°C]	560
Volume Electrical Resistivity [ohm.cm]	170
Thermal Conductivity [W/m.K]	7.2
Tensile Strength MPa	1000
Elastic Modulus GPa	114
Hardness [Rockwell C]	36

TABLE 2
Chemical composition of Ti6Al4V

Al	V	N	C	H	Fe	O
6.0%	4.0%	0.05%	0.1%	0.0125%	0.3%	0.2%



a b

Fig. 1. The initial microstructure of the Ti6Al4V model alloy a) Character of microstructure, b) Detail of lamellar structure (α +β)

2.2. Tool materials

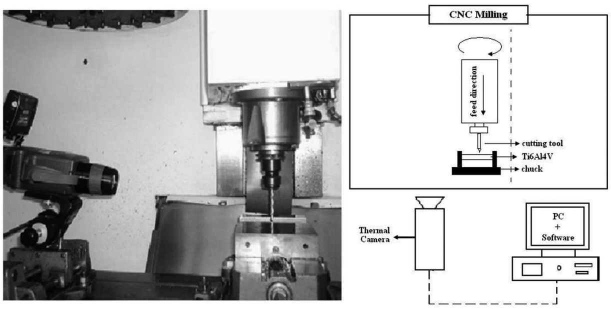
This work utilizes the cutting tools are TiN coated cobalt twist drill. Specially TiN tool has been preferred due to excellent wear resistance and low coefficient of friction. The geometries of the tool are tool diameter 8 mm. and point angle 135°.

The twist drills have been manufactured by FASTENAL are Type190-AG 135Deg TiN Coat Split Point Jobber Drills. Type 190-AG drill bits are made with a special Hi-Molybdenum tool steel.

2.3. Equipment

The equipments used for drilling are consisted of CNC milling machine (FADAL CNC 88) and thermal camera (ThermaCAM SC1000). The experimental setup for this study is shown in Fig. 2.

For temperature measurement, ThermaCAM SC 1000 thermal camera has been used as seen in Table 3. ThermaCAM is a palm-sized focal plane array (FPA) radiometer with full-screen temperature measurement and built-in image storage and analysis capabilities. ThermaCAM uses a 256×256 platinium silicade focal plane array (FPA) detector, which provides a superior image without the use of mechanical scanning. When drilling the thermal pictures of the material were taken by the camera. All pictures are analyzed by ThermaCAM researcher software on PC.



a b

Fig. 2. The experimental setup a. Photo b. Schema

TABLE 3
The settings of the thermal camera

Background Temp	23°C
Distance (meters)	1
Relative Humidity (%)	50
Atmospheric Temp	23°C
Ext. Optics Trans (%)	100
Ext. Optics Temp	23°C
Secondary Lens Trans (%)	100
Allowed Temp Ranges	RNGS 1-4
Polarity	NORMAL
TIFF Format	12-BIT
Remote Temperature Out	OFF
Auto Temperature Mode	HOTSPOT

2.4. Cutting conditions

The experiments have been carried out under dry cutting conditions. The machining parameters included were cutting speed, depth of cut and feedrate. The cutting conditions in the experiments were several cutting speeds 20, 40 and 60 m/min; several depths of cut 2, 4 and 6 mm; several feedrates 0.1, 0.2 and 0.3 mm/rev; and the same point angle 135° with TiN coated cobalt twist drill. The drilling of Ti-6Al-4V is seen in Fig. 3.

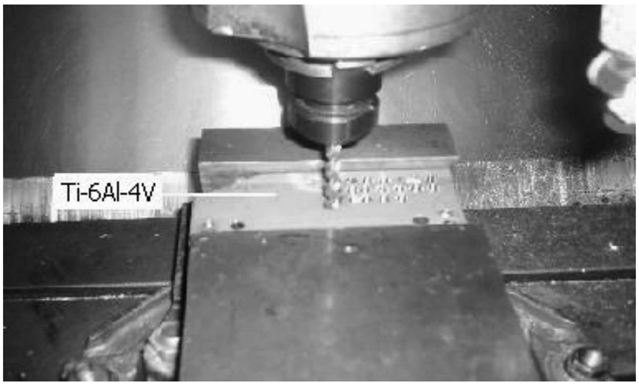


Fig. 3. Drilling of Ti-6Al-4V

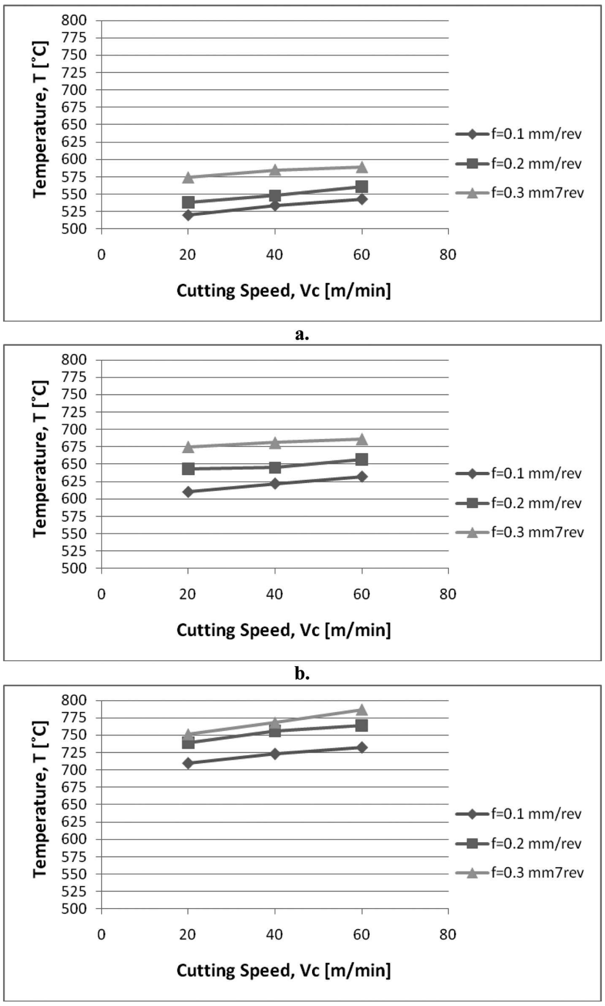
3. Modelling

Experiments were conducted and a data set was obtained containing 27 sets of input parameters (cutting speed, depth of cut and feed rate) and the corresponding output parameter (maximum tool temperature). This data set was used for training and testing the neural network model. The set was then divided into two parts. One part contained 21 data points and was used for training the network. Another part contained 6 data points and was used for testing the network. The data set used for testing the network, was chosen randomly from the experimental data set. In this study, RBFN model ANN [21] was used. A three layer network with one input layer, one hidden layer, and one output layer, was formed for the present study. The input layer has 3 neurons and hidden layer has 19 neurons. The output layer consisted of one neuron corresponding to one output variable (maximum tool temperature).

4. Results

4.1. Experimental Results

According to the cutting parameters the following results were obtained as seen in Fig. 4.



c.

Fig. 4. The comparison of Cutting speed and Temperature. a. a=2 mm; b. a=4 mm; c. a=6 mm

It is clearly seen that;

- Increasing of cutting speed, feedrate and depth of cut increase temperature.
- Increasing of depth of cut distinctly increases temperature.
- Increasing of feedrate is inconsiderable at the same depth of cut

4.2. Modeling Results

The trained ANN was initially tested with the 21 input patterns that had been employed for the purpose of training. For each input pattern, the predicted value of the output variable was compared with the respective experimental value. Figure 5 and 6 shows the plot of the predicted and the experimental values of the output variable for training and testing set respectively. The maximum absolute error for training patterns was found to be 3% and the minimum was 0.2% and the error was less than 1.5% for most cases. The network was then tested with the 6 test data points that had not been used for the purpose of training. Figure 5 shows the plot of the predicted and the experimental values of the output variable for training set. From the test results, it can be observed that the predicted values are very close and follow almost the same trend as the experimental values. The maximum absolute error for testing patterns was found to be 3.4% and the minimum was 0.33% and for half of the cases the error was less than 0.8%. Prediction accuracy is 98.7%. The method employed

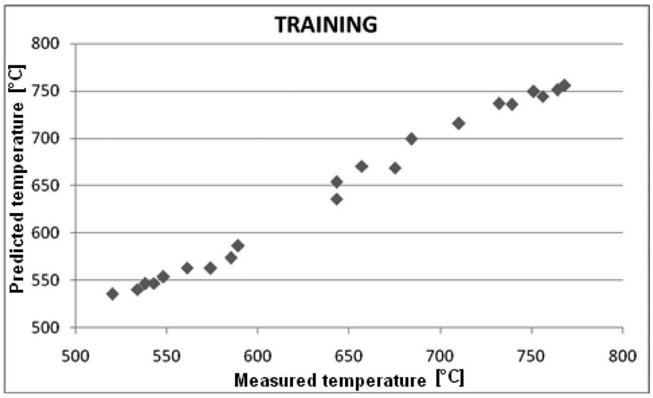


Fig. 5. Comparison of measured and predicted temperature values for training data

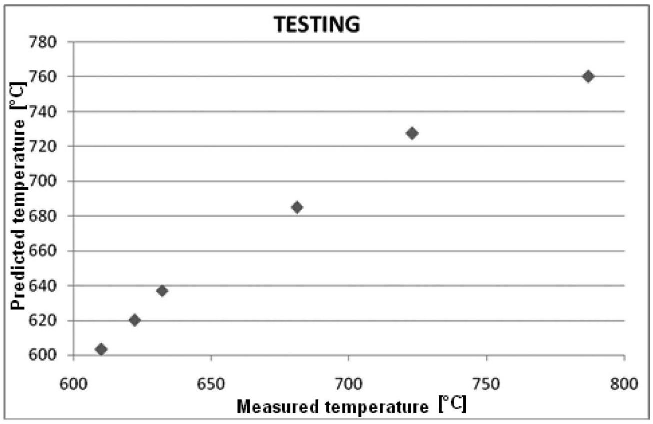


Fig. 6. Comparison of measured and predicted temperature values for testing data

found that depth of cut is the most important factor (75%) affecting tool temperature. Feed rate (16.6%) and cutting speed (8.4%) follows depth of cut. The Least important factor is the cutting speed. Figure 7 shows the importance values. It is quite clear from Figures 5 and 6 that damage factor predicted by the ANN model matches well with the training data as well as the test data. The ANN model developed can be used as an effective tool for controlling the surface temperature in drilling of Ti-6Al-4V.

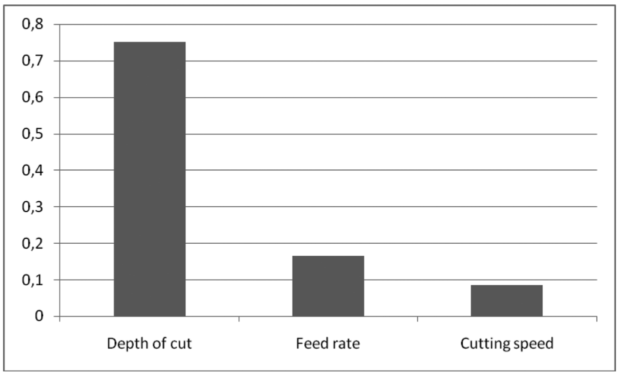


Fig. 7. Importance percentages of the factors

5. Conclusion

In conclusion, while titanium alloys present a unique set of machining problems, many of those problems can be alleviated or eliminated by adhering to the following set of guidelines:

1. Performing shallow finish machining pass to remove the damaged layer.
2. Using large volumes of recommended cutting fluids.
3. Using abrasion and heat resistant cutting tools.
4. Replacing cutting tools at the first sign of wear.

According to the experiments:

– Increasing of cutting speed, feedrate and depth of cut increase temperature
– Increasing of depth of cut distinctly increases temperature
– Increasing of feedrate is inconsiderable at the same depth of cut

According to modeling results:

– ANN is an effective tool (with 98.7% prediction accuracy) to model the process
– Depth of cut is the most important factor for the process

REFERENCES

[1] A.R. Zareena, M. Rahman, Y.S. Wong, High Speed Machining Of Aerospace Alloy Ti-6Al-4V, 33rd ISTC - Seattle, WA - November 5 - 8, 2001.

[2] R.R. Boyer, An overview on the use of titanium in the aerospace industry, Mater Sci Eng A **213**(1-2), 103-114 (1996).

[3] E.O. Ezugwu, J. Bonney, Y. Yamane, An overview of the machinability of aeroengine alloys, J Mater Process Technol **134**(2), 233-253 (2003).

[4] S. Sun, M. Brandt, M.S. Dargusch, Characteristics of cutting forces and chip formation in machining of titanium alloys, Int J Mach Tool Manuf **49**(7-8), 561-568 (2009).

[5] J. Barry, G. Byrne, D. Lennon, Observations on chip formation and acoustic emission in machining Ti-6Al-4V alloy. Int J Mach Tool Manuf **41**(7), 1055-1070 (2001).

[6] Rajiv Shivpuri, Advances In Numerical Modeling Of Manufacturing Processes: Application To Steel, Aerospace And Automotive Industries, Trans. Indian Inst. Met. **57**, 4, 345-366 (2004).

[7] A. Modgil, Effects Of High Speed Machining On Surface Topography Of Titanium Alloy (Ti-6Al-4V), A Master Thesis, University of Florida (2003).

[8] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability-A review, Journal of Materials Processing Technology **68**, 262-274 (1997).

[9] E.O. Ezugwu, J. Bonney, Y. Yamane, An overview of the machinability of aeroengine alloys, Journal of Materials Processing Technology **134**, 233-253 (2003).

[10] P.S. Sreejith, B.K.A. Ngoi, Dry machining: Machining of the future, Journal of Materials Processing Technology **101**, 287-291 (2000).

[11] P.A. Dearnley, A.N. Grearson, Evaluation of principal wear mechanism of cemented carbides and ceramics used for machining titanium alloys IMI318, Material Sciences and Technology **2**, 47-58 (1986).

[12] J.L. Cantero, M.M. Tardıo, J.A. Canteli, M. Marcos, M.H. Miguelez, Dry drilling of alloy Ti-6Al-4V, International Journal of Machine Tools & Manufacture **45**, 1246-1255 (2005).

[13] R.P. Zeilmann, W.L. Weingaertner, Analysis of temperature during drilling of Ti6Al4V with minimal quantity of lubricant, Journal of Materials Processing Technology **179**, 124-127 (2006).

[14] L. Reissig, R. Volkl, M.J. Mills, U. Glatzel, Investigation of near surface structure in order to determine process-temperatures during different machining processes of Ti6Al4V, Scripta Materialia **50**, 121-126 (2004).

[15] Bouzakis K-D, Michailidis N, Gerardis S, Katirtzoglou G, Lili E, Pappa M, Brizuela M, Garcia-Luis A, R. Cremer, Correlation of the impact resistance of variously doped CrAlN PVD coatings with their cutting performance in milling aerospace alloys, Surf Coat Technol **203**(5-7), 781-785 (2008).

[16] G. Krishna Mohana Rao, G. Rangajanardhaa, D. Hanumantha Rao, M. Sreenivasa Rao, Development of hybrid model and optimization of surface roughness in electric discharge machining using artificial neural networks and genetic algorithm, Journal of Materials Processing Technology **209**, 3, 1512-1520 (2009).

[17] G. Casalino, F. Curcio, F. Memola Capece Minutolo, Investigation on Ti6Al4V laser welding using statistical and Taguchi approaches, Journal of Materials Processing Technology **167**, 2-3, 422-428 (2005).

[18] Weixin Yu, M.Q. Li, Jiao Luo, Shaobo Su, Changqing Li, Weixin Yu, Prediction of the mechanical properties of the post-forged Ti-6Al-4V alloy using fuzzy neural network, Materials & Design **31**, 7, 3282-3288 (2010).

[19] N.S. Reddy, You Hwan Lee, Chan Hee Park, Chong Soo Lee, N.S. Reddy, Prediction of flow stress in Ti-6Al-4V alloy with an equiaxed $\alpha+\beta$ microstructure by artificial neural Networks, Materials Science & Engineering: A **492**, (1-2), 276-282 (2008).

[20] G. Sathyanarayanan, I.J. Lin, M. Chen, Neural network modelling and multiobjective optimization of creep feed grinding of superalloys, International Journal of Production Research **30**(10), 2421-2438 (1992).

[21] P.V. Yee, S. Haykin, Regularized Radial Basis Function Networks: Theory and Applications, John Wiley, 18-24 (2001).

Received: 20 September 2013.