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Taguchi Method–GONNS integration: Complete procedure covering from experimental design to complex optimization

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ABSTRACT

Determination of the optimal operating conditions from the experimental data without fitting any analytical or empirical models is very convenient for manufacturing applications. In this paper, integration of Taguchi Method and Genetically Optimized Neural Networks (GONNS) is proposed. The proposed procedure covers all the steps from experimental design to complex optimization. The feasibility of the approach was evaluated by estimating the optimal cutting conditions for the milling of Ti6Al4V titanium alloy with PVD coated inserts. The test conditions were determined by the Taguchi Method. The optimal cutting condition and influences of the cutting speed, feed rate and cutting depth on the surface roughness were analyzed with the same method. GONNS estimated that the optimal cutting conditions were very close to the Taguchi Method when the same criterion was used. GONNS was also capable to minimize or maximize one of the output parameters while the others were kept within the desired range. Study demonstrated that Taguchi Method and GONNS complement each other for creation of a robust procedure for determination of the test conditions, analysis of the quality of the collected data, estimation of the influence of each parameter on the output(s) and estimation of optimal conditions with complex optimization objective functions.

1. Introduction

In today's extremely competitive marketplace, manufacturers have to find the optimal operating conditions quickly and accurately to keep their profit margins acceptable to their share holders. Finding the best operating conditions is a challenge when new and hard to cut materials such as titanium alloys (Ginting & Nouari, 2006) are going to be used. The objective of this paper is to propose integration of well know Taguchi Method with Genetically Optimized Neural Networks (GONNS) to present a statistically sound procedure which fully uses the number crunching power of microcomputers.

Titanium alloys such as Ti6Al4V have low density. The difficulty of dislocation motion through the microstructure gives them additional desired characteristics such as, high strength even at elevated temperatures and excellent mechanical resistance (Boyer, 1996). Parts made of titanium alloys are highly desirable at the critical applications of aerospace, automotive, chemical, and medical industries. Compressor blades, discs and rings for jet engines, airframe and space components, pressure vessels, rocket engine cases, helicopter rotor hubs and fasteners have been made by using Ti6Al4V titanium alloys (Arrazolaa et al., 2009; Lia, Hegdeb, & Shiha, 2007). However the above desirable characteristics, low thermal conductivity (Molinari, Musquar, & Sutter, 2002; Polmear, 1989) and high chemical reactivity with cutting tool materials make the selection of optimal material removal rates very critical (Haron & Jawaid, 2005; Umbrello, 2008) to keep the tool life and manufacturing cost acceptable (Ginting & Nouari, 2006). Since the cutting process is interrupted while each cutting edge of the tool constantly nibbles the workpiece, mechanical and thermal shocks are created. These shocks drastically reduce tool life.

Taguchi Method was developed for statistical design of experiments (Onders, Seshuy, & Naganathan, 1996), and selection of the optimal conditions (Kurt, Bagci, & Kaynak, 2009). This approach significantly improved with time as the contributions of many researchers increased. It aims to keep the number of experiments minimum, and soundness of the currently followed steps has been proven by the time and many successful applications (Tsao & Hocheng, 2004). Taguchi Method has been used for the design of experiments in selection of optimal operating conditions in machining (Bağcı & Aykut, 2006; Benardos & Vosniakos, 2002; Ghani, Choudhury, & Hassan, 2004; Oktem, Erzurumlu, & Uzman, 2007; Ross, 1988; Taguchi, 1986; Tzeng & Chiu, 2003).

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Artificial neural networks (ANN) were developed to simulate the thinking process of many living creatures by using the computers (Rumelhart, Hilton, & Williams, 1986; Tansel, 1990). These programs learn the characteristics of the system after a training process. In addition to hundreds of other applications, ANNs have been used to help researchers for selection of the optimal machining conditions (Azouzi & Guillot, 1997; Benardos & Vosniakos, 2003; Tansel et al., 2000; Tsai, Chen, & Lou, 1999). Genetic algorithm (GA) (Carroll, 1996; Goldberg, 1989), statistical analysis (Sanjay, Neema, & Chin, 2005), particle swarm optimizer (Baskar, Asokan, Saravanan, & Prabhaharan, 2005; Tandon, El-Mounayri, & Kishawy, 2002), surface roughness model (Baek, Ko, & Kim, 2001; Reddy & Rao, 2005), ant colony algorithm (Baskar et al., 2005; Lo, 2003), and fuzzy logic were used for calculation of the optimal conditions (Lo, 2003). Genetically Optimized Neural Network System (GONNS) were developed for automation of the modeling and optimization process (Aykut, Demetgul, & Tansel, 2010; Tansel, Demetgul, Leon, Yenilmez, & Yapici, 2009; Tansel et al., 2006; Yang, Girivasan, Singh, Tansel, & Kropas-Hughes, 2003; Yang, Tansel, & Kropas-Hughes, 2003) without any analytical or empirical models. GONNS uses multiple Backpropagation (BP) (Rumelhart et al., 1986; Tansel, 1990) type ANNs to represent the system after a training process. GA(s) search(es) for the optimal solution by minimizing or maximizing one of the outputs while all of the other outputs of the system are kept within the desired range. Although, the objective function may be modified for any objective function.

The objective of this paper is to present a complete procedure for selection of the optimal cutting conditions by combining Taguchi Method and GONNS. The performance of this procedure was evaluated by estimating the optimal machining conditions for a superalloy from the experimental data. The experimental data was collected by face milling Ti6Al4V titanium alloy. The same procedure may be used for optimization of many manufacturing processes as long as user may determine the test conditions for data collection and ANNs can represent the characteristics of the data. In the following sections, the theoretical background, proposed procedure, experimental setup, results and conclusion will be presented.

2. Theoretical background

In this section, Taguchi Method and GONNS will be outlined very briefly. The reader may find more detailed information at the listed references.

Taguchi (Kurt et al., 2009; Onders et al., 1996) developed the framework for design of experiments, and effectively used the loss function concept for optimization. His approach works whether the objective is maximization, minimization or reaching to certain target. His ideas have been widely used in manufacturing since the main objective of Taguchi Methods was minimization of experimental cost for collection of data and finding the optimal solutions for the production. Taguchi proposed the use of outer arrays for simulation of the randomness of the environment. Although, there is some controversy on the characteristics of Taguchi's outer arrays (saturated arrays), this approach have been improved by the contributions of other researchers, and have been widely used. Taguchi used the S/N ratio as an index of robustness. The magnitude of this value indicates the robustness of the system against noise (Tzeng & Chiu, 2003). For the analysis of the experimental data, analysis of variance (ANOVA) was effectively used (Oktem et al., 2007).

BP type ANNs (Rumelhart et al., 1986) may be used to model any linear or non-linear system as long as the selected structure and parameter estimation algorithm are capable to represent the characteristics of the system and calculate the parameters with acceptable accuracy. User determines the structure by selecting the number of the hidden nodes and layers. Generally, final structure selection is determined by comparing the performance of different combinations of hidden layers and hidden neurons when models are fitted to the training data. Once the ANN based model(s) of the system is/are prepared, GONNS uses one or multiple GAs for estimation of the optimal operating conditions. GAs are not as efficient as many other optimization algorithms. However, they work effectively even with non-linear systems and they are believed to converge to the global minimum much better than many other optimization algorithms. GONNS is designed to maximize or minimize one of the outputs of the system while keeping the others within the user defined range. This approach eliminates

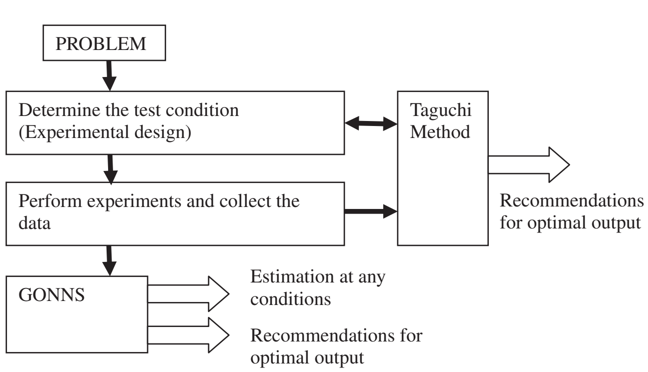

Fig. 1. Integration of the Taguchi Method–GONNS for experimental evaluation of the characteristics of a system.

Table 1
Chemical composition of Ti6Al4V alloy.

Element	C	N	H	Fe	O	Al	V	Ti
Weight (%)	0.08	0.05	0.015	0.40	0.20	5.5–6.75	3.5–4.5	Balance

Table 2
Physical and chemical properties for Ti6Al4V alloy.

Density (g/cm^3)	4.45
Thermal conductivity (W/m K)	7.2
Tensile strength, ultimate (MPa)	900–1100
Tensile strength, yield (MPa)	890
Elastic modulus (GPa)	115
Hardness (HRC)	36
Melting point (°C)	1670
Poisson's ratio (%)	0.342

Table 3
Properties of PVD coated inserts.

Coating thickness (m)	3–4
Hardness (HRC)	78
Operating temperature (°C)	600
Thermal expansion coefficient (10^{-3} K^{-1})	9.4
Density of insert (g/cm^3)	14.2

Table 4
Levels of test factors for face milling operation.

Sample	Cutting conditions	Level 1	Level 2	Level 3
A	Depth of cut (mm)	0.2	0.6	0.8
B	Feed rate (mm/min)	60	140	200
C	Cutting speed (m/min)	50	70	90