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Fuzzy rule based predictive model for cutting force in turning of reinforced PEEK composite

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ABSTRACT

Carbon fiber reinforced plastics have gained large interest among the community of composites manufactures and consumers due to their excellent adaptability to various industrial applications. In particular, there exists a demand for optimizing machining conditions of mechanical parts made from poly ether ether ketone reinforced with 30% of carbon fiber when using TiN coated cutting tools. In this work, predictive models that describe the relationship between the independent machining variables: cutting speed, feed rate and depth of cut, and the criteria of machinability: cutting force, cutting power and specific cutting pressure were derived. This was achieved by using either classical response surface regression technique or by implementing fuzzy logic models which are based on the compositional rule of inference that establish a parametric relation between a given response and the independent input variables. Effectiveness of these models has been proved by analyzing their coefficients of correlation and by comparing predictions they give with experimental results.

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1. Introduction

Non-reinforced and reinforced Poly Ether Ether Ketone (PEEK) plastics have excellent mechanical and thermal properties. These enabled PEEK composites to represent highly attractive substitutes for classical materials such as metals. The potential fields of their application include various industries such as electrical, electronic, automotive, aerospace, and marine. Machining is an efficient process that can be used to manufacture specific mechanical parts made from PEEK composites. This manufacturing process imparts dimensional accuracy and surface finish for desired performance and longer service life of the product. As PEEK composites are rather new with regards to machining processes, there is hence a crucial need to understand in depth their machinability.

Machinability can be defined as the property of the material which governs the ease or difficulty with which it can be machined under a given set of conditions. In this way, saying that a work material is more machinable than another signifies that it causes longer tool life, requires lesser cutting force and power and provides better surface finish. Machinability is assessed in terms of machinability criteria and consists essentially in minimizing the cost and maximizing the rate of production. Machinability criteria depend on many factors that are related to operating conditions and product quality. These include mainly tool

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life which influences productivity and cost, magnitude of the cutting force which affects power consumption and dimensional accuracy and surface finish which plays a key role on service life of the product. Other machinability criteria that could be of interest in assessing machinability are cutting temperature and chip form. Machinability will be considered highly performing when the cutting force, temperature, surface roughness and tool wear are less and chips are ideally uniform and short. To optimize machining process, some desired machining criteria are commonly specified: the required surface finish, time of execution, power consumption, tool life and environmental footprint. Since these depend crucially on the cutting force and its derivatives: cutting power and specific cutting pressure, machining criteria include also these quantities.

Machinability of PEEK is considered in this work when using TiN coated tools that are cheaper than the other known commercial tools. The aim is to perform the best selection of cutting parameters to be used during the machining process [1,2]. As a first step, analysis of the machining criteria that include the cutting force, cutting power and specific cutting pressure should be performed. The main raison is that, in view of the rigidity of the machine tool, it is necessary to limit the value of cutting force in order to avoid vibrations during machining. Cutting force is also recognized to be the most influential factor in bulk machining.

The addition of short fibers to thermoplastic composites enhances their mechanical properties such as stiffness, strength and hardness. It also increases the service temperature in comparison with non-reinforced thermoplastics [3–7]. The carbon and glass fibers are the common reinforcements adopted in thermoplastics. It has been reported that the addition of short carbon fibers, not only reduces the coefficient of friction and wear, but also decreases the thermal expansion coefficient [8] which enhances material stability with regards to temperature variations. The carbon fiber reinforcement provides also maximum rigidity and load bearing capacity [9,10] as well as high temperature service [11]. While enhancing material performance of PEEK composites, reinforcement fibers modify their machining criteria. Performance of the machining operation is in general significantly affected by the presence of fibers in reinforced work material. Reinforced poly ether ether ketone is extremely abrasive when machined. Cutting forces are more oscillating and vary periodically. This entertains oscillations that are originated from repeated running of cutting tool into fibers and matrix phases, which could produce strong variations of cutting forces magnitudes. The periodic nature of the cutting forces arises from the periodic changes of fiber orientation relative to the cutting speed vector as a result of the continuous turning of the work piece. The cutting forces generally increase with increasing the feed rate and the depth of cut. However, the dependence of cutting forces on cutting speed is not uniform across all different types of Fiber Reinforced Plastics (FRPs).

Since they enable reducing considerably the experimental effort, predictive models that describe the relationship between the independent machining variables and the criteria of machinability are of first interest. They allow quick estimation of the considered response as function of the set of machining parameters. Mathematical predictive models can be derived by using various techniques. Some of them are reviewed in the subsequent.

Mata et al. [3] conducted an analysis of the entire individual input machining parameters in an attempt to model two aspects of machinability, namely, power and specific cutting pressure by developing second order mathematical models based on response surface methodology (RSM). A statistical technique, using orthogonal arrays and analysis of variance, was employed to investigate the interaction effects between the controllable factors and responses during machining of unreinforced and reinforced PEEK composites using PolyCrystalline Diamond (PCD) tools. The analysis showed the dependency of both power and specific cutting pressure on cutting conditions.

Davim et al. [12] used RSM approach to study the machinability aspects of unreinforced PEEK, reinforced PEEK with 30% of carbon fibers (PEEK CF30) and with 30% of glass fibers (PEEK GF30) composites, when using cemented carbide (K10) tool machining. The study showed that K10 tool provides better machinability for PEEK and PEEK CF30 materials as compared to PEEK GF30 work material.

Tsao [13] compared the RSM and Radial Basis Function Network (RBFN) for core-center drilling of composite materials. RBFN is an artificial neural network that uses radial basis functions as activated functions. A radial function is a real-valued function whose values depend only on the distance from the origin. He has concluded that, for evaluating of drilling-induced thrust force, RBFN is more practical and more effective than the rough response surface method.

The performances of Fuzzy Rule Based Model (FRBM) based on Mamdani and Takagi Sugeno Kang (TSK) types of fuzzy logic rules have been investigated with different shapes of membership function distributions for prediction and performance analysis of machining with Minimum Quantity of Lubrication (MQL) in drilling of aluminium alloy [14]. A comparison of the model predictions with experimental results and those published in the literature showed that FRBM with TSK-type fuzzy rules describes excellent trade-off with experimental measurements. Adaptive Network based Fuzzy Inference System (ANFIS) was employed to accurately predict the amount of tool wear as a function of spindle speed, feed rate and measured cutting forces in end milling of glass fiber reinforced polymer [15]. The results showed that ANFIS is capable of estimating tool wear with excellent accuracy in the highly nonlinear region of tool wear and the cutting forces relationships.

Palanikumar [16] showed that combining the Taguchi method with RSM allows for minimizing the surface roughness in machining Glass Fiber Reinforced Plastics (GFRPs) with a PCD tool. António et al. [17] used genetic algorithm methodology in Artificial Neural Network learning and achieved modeling of machining conditions for orthogonal cutting of PEEK composite materials. Gupta et al. [18] used Taguchi method with logical fuzzy reasoning for multiple output optimization of high speed CNC turning of AISI P-20 steel using TiN coated tungsten

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