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Application of grey fuzzy logic for the optimization of CNC milling parameters for Al–4.5%Cu–TiC MMCs with multi-performance characteristics

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ABSTRACT

With the major application of MMCs, it is thus necessary to develop an appropriate technology for their efficient machining. Milling is the most common and versatile technology among different machining processes, characterized by an extensive range of metal cutting capacity that places it in a central role in the manufacturing industries. In the present study an attempt has been made to find out the most optimal level of process parameters for CNC milling of Al–4.5%Cu–TiC metal matrix composites using grey-fuzzy algorithm. Taguchi's L_{25} orthogonal array design is used for performing CNC milling operation on the composite plates. The Grey fuzzy optimization of CNC milling parameters consist of three different output characteristics; such as, cutting force Fc, surface roughness Ra and surface roughness Rz. It was found that a cutting speed of 600 rpm, feed of 40 mm/min and a depth of cut of 0.30 mm is the optimal combination of CNC milling parameters that has produced a high value of grey fuzzy reasoning grade of 0.8191 which is close to the reference value. ANOVA analysis is carried out and it is found that among three different process parameters, the cutting speed played a major role on the determination of GFRG.

1. Introduction

Nowadays metal matrix composites are being used in many applications in different engineering fields, which are very significant in the recent progress in material science and hence it is acting as a substitute for several engineering materials. Particularly aircraft, automotive, and locomotive industries are replacing steel and cast iron in different mechanical components with lighter high strength alloys and composites like aluminium (Al) matrix composites. As an outcome of this trend, the machining of metal matrix composites becomes very vital in the final stage of manufacturing, which needs further research.

The first generation of aluminium based composite materials having ceramic reinforcements are found to reveal good quality strength to weight ratio and better corrosion resistance. Currently, the research consideration is directed toward the hybrid composites having more than one reinforcing phase [1]. An ample spread application of these second generation MMCs are not possible without solution to the problems related to cutting [2,3].

Manna and Bhattacharyya [4] have investigated the effect of cutting speed, feed and depth of cut on wear of the cutting tool and built-up edge formation during the turning operation of Al–SiC particulate composite, using a rhombic uncoated tool of carbide material. However, less amount of built up edge formation was found at a lower depth of cut and at higher cutting speed. Ciftci et al. [5] have examined the effect of SiC particulate size on the wear of the tool and surface finish with cubic boron nitride (CBN) tool insert at constant depth of cut, feed and at varying cutting speeds. It was suggested that for 30 μm and 45 μm size of SiC in aluminium metal matrix, optimum cutting speed was achieved at 150 m/min. For better size of SiC reinforcements (110 μm), CBN tool was not found appropriate for turning operation. Chambers [6] have found that the performance of PCD insert was significantly superior than carbides insert while turning Al—5Mg reinforced with a combination of 5 vol.% saffil and 15 vol.% SiCp. Looney et al. [7] have performed

Abbreviations: RSM, response surface methodology; RSA, response surface analysis; GRG, grey relational grade; GFRG, grey fuzzy relational grade; TiC, titanium carbide; MMC, metal matrix composite; Ra, centre line average roughness; Rz, average maximum height of the profile; Fc, cutting force in the direction of tool travel; CNC, computer numerical control; ANOVA, analysis of variance; ANN, artificial neural network; GA, genetic algorithm; GRC, grey relation coefficient.

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a series of turning operations on the Al–25%SiC metal matrix composite using CBN, carbide, and silicon nitride inserts. From these inserts, cubic boron nitride insert has formed the best cutting, and silicon nitride inserts was the worst among all. El-Gallab and Sklad [8] have determined the quality of the surface of Al–20%SiC composite in high speed turning under different cutting parameters. It was found in their investigation that the polycrystalline diamond tools (PCD) exhibited appropriate cutting tool life as when being compared with coated carbide tools and alumina.

Ding et al. [9] has investigated the machining behaviour of Al–SiC MMC using the PCBN and the PCD tools. Surface cracking was observed at the flank face surfaces of the cutting tools; intergranular fractures were observed on the rake faces. The PCD inserts performance was better than the PCBN inserts. Yanming and Zehua [10] reported the mechanism of cutting tool wear during the machining of Al–SiC composite. The cutting tool flank surface was being affected by abrasive wear and it was found that the carbide tool was appropriate for the fine size of SiC reinforced composite. It was also seen that the size of the reinforcement and the volume fraction played a great role in the cutting tool life.

Muthukrishnan et al. [11] reported that better quality of surface finish in turning of A356/SiC MMCs could be achieved by means of medium grade PCD 1500 inserts with less power utilization at the elevated cutting speed. BUE formation was seen on the tip of cutting tools at lower cutting speed. Pramanik et al. [12] have explained the effect of factors, such as tool particle connections, difference in strain, thermal softening, and work hardening, on the variation of cutting forces for metal matrix composites and its alloy. Tamer et al. [13] investigated the influence of machining parameters such as cutting speed, feed and depth of cut on the cutting tool wear and surface roughness of $AlSi_7Mg_2$ reinforced with 5, 10 and 15 wt.% of SiCp. Mahamani [14] has optimized the cutting parameters in machining of in situ Al–5Cu–TiB_2 composite using uncoated tungsten carbide inserts. Anandakrishnan and Mahamani [15] have studied the machinability of in situ Al–6061–TiB2 MMCs. The flank wear rate, cutting force, and surface roughness were found to be higher with a higher value of depth of cut.

Rai et al. [16] have studied the cutting force development and chip formation while doing shaping operation of Al–TiC composites and compared them with Al–$TiAl_3$ composite and Al—Si alloys. There was improvement in the quality of the surface machined with the increased quantity of TiC reinforcing particles in the composite. The cutting force developed while machining Al–TiC metal matrix composite was lower than the cutting force developed while machining Al–$TiAl_3$ composite and Al—Si alloy. Kumar et al. [17] have studied the feasibility, dry turning characteristics of Al–4.5%Cu/TiC composites using uncoated ceramic inserts. The influence of the input process parameters on the surface roughness and cutting force was observed. BUE formation was found lower at higher cutting speeds and was found higher at lower cutting speeds. Razavykia et al. [18] evaluated machining process parameters and the modifier element effects on the cutting force and the surface roughness in the dry turning of the Al–Mg_2Si in-situ MMC. The addition of the Bi element as modifier reagent results in the lower cutting force and the lower surface roughness. Kumar and Chauhan [19] also investigates the effect of the cutting speed, feed, approach angle on the surface roughness of Al7075 ceramic composite (10% SiC) and Al7075 hybrid composite (7%SiC and 3% graphite). It was found that in the turning operation of both the composite surface roughness of the hybrid, composite was less than the ceramic composite. Karabulut [20] has fabricated AA7039/Al_2O_3 MMC by using powder metallurgy technique and found that material structure was the most effective factor in affecting the cutting force, and surface roughness. The milling test was being performed based on the Taguchi design of experiment. Shoba et al. [21] also investigated the effect of the cutting speed, feed, and depth of cut on cutting force. A comparison study was performed for the reinforced and unreinforced composites, and the result shows that cutting force decreases with the increase in the weight percentage of the reinforcements.

The multi-output optimization problems could be solved by using different methods such as grey relational analysis (GRA), genetic algorithm (GA), artificial neural network (ANN), response surface methodology (RSM) and fuzzy logic [22].

The investigation based on fuzzy-logic finds applications in unclear and undecided environment. In the recent research trends, fuzzy-logic-based multi-criteria decision making techniques have become very popular in doing optimization of different manufacturing processes. Grey system initiated by Deng [23] is a powerful tool to deal with the poor, incomplete and vague data [24,25]. In recent years, researchers have effectively used grey relational technique for solving the intricate interrelationships between the multiple objectives in a variety of fields of manufacturing [26–30]. A grey relational grade (GRG) is calculated by doing average of the grey relational coefficient of each response to convert the optimization of the complex performance characteristics into optimization of a single GRG [27]. Lin and Lin [30] researchers have done optimization of EDM process of SKD11 alloy steel with many process responses using grey-fuzzy-logic method. The theory of fuzzy logic proposed by Zadeh can successfully deal with the uncertain and vague information [31]. Therefore, the application of the fuzzy logic theory to the grey relational analysis may further develop its performance in solving multi-response problems for process parameter optimization. In the past, researchers have fruitfully employed grey fuzzy logic [24–29] for optimizing the multiple objectives of the complex manufacturing problems. They found that grey based fuzzy technique can make significant improvement in the performance characteristics of the process.

Rupajati et al. [32] has optimized several performances like recast layer thickness and surface roughness using fuzzy-logic method with Taguchi's L_{18} mixed- orthogonal array. It was found that the application of this optimization technique has significantly improved multiple output responses. Kumar et al. [33] investigated the cutting force development while performing the turning operation on unidirectional glass fibre reinforced plastics composite. Taguchi's L_{18} orthogonal array was being used for conducting the experimentations.

Soepangkat and Pramujati applied integrated approach comprising of GRA and fuzzy-logic for optimizing wire EDM of AISI D2 steel for minimizing surface roughness and layer thickness [34]. Related optimization techniques have been effectively utilized in a variety of manufacturing processes, which are mostly carried out under complex and uncertain environment [24,35–38].

Even though a very few research works have been carried out to study the influence of CNC milling parameters on different quality and productivity aspects, it is very necessary to establish optimal parametric combination with the intention of obtaining improved machined surface. Thus, the present work is focused on optimization of CNC milling machining parameters of Al–4.5%Cu–TiC metal matrix composite using grey-fuzzy analysis. The experimental work is done on the basis of Taguchi's L_{25} orthogonal array. The essential input milling parameters selected are cutting speed, feed and depth of cut, and the outputs considered are surface roughness and cutting force. For minimizing the values of all the performance characteristics, an optimal combination of input process parameters are required.

2. Experimental description

The material used for the experimentation is Al–4.5%Cu–TiC metal matrix composite prepared through the stir casting process.