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Research Paper

A computational fluid dynamics analysis of cryo-CO_2 flow and thermal behaviour in high-speed milling process

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ABSTRACT

Cryogenic CO_2 machining performance is mainly dependent on how well heat generated during cutting is dissipated from the cutting zone. Understanding the heat transfer phenomenon is crucial for optimizing thermal behavior and its effects, which remain challenging to capture experimentally. Thus, this novel study aimed to optimize the thermal behaviour of the cutting tool and workpiece of high-speed milling under cryo-CO_2 cooling by the combination of computational fluid dynamics (CFD) analysis and RSM-Box Behnken design. A complex 3D cryo-CO_2 model was developed and validated against experimental data of cryo-CO_2 flow temperature and it showed differences of less than 6 % when compared with CFD results. By the RSM-BBD method, 15 sets of parameters were simulated where the influence of cryo-CO_2 flow rate, nozzle distance (D), and nozzle diameter (∅) on heat transfer coefficients (h) and heat transfer rates (Q) were analyzed through ANOVA. The simulations resulted in h ranging from 33.75 W/m^2 to 88.92 W/m^2 and Q of between 126.22 W to 301.25 W. Cryo-CO_2 temperature trajectory and splashing effect from the nozzle to the cutting zone were also observed. The proportion of the h had a significant influence on the heat transfer. Further studies on tool and workpiece surface temperatures were conducted, where a higher flow rate had been suggested for advanced heat dissipation. ANOVA revealed both responses were dominantly influenced by flow rate followed by nozzle distance and their interaction. By multi-objective optimization, an optimum set of parameters was identified: flow rate = 13 L/min, D = 15 mm; ∅ = 1.3 mm and predicted to produce h at 77.23 W/m^2 and Q at 264.45 W for maximum heat dissipation. Thus, it is worth mentioning that this study provided some potential approaches and a promising way for the enhancement of cryo-CO_2 system towards optimizing the efficiency and performance of cryo-CO_2 machining.

1. Introduction

Machining of superalloys such as nickel-based alloys presents challenges such as elevated temperatures at the cutting zone, compromised machined surface quality, and rapid tool wear. Their excellent mechanical and chemical properties coupled with low thermal conductivity lead to excessive heat generation that increases temperature during cutting [1]. For effective heat dissipation particularly during high-speed cutting, researchers have explored different external cooling methods such as flood cutting, minimum quantity lubrication (MQL), cryogenic, as well as the hybrid approach of cryo-MQL [2–4]. Among them, cryogenic machining has generated strong interest within the discipline of sustainable machining due to its eco-friendly and extreme cooling approach. It involves the use of coolants such as liquid nitrogen (cryo-LN_2) and carbon dioxide (cryo-CO_2) gases to provide an intense cooling effect that deeply penetrates the interfaces between tool-chip and tool-workpiece, thereby drastically reducing cutting temperatures [5]. It is also environmentally benign as its consumption leaves no residue, thus offering neat and healthy machining processes to machine operators. Literature has shown that cryo-CO_2 is considered to substitute for cryo-LN_2 as its lower cooling capacity at −76 °C has resulted in less work-hardening on the sub-machined surface and a slower wear rate [6,7]. The extreme cooling of cryo-LN_2 at −196 °C in the intermittent milling process generated drastic temperature changes that led the tool to contract and expand repeatedly, which caused rapid fatigue and micro-cracking [8]. Thus, some researchers have preferred cryo-CO_2 in cryogenic machining as it offers fewer temperature variations which suits

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