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Influence cutting parameters on the surface quality and corrosion behavior of Ti–6Al–4V alloy in synthetic body environment (SBF) using Response Surface Method

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A B S T R A C T

Most of the global manufacturing of titanium alloys is related to produce biphasic structures with grains alpha and beta. The development of modern applications of titanium alloy is a great challenge due to the chemical composition of Ti–6Al–4V alloy and the complexity of the manufacturing technology. This study proposed an optimal investigation of the variation of cutting speed, feed rate, and depth of cut in the turning of Ti–6Al–4V alloy on surface roughness, cutting efforts, and corrosion resistance. Response Surface Method has been established to optimize and model the responses mathematically. The adequacy of the models and a significant contribution of parameters were determined by analysis of variance (ANOVA). The biocompatibility of the machined surface for different cutting parameters was evaluated by the electrochemical polarization in simulated body fluids (SBF). Furthermore, desirability function analysis was used to determine the optimal values for surface quality, the turning force, and the passivation rate. It was clearly noticed that the multi-responses of the desirability function improved the machine process. The feed rate and depth of cut were the most relevant factors to minimize surface roughness and the turning forces. Moreover, the experimental results showed that the corrosion behavior was strongly related to minimal surface roughness. Finally, the optimization reduced the surface roughness Ra and Rz in 5.5% and 11.9%, respectively and increased the corrosion resistance in 18.8%.

1. Introduction

The use of titanium and its alloys has grown over last decade due to their excellent properties for application as biomaterials or aeronautic materials. The main properties of titanium that should be considered are corrosion resistance, high strength at high-temperature values, and strength-to-weight ratio. However, the use of titanium as a biomaterial depends on the high quality of products, mainly when the surface quality is considered. The quality of machined products is related to good surface roughness that can represent a decrease of the friction or avoid surface corrosion. However, according to Sun et al. [28] titanium is classified as hard-to machine material because of its low thermal conductivity, high chemical reactivity, and low modulus of elasticity.

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The mechanical components have been exposed in several instances to moderate or severely harsh environments, mainly to corrosive environments, such as sea water, industrial wastes, and the human body [19]. The environment of the human body fluids, especially, is chemically and physically different from any other natural exposure conditions [6]. This behavior affects the metal performance and can generate a toxic reaction inside the human body. Besides, the component manufacturing process can influence this behavior; it should have high quality so as to restore the function into the human body. Gravier et al. [10] state that corrosion behavior is largely dependent on the machined surface characteristics in salt atmosphere. Prakash et al. [19] postulated that the rake angle and turning speed affected the corrosion behavior of mild steel. The authors concluded that the corrosion rates in salt atmosphere increase with the decrease in rake angle, and on the other hand the decrease occurred with the increase in turning speed.

Several investigations has been proposed to enable high levels of the machinability of titanium alloys. Generally, these studies cover the usage of new cutting fluids [25], new cutting parameters [6] and new tool materials [26]. Turning is a process that is widely used in the metalwork sector, mainly because it provides the machining of complex surfaces on hardened materials. This technology has been used throughout the industry since the 1940 s, and it was adapted to the biomechanical and dental technology with the goal of accelerating precision manufacturing in macro and micro scale. Moreover, the need for devices and components of high complexity contributed to the evolution of manufacturing in a variety of materials [16]. The economic importance of micro and macro systems grows, constantly, and is mainly applied to industries such as automotive, medical, and telecommunications. An idealization of this importance would be best when integrating micro and macro components to traditional products, which involves an optimization of the production cells in the molds and dies industries.

In the turning process, the temperatures and shearing stresses on the workpiece surface can reach high levels and thus generate a layer on the metal surface in a microscopic scale, which may be called area affected by the cutting forces and high temperature [31]. This feature introduces defects to the surface of metals that are not reduced or eliminated contributing to a premature failure of materials. Consequently, surface roughness or surface texture is generated by pits or marks left on the surface of the machined material. It occurs due to contact between the tool edge and workpiece interface, which is superimposed, and a ripple profile is caused by deficiency in machine movements, deformation, heat treatment, residual stresses, among others.

Surface roughness has a significant relation to the application of the product and may influence the optical, mechanical, electrical, and magnetic properties. However, there is still no general theory that explains the influence of the roughness on the physical and electrochemical phenomena. The surface roughness in micro and macro machining is one of the first conditions for the success of any operation and has been cited as a major influence of the microstructure of machined material. The performance of micro components is influenced by the quality of the surfaces generated by machining processes [20].

Mathematical modeling is one of the attractive ways to study the integrity of surface and the cutting forces in machining processes. The techniques and methods involved in predicting the responses of the turning process are extremely complex, show a nonlinear behavior, and involve multiple variables. The current algebraic models are usually based on the adjustment of curves extracted from experiments [27]. Due to the variety of the machining process, the proposed model has, therefore, an important role in determining the features and relationship of the input factors and their interactions with the experimental responses. Among the optimization methods, the highlight is the Response Surface Method (RSM), mainly because this methodology is able to analyze and solve problems in which the responses of interest are influenced by the many input variables and defines conditions that optimize these responses [4].

The RSM has been widely used for optimization of the cutting parameters in a variety of the machining processes. Aouici et al. [3] evaluated the influence of the feed rate, depth of cut, cutting speed, and hardness of workpiece on the surface roughness and cutting forces using RSM technique in hard turning of AISI H11 steel with tools of cBN 7020. Yan and Li [32] reported a multi-objective optimization approach in which an optimal combination between sustainability, production rate, and cutting quality during milling the medium-carbon steel was identified. Davoodi and Eskandari [7] modeled the tool life of PVD TiAlN-coated carbide tools and material removed of workpiece, as a function of cutting speed and feed rate, using the response surface methodology in turning of the N-155 iron–nickel-base super alloy. Kumar and Chauhan [14] optimized the surface roughness in turning of the alloys Al 7075 hard ceramic composite and Al 7075 hybrid composite using the RSM, artificial neural networking (ANN), and the multi response optimization providing a good technical database for aerospace, automobile, and military applications.

The present research aims to understand and evaluate the effects of machining parameters (cutting speed, feed rate, and depth of cut) on the corrosion behavior, surface quality, and cutting forces of a Ti–6Al–4V alloy. Furthermore, this study investigated the effect on biocompatibility of the titanium alloy by the variation of the cutting parameters on the surface quality with the help of electrochemical polarizations using synthetic body fluids (SBF) as electrolyte. The mathematical prediction models of the responses have been developed employing a Response Surface Method (RSM). The results have been optimized using Central Composite Design (CCD) and desirability function analysis. ANOVA was carried out to determine the adequacy of the models and a significant contribution of the cutting parameters. Finally, the electrochemical measurements of the machined surfaces were compared to polished samples to better understand the effect of machining on surface roughness and the subsequent relation with corrosion behavior.