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An Experimental Evaluation of the Cutting Capability of SS 431 Steel Using Abrasive Water Jet Machining (AWJM) †

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Abstract: The study begins with a comprehensive experimental investigation into the cutting capability of SS 431 steel using abrasive water jet machining (AWJM), focusing on optimizing the process through a response surface methodology (RSM-BBD) approach. Parametric analysis of the AWJM process identified the key factors affecting the cutting performance, such as the abrasive water pressure, standoff distance, and traverse speed. An increase in the water jet pressure and standoff distance which improves the material removal rate by 42.25%. As the standoff distance decreased, surface quality was improved by 7.89%. The surface characteristics and material removal rate results correlated with the optimized machining parameters, providing insights into the trade-off machining efficiency.

Keywords: SS 431; AWJM; RSM-BBD; surface quality; optimization; micro hardness

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1. Introduction

In the present manufacturing era, the quest for advanced materials and innovative machining techniques is continually pushing the boundaries of what is possible. Stainless steel, renowned for its durability and corrosion resistance, is pivotal in many industrial applications [1]. SS 431 steel, particularly, is martensitic stainless steel with remarkable mechanical properties, making it ideal for applications requiring high tensile strength and resistance to environmental factors. Understanding how to effectively cut and shape SS 431 steel is crucial in unlocking its full potential in various industries [2,3]. The unique advantage of AWJM lies in its ability to cut complex shapes without generating significant heat-affected zones or mechanical stress: a distinct advantage when working with materials such as SS 431 steel, which can be sensitive to thermal alterations. This research focused on an in-depth experimental evaluation of the cutting capability of SS 431 steel using the AWJM process. The study systematically explored the key process parameters influencing machining performance, including abrasive water pressure, standoff distance, and traverse rate. Response surface methodology (RSM-BBD) was adopted to optimize these parameters effectively, allowing for robust and efficient parameter setting that enhanced machining efficiency while preserving material integrity [4]. The findings of this study promise to contribute significantly to the advancement of precision cutting technologies and the utilization of SS 431 steel in diverse industrial sectors.

2. Materials and Methods

2.1. Abrasive Water Jet Machining(AWJM) of AISI 431 Steel

In this study, an AISI 431 steel plate was purchased and cut into 100 mm × 30 mm size and thickness of 3 mm for the AWJM process. The chemical composition was initially tested using a positive material identification (PMI) tester. An abrasive water jet machine (Model: Aqua Jet) was used to machine the SS 431 alloy. Garnet was used as an abrasive particle with a mesh size of 80, and a nozzle diameter of 1 mm was selected. The input parameters of the water jet pressure (WJP 150–300 range), stand of distance (SOD = 1–2 range), and traverse speed (TS = 70–90 range) were considered in the machining of the AISI 431 alloy. Fifteen sets of experiments were conducted. The ranges of input parameters were determined using the machine restrictions and information in the literature [5]. Scanning electron microscopy (SEM) was used to analysis the surface characteristics of the machined alloy steel.

2.2. Measurements of MRR and Ra

The material removal rate is an essential output response in manufacturing any component in machining areas. The machined work, MRR, was estimated using Equation (1) [6]. As a result, this machining parameter aimed to optimize the machining inputs for an enhanced MRR and lower Ra.

$$MRR \quad (\mathrm{mm}^3/\mathrm{min}) = D \times Ts \times Tkw \tag{1}$$

The kerf value was measured using an optical microscope. D is the depth of cut, Ts is the traverse speed, and Tkw is the top kerf width. The Ra was measured using a SJ-210 tester. The measured MRR and Ra values for the set of 15 combinations were considered. Design Expert software 13.0 was used for the optimization of experiments.

3. Results and Discussion

3.1. A Statistical Study of the MRR on AISI 431 Steel

Figure 1a shows the interaction plot of W_{JP} and SOD for MRR. When the water jet pressure was set at the maximum value of 300 MPa and the SOD increased to 2 mm from 1 mm, the MRR increased from 4.353 to 4.672 mm^3/min. This was due to the water jet pressure helping the abrasive particles penetrate the material more efficiently, resulting in a greater depth of cut and a wider cut width. This increased material removal means that more material is removed in a given time, contributing to a higher MRR [7]. Conversely, when the SOD was set at the maximum value of 2 mm and the traverse speed increased from 70 mm/min to 90 mm/min, the MRR rose from 3.158 mm^3/min to 3.904 mm^3/min. When combined with the water jet pressure, the higher traverse speed increased the cut depth and overall material removal, contributing to a higher MRR [8].

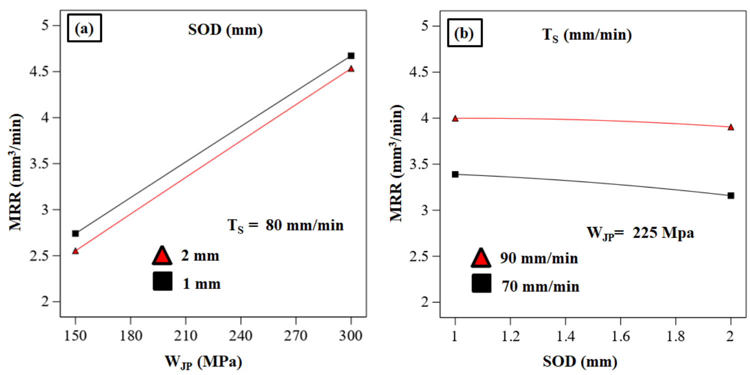

Figure 1. (**a**,**b**) Interaction plots for MRR.

3.2. A Statistical Study of the Surface Roughness (Ra) on AISI 431 Steel

Figure 2a shows the interaction plot of W_{JP} and SOD for Ra. When the water jet pressure was set at a maximum value of 300 MPa and the SOD was reduced from 1 mm to 2 mm with a constant traverse speed of 80 mm/min, the Ra was reduced from 3.340 µm to 3.157 µm. Notably, a higher W_{JP} increased the Ra, whereas a lower SOD improved the surface quality [9,10]. Figure 2b depicts the interaction plot of SOD and T_S for Ra, which shows that when the SOD was set at maximum value of 2 mm with a constant water jet pressure of 225 MPa, and T_s was adjusted from 90 mm/min to 70 mm/min, the Ra was reduced from 2.626 µm to 2.060 µm. When the standoff distance is increased, the abrasive particles have less kinetic energy when they reach the workpiece, leading to less damage on the work surface.

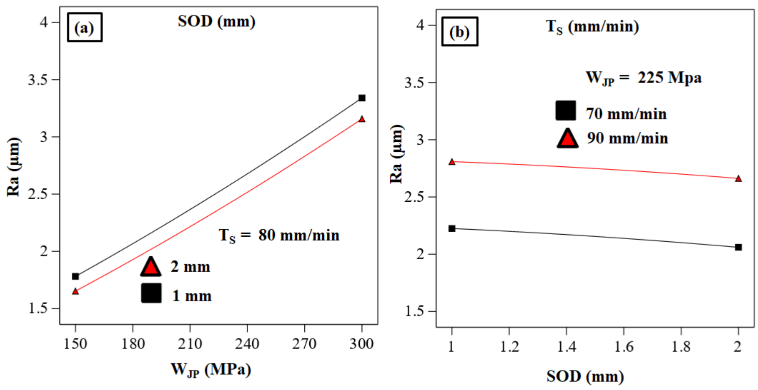

Figure 2. (**a**,**b**) Interaction plots for Ra.

3.3. Parametric Optimization of AWJM Machining

The optimized parameters are shown in Table 1.

Table 1. Optimized machining parameters.

Optimized Level			Predicted Values		Experimental Values		% of Error	
W_{JP}	SOD	T_S	MRR	Ra	MRR	Ra	MRR	Ra
260	1.5	70	3.733	2.496	3.584	2.388	3.991	4.52

SEM and Ramp graphs of the optimized machined sample are illustrated in Figure 3a,b. Figure 3a shows an SEM micrograph of the AISI 431 alloy at optimized parameters, which indicates the smooth surface. Figure 3b shows that the ramp diagram is highly effective for validating the interaction between process variables and reactions to achieve optimum conditions for the AISI 431 alloy [11]. A high value of W_{JP} and T_S significantly increased uniform erosion, offering a smoother surface and higher MRR.

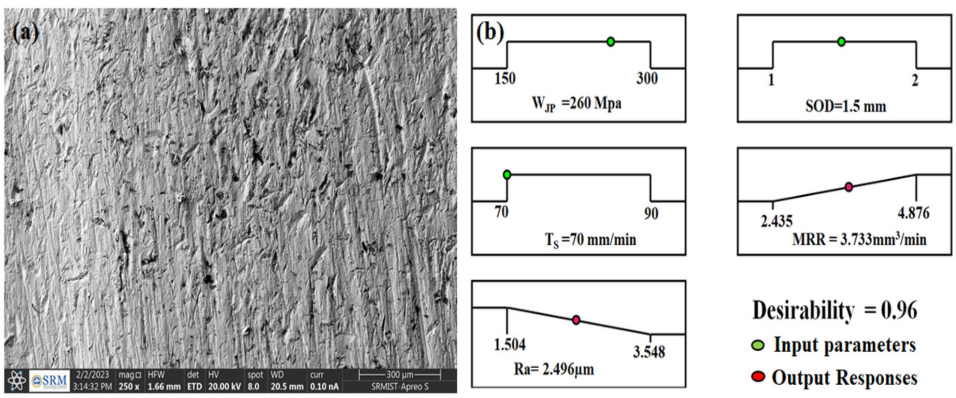

Figure 3. (**a**,**b**) SEM and ramp graph for optimal machining parameters.

4. Conclusions

The findings show that increasing the W_{JP} considerably increases the MRR. This is due to the high abrasive water jet and increased abrasive flow rate, and the material removal is performed more uniformly in the direction of water jet penetration. Alternatively, T_S and

SOD were proven to have an adverse effect on the MRR and Ra of the machined section. A large SOD caused jet boundary divergence and jet pressure, severely limiting the machining capabilities in the machined region of the AISI 431 alloy.

When the water jet pressure was 360 MPa, the SOD was 1.5 mm, and T_S was 70 mm/min, the optimal machining parameters for a high MRR and low Ra utilizing the RSM-BBD approach were 3.584 mm^3/min and 2.388 μm, respectively. Therefore, AWJM is versatile and suitable for machining AISI 431 alloy steel.

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