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EXPERIMENTAL STUDY ON MULTIPASS AWJ PERFORMANCE ON HARDOX 500 WORKPIECES

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Abstract: *In this paper, we discussed the cutting performance of multipass abrasive waterjet (AWJ) machining by presenting findings from an experimental study conducted on Hardox steel. To determine the geometry of the cut profile for the Hardox-500 material sample during multipass AWJ machining, experiments were carried out for a wide number of passes, namely 1 to 4 under different jet pressure and mass flow rate values. Research has demonstrated that setting the right cutting parameters can result in superior performance with multipass cutting compared to single-pass cutting. It was shown that multipass cutting is rather efficient in increasing the depth of penetration and reducing kerf taper angle, as 3 to 9 times higher depths and 2 to 4 times lower kerf angles were able to be obtained especially for pressure and abrasive mass flow rate values of 250 MPa and 7 g/s, respectively, whereas kerf width was affected to a lesser extent by the number of passes.*

Keywords: *Abrasive Waterjet Milling, multipass, Hardox Steel, pressure, abrasive mass flow rate.*

1. INTRODUCTION

A well-known unconventional manufacturing method called abrasive waterjet (AWJ) technology uses a high-pressure fluid jet with abrasive particles to erode and remove material. This technology has many benefits, including no heat-affected zone, the ability to machine a variety of materials including those that are difficult to machine, and sustainability. However, the method needs to be modernized to reach the desired levels of quality and efficiency and meet the criteria of high-end industries, like automotive and aerospace ones.

In 2005 P.H. Shipway, G. Fowler, and I.R. Pashby[1] studied the use of AWJ technology to mill components out of hard-to-cut materials. Their research investigates the behaviour of Ti6Al4V during abrasive waterjet milling in terms of the surface characteristics of the milled component, such as roughness, waviness, and level of grit embedment. They found that the surface quality after milling is substantially influenced by the machining parameters, such as the waterjet pressure, abrasive size, and jet-workpiece traverse speed [1]. Their research was later expanded to include additional input and output parameters, including the number of passes over the geometry being machined. The main focus of this work is the control of depth and surface quality in abrasive water-jet (AWJ) milling. The effects of traverse speed, number of passes, and abrasive grit size on material removal rate, surface waviness, and surface roughness were investigated [2]. J Wang and D.M Guo [3] conducted an experimental examination of machining alumina ceramic workpieces and presented an analysis of the cutting performance of multipass abrasive waterjet (AWJ) machining. It has been shown that multipass cutting outperforms single-pass cutting when cutting parameters such as nozzle traverse speed are well-balanced [3].

Moreover, J. Wang and Y. Zhong [4] proposed a new cutting method that combines multipass techniques with controlled nozzle oscillation. It has been discovered that employing multipass cutting with nozzle oscillation, as opposed to single-pass cutting, can result in an average increase of 50.8% in the total depth of cut [4]. In a work by Miao et al. [5], the ideal cutting times for multipass abrasive water jet cutting of

AISI 304 stainless steel were examined from two perspectives, namely surface quality and kerf taper They proposed two types of multipass abrasive water jet cutting; the first type is "multipass trimming-cutting" in which the workpiece is cut off after the first cutting, and the second type is “multipass deepening-cutting”, which stands for enlarging the depth of penetration in every passing [5].
Xiong et al. [6] conducted experiments with tw o machining passes by changing the directions, under various stand-off distance values and traverse feed rates, in order to decrease surface roughness. It had been concluded that the reduction of stand-off distance improved kerf taper and that the second pass improved quality.
The excellent toughness, hardness, and abrasion resistance of Hardox steel make it ideal for demanding applications in the mining, construction, and recycling sectors. Hardox steel is available in several grades, each of which has unique qualities to satisfy a range of demands for strength, hardness, and wear resistance.
Material with such properties belongs to the group of difficult materials for processing, therefore research on the use of unconventional methods of cutting them has been carried out. A few studies have been conducted to examine the influence of input parameters of the AWJ machining process on Hardox steel workpieces regarding declination angle and roughness [7-10].
Experimental testing was performed by Perec et al. [9, 10] to determine the impact of various pressure levels, traverse speeds, and abrasive mass flow rates on the depth of penetration, kerf width, and roughness of the cut surface of the Hardox 500 steel.
Thus, given that the amount of work on AWJ machining of hard-to-cut Hardox steel is limited and no attempts to study the effect of multiple passes during the processing of this material, in the present work experiments were carried out with a view to determine the effect of multipass strategy on machining of Hardox steel by AWJ technology under various conditions.
After the statistical analysis is performed on the results, useful conclusions are drawn regarding the efficiency of the multipass strategy.

2. MATERIALS AND METHODS

This study was carried out on a model HWE 15 20 H.G. RIDDER Automatisierungs GmbH machine (H.G. RIDDER H., Hamm, Germany), on which the AWJ milling experiments were conducted. The Workpiece material was 500 Hardox Steel and#60 mesh size garnet abrasive was used.
16 experiments were conducted in total by performing tests using four levels of jet pressure (denoted as P), ranging from 100 to 250 MPa and abrasive mass flow rate (denoted as ma), ranging from 1 to 7 g/s, as well as 1 to 4 passes, while the other parameters were constant. More specifically, the stand-off distance was set at 3mm, the diameter of the nozzle was 1 mm, the traverse feed rate was 600 mm/min and the jet impingement angle was set at 90 deg. Grooves were measured using a VH X-7000 ultra-deep field microscope (KEYENCE, Mechelen, Belgium), with the studied output parameters being the penetration depth, top kerf width and kerf taper angle. Measurements were repeated three times to observe the results' statistical variation.

3. RESULTS AND DISCUSSION

After the experiments were conducted, the effect of the jet pressure, abrasive mass flow rate, and number of passes on the depth of penetration was examined. Figure 1 depicts the effect of the number of passes on the depth of penetration under various conditions.
Different colours represent different numbers of passes and for every case, the jet pressure and abrasive mass flow rate values were changed as shown underneath the bars.
It is observable that the depth-pressure relationship function has an ascending nature. An increase in the vertical cutting force reflects AWJ's increased capability of obtaining a higher depth of penetration [12]. Moreover, given that more abrasive particles hit the material, there is

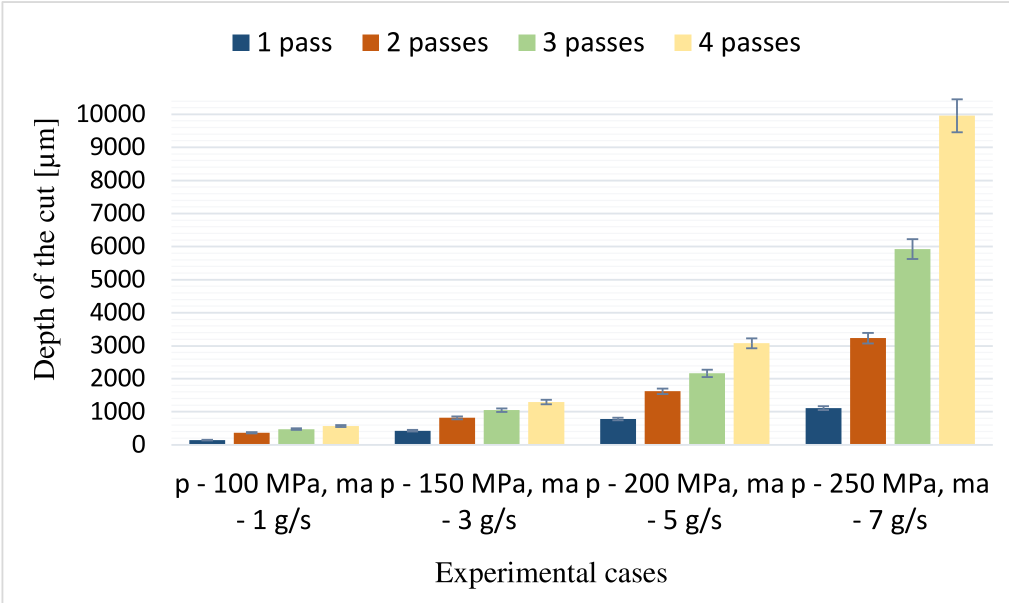

Fig. 1. Influence of the number of passes on the depth of penetration under different process conditions

a correlation between an increase in the mass flow rate of abrasive particles and an increase in the depth of cut [13]. It's clear that there's a distinction between the bars representing the same quantity of passes in various groups, caused by the rise in pressure and abrasive mass flow rate. It can also be noted that the differences between the individual bars in the group increase progressively with the change in processing parameters and the number of passes. Thus, although, every additional pass through the slot generated deeper grooves, different process

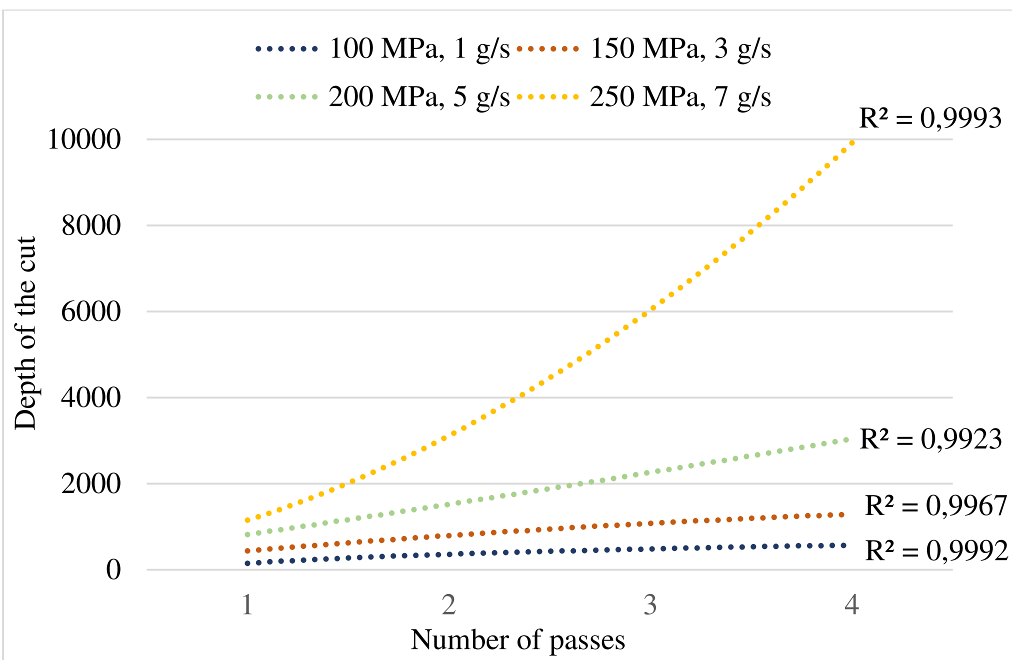

Fig.2. Correlation between the number of passes and depth of penetration under various conditions

conditions can lead to a much higher increase in depth after each pass [14].

For each process condition, the effect of multiple passes on depth is also depicted in Figure 2. In order to determine the type of correlation between the number of passes and depth of penetration, regression analysis was carried out. The coefficient of determination R2 determines how much of the data is explained by the model - the larger the better the regression straight line fits the data. The coefficient of determination R^2 takes values from 0 to 1, meaning that practically values above 0.9 indicate a very good fit. The trend functions which obtained the larger R^2 values are shown also in Fig. 2. Trend lines were generated to demonstrate the nature of the relation between the number of passes and the depth of penetration under different input parameters. indicating that the penetration depth value increases nonlinearly with respect to the number of passes. The function selections were determined by analyzing the R^2 values, with the logarithmic type yielding the highest value when operating at the lowest pressure and mass flow rate settings. In all other cases, we utilized second-degree polynomial functions. The distances between the trend lines increase with increasing machining parameters, thus inferring that at higher values of pressure and abrasive mass flow, the impact of the multipass strategy

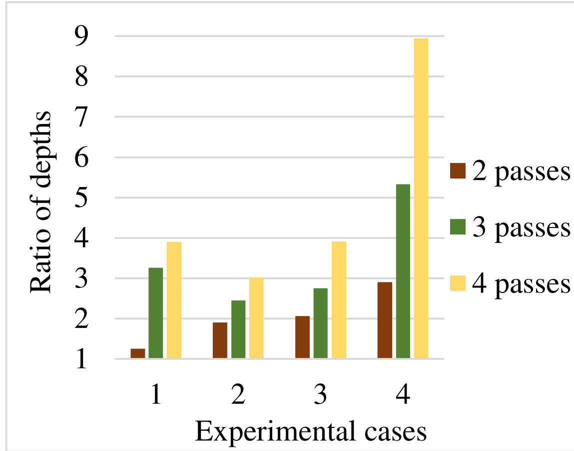

Fig.1. The ratio of depth obtained with 2, 3, or 4 passes, concerning the depth of the first pass under various experimental conditions

on the results increases. The ratio of depths, shown in Figure 3, was defined as the ratio of depths between each pass and the first one, increased for each consecutive pass, as was proven that passes and depth did not correlate linearly. For the selected parameters used in the experiment, it can be deduced that at low-pressure and abrasive flow rates (up to 150 MPa and 3 g/s), the second pass could not generate a groove twice as deep, which is possible for higher values of the input parameters. This might be correlated with the loss of energy. For three passes, it was possible

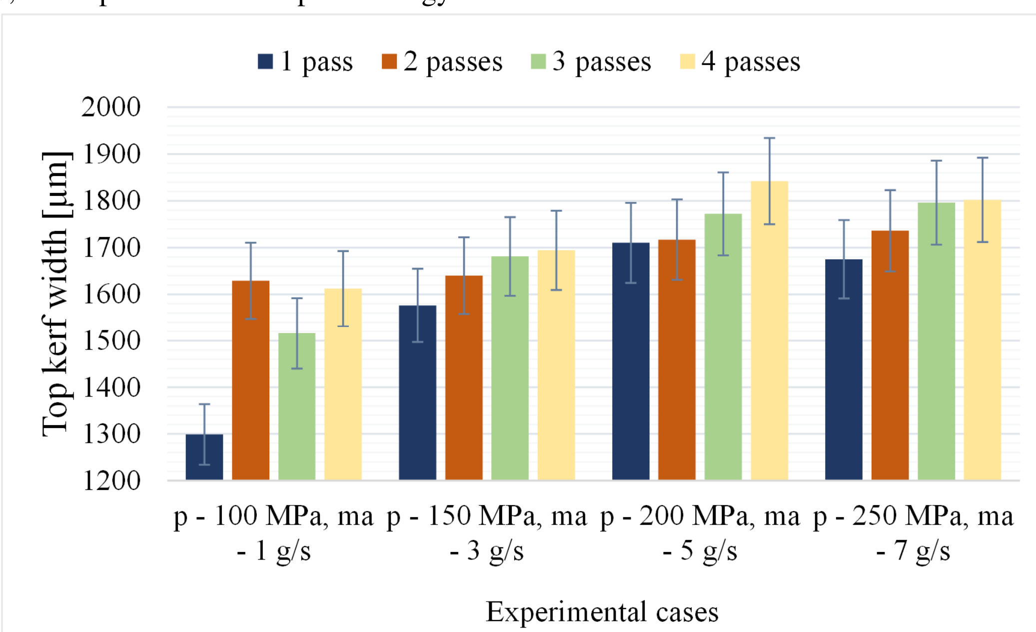

Fig.2.Influence of multipass strategy on the kerf width under various conditions

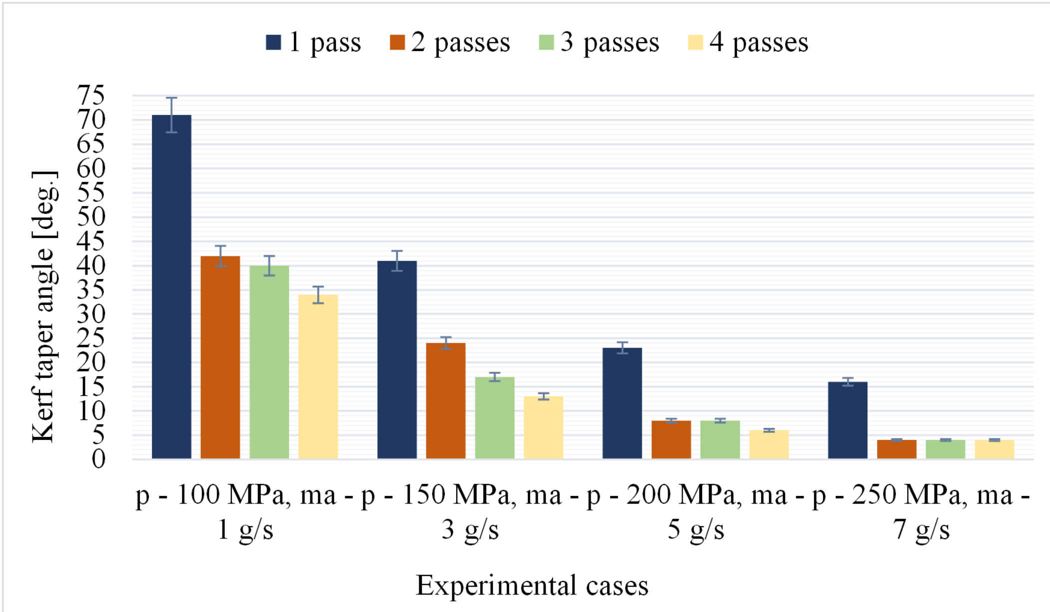

Fig.3. Influence of multipass strategy on the kerf taper angle under various conditions

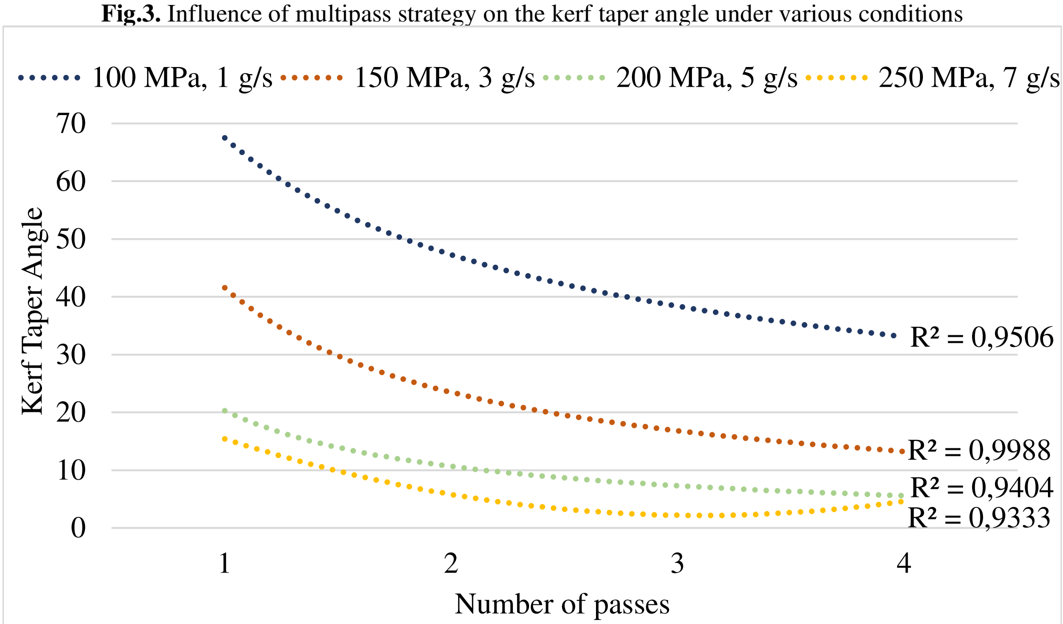

Fig.4. Correlation between the number of passes and kerf taper angle under various conditions

to obtain at least twice as deep grooves, while for the highest parameters, i.e. operating pressure of 250 MPa and an abrasive mass flow rate of 7 g/s, it was possible to produce a groove of more than five times as deep as the groove made by a single pass. Four passes allowed for achieving 3 to 9 times deeper grooves. The relationship between the jet pressure, abrasive mass flow rate, and number of passes on top kerf width is presented in Fig. 4. As is generally known, the most important parameter affecting the width of the groove is the distance between the nozzle and the material. Parameters such as abrasive mass flow and pressure do not greatly affect the results, although increasing the pressure tends to cause a slight increase in the width of machined grooves. This can be observed as an increase between the bars indicating the machining process with the use of the same number of passes. However, given the statistical variation of kerf width, as can be seen in Figure 4, it can be also deduced that increasing the number of passes caused no significant variation in kerf width in most cases. Finally, one of the important output parameters that indicate the perpendicularity of the machined slot to the sample face is the taper angle. To improve the quality, it is necessary to work towards reducing the kerf angle. By referring to Figure 5, it is apparent that utilizing a multipass approach makes it possible. The results show a considerable downward trend for the number of passes over 2 in every case, something that can be attributed to the high increase of penetration depth in conjunction with the minimal variation of kerf width. Moreover, when increasing the two process parameters, kerf angle reduction also occurs [15]. In Figure 6, trend lines were provided in order to determine the type of correlation between the number of passes and the kerf taper angle. The shape of the optimum trend line which was determined for 100 MPa pressure and 1 g/s abrasive mass flow rate values indicates that the correlation is clearly non-linear and especially, it is second-degree polynomial. Functions generated for higher jet pressure and abrasive mass flow rate values were power trendlines. The choice of trend lines was based on fitting the results in different types of functions and applying the one with the highest R^2value. In addition, if we observe the gap between the trend lines, we can notice that the decrease is less significant in the later experiments as compared to the initial ones, despite the increase in jet pressure and abrasive mass flow rate values. Moreover, analyzing the gaps between the functions related to each set of parameters reveals that the reduction in angle is more significant for lower pressure and abrasive flow values than for higher ones. Figure 7 displays a ratio between one pass and multiple passes for better comparison. According to the measurement results, when comparing one pass to several passes, the ratio was less than one. This suggests that the kerf taper angle decreases as the number of passes increases [16]. As can be seen on the graph when using 250MPa jet pressure and 7 g/s (i.e. test number 4) abrasive mass flow rate using more than 2 passes no longer reduced the kerf taper angle.

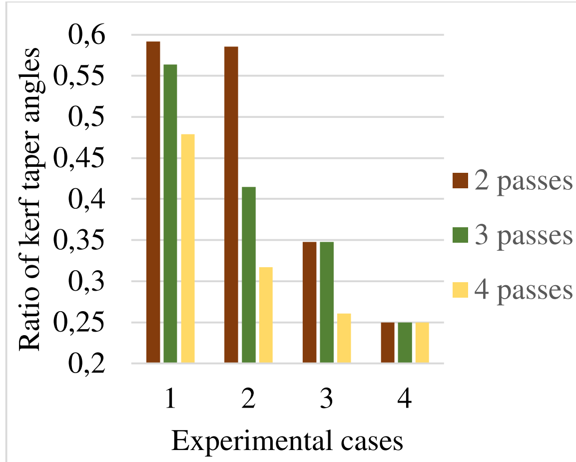

Fig.7. The ratio of kerf taper angle obtained with 2, 3, or 4 passes, concerning the depth of the first pass under various experimental conditions

4. CONCLUSIONS

Based on the obtained results, the researchers examined the effect of the multipass strategy on the depth of penetration, top kerf width and kerf taper angle in the multipass abrasive waterjet milling of 500 Hardox steel under various conditions. The analysis showed that the number of passes contributed to the deepening grooves with a nonlinear correlation identified between them. It was also found that the effect of the number of passes on the depth of penetration is also highly dependent on other process conditions such as the jet pressure and mass flow rate. However, the variation of top kerf width is barely significant with respect to the number of passes, with only a slight increase observed in some cases. The use of a multipass strategy also led to a reduction in the kerf taper angle, particularly with two passes, and subsequent passes had diminishing effects. When using a jet pressure of 250 MPa and an abrasive mass flow rate of 7 g/s, additional passes no longer resulted in a reduction of the kerf taper angle. By reducing the kerf angle, it was possible to achieve a value of 4 degrees as the best result, indicating an almost perfectly straight groove. These results can be useful regarding the appropriate choice of multipass strategy in

AWJM, which can effectively lead to a higher depth of penetration and reduce kerf taper angle when combined with the appropriate process conditions. For that reason, in future research, the effect of other process parameters, in conjunction with the multipass strategy will also be evaluated.

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Studiu experimental privind performanța prelucrării AWJ pe piese din oțel HARDOX 500

În această lucrare, se prezintă performanța procesului de tăiere cu jet de apă abraziv (AWJ), studiu experimental a fost efectuat pe oțel Hardox 500. Pentru a investiga variațiile geometriei profilului tăiat în timpul prelucrării AWJ cu mai multe treceri, au fost selectate diferite condiții cu valori diferite ale presiunii și ale debitului masic abraziv și au fost utilizate metode statistice pentru a descoperi orice relații potențiale între variabile. Cercetările au demonstrat că setarea parametrilor de tăiere optimi poate avea ca rezultat o performanță superioară cu procesul de tăiere în mai multe treceri în comparație cu tăierea cu o singură trecere. După efectuarea analizei, am determinat tendințele în ceea ce privește calitatea tăieturii și caracteristicile geometrice ale tăieturii pe baza numărului de treceri, a presiunii și a ratei debitului de masă abrazivă.

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