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Experimental Investigation and Optimization of Tool Life in High-Pressure Jet-Assisted Turning of Inconel 718

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Abstract: The application of high-pressure jet-assisted (HPJA) machining can increase tool life during machining, as the cutting fluid penetrates better into the interfaces between the tool and the workpiece. In this work, tool life in semi-finish turning of Inconel 718 with coated carbide tools and a high-pressure coolant supply is investigated. In a preliminary experiment, tool life was compared between conventional flooding and HPJA machining. The results show tool life that is more than twice as long with HPJA at higher cutting speeds. In the main experiment, tool life was investigated as a function of various high-pressure-jet parameters (nozzle diameter, distance between the point of impact of the jet and the cutting edge and pressure of the jet) and basic cutting parameters (cutting speed and feed rate). The relationship between the above-mentioned process parameters and tool life was analyzed and modeled using response surface methodology (RSM). Analysis of variance (ANOVA) was performed to evaluate the statistical significance of each process parameter for the response. The results revealed that cutting speed is the most important factor for maximizing tool life, followed by pressure of the jet and feed rate. In addition, optimization using the biogeographic optimization (BBO) algorithm was performed and validated in this study. The results of the confirmation experiments show that the proposed optimization method is very effective and results in approximately 8.4% longer tool life compared to the best trial results.

Keywords: high-pressure jet-assisted turning; tool life; Inconel 718; optimization

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1. Introduction

Nickel-based alloys are the most commonly used difficult-to-cut materials in the manufacture of aircraft engine parts, particularly gas turbines, engine compressor disks, bearing rings, blades and other components that operate at very high temperatures. These alloys offer better physical properties at high temperatures, as well as better corrosion and creep resistance and higher performance, compared to conventional materials [1]. Inconel 718 is the most commonly used nickel-based alloy in the aerospace industry due to its excellent mechanical properties and corrosion resistance at high temperatures. However, due to its inherent properties—such as work hardening, low thermal conductivity, presence of abrasive carbides, extreme toughness, high chemical affinity to numerous cutting materials, etc.—it is widely known to have remarkably poor machining performance [2]. Currently, the main problems with conventional machining of superalloys are extreme heat generation in the cutting zone and heat-dissipation problems, which rapidly accelerate the undesirable wear of cutting tools and reduce tool life [3]. In addition, the dimensional accuracy and surface integrity of the machined part also deteriorate as a result.

The choice of a suitable cooling/lubrication technique is crucial to improving the machinability of difficult-to-cut materials. The selection of a suitable cooling/lubrication technique has impacts on tool life, surface integrity, machining accuracy, cutting forces, energy consumption, etc. In recent decades, the use of cooling lubricants has become established as a common technique for dissipating the heat generated in the cutting zone as a result of friction at the interfaces between the tool and the workpiece and between the tool and the chip. When one is machining difficult-to-cut materials, however, the use and disposal of cooling lubricants can be very costly. In addition to the economic benefits, new, restrictive environmental and health regulations related to the use of conventional coolants have led to the rise of environmentally friendly manufacturing [4]. Currently, the negative environmental impact of metalworking fluids is becoming more problematic due to increasing regulations on emissions, waste, health and safety. Environmental and health regulations are expected to become even stricter in the future, leading to a decrease in the use of metalworking fluids and an increase in machining costs. At the same time, many industries are beginning to incorporate environmentally friendly cooling/lubrication techniques into their machining processes.

Due to the economic, health and environmental issues associated with coolants/lubricants, new techniques have been developed that allow a significant increase in machining performance. The best way to reduce the costs associated with the use of cooling lubricants is to completely eliminate them, instead employing a procedure known as dry machining. Nevertheless, dry machining has some disadvantages that make it not suitable for all machining operations. The main disadvantage of this environmentally friendly technique is that with some combinations of cutting tools and workpiece materials, strong adhesion occurs at the interface between the tool and the chip [5]. In addition, the high temperatures and stresses generated during dry cutting can significantly reduce tool life. Therefore, because of the importance of improving machinability and increasing productivity, coolants/lubricants cannot be completely dispensed with when machining difficult-to-cut materials, even when the latest coatings are used [6].

Several alternatives to flood cooling, the most common cooling method used in the machining process, have been developed for machining difficult-to-cut materials, e.g., high-pressure jet-assisted (HPJA) machining, minimum-quantity lubrication (MQL) and cryogenic cooling. HPJA machining attempts to improve on conventional machining by directing a high-pressure jet of coolant/lubricant into the cutting zone, either on the flank or the rake face of the tool or, in some cases, on both. HPJA machining is an effective way to increase productivity, reduce the temperature in the cutting zone and improve chip control. In addition, HPJA machining of difficult-to-cut superalloys resulted in significantly lower overall machining costs than conventional flood machining did [7].

In the modern manufacturing industry, the main aims are to increase the quality of machined parts in terms of dimensional accuracy and surface finish and to reduce production costs. In metal cutting, tool wear is an unavoidable phenomenon caused by the interaction between the cutting tool and the machined part. The main objective of supplying cutting fluid under high pressure to the cutting zone is to reduce the temperature generated at the interfaces between the tool and the chip and between the tool and the workpiece, thus increasing tool life for machining. Increased tool life and the achievement of other technical goals play crucial roles in meeting sustainability targets such as reductions in production costs and energy consumption. In addition, tool life has a significant impact on overall production costs. Economic analyses have shown that the cost of the cutting tool for machining Inconel 718 accounts for between 20 and 30% of the total machining cost [8]. Therefore, many researchers have made great effort to investigate the potential

for HPJA machining to improve the performance of cutting tools used in the machining of difficult-to-cut nickel-based alloys.

Ezugwu et al. [6,9,10] investigated the effects of conventional and HPJA machining (pressures < 20 MPa, flow rates 20–50 L/min) when turning Inconel 718 with different cutting tools. They reported significant improvements in tool life—up to sevenfold—at higher cutting speeds (50 m/min) when PVD-coated carbide tools were used. However, when ceramic tools were used, HPJA machining resulted in reduced tool life, as the contact area between chip and tool became smaller. Sharman et al. [11] also compared conventional and HPJA machining in similar pressure and flow ranges (up to 45 MPa, 25 L/min) when finishing Inconel 718 with uncoated carbide tools. No significant improvement in tool life was observed with HPJA. The wear behavior of the tools was further investigated when machining Inconel 718 and Ti6Al4V [12] under different pressures (up to 30 MPa) and at different flow rates (up to 55 L/min), and material-specific wear mechanisms were observed. Machado et al. [13] reported improved tool life for Ti6Al4V but reduced tool life for Inconel 901 at a pressure of 14.5 MPa. Another study by Colak [14] confirmed that the use of high-pressure coolant (10–30 MPa) reduces flank wear and cutting forces and changes the chip shape. Magri et al. [15] used a pressure of 7 MPa and a flow rate of 80 L/min to improve tool life and sometimes surface quality when turning Inconel 625. Vagnorius et al. [16] also found a reduction in flank wear and improved tool life with HPJA. Hoier et al. [17] investigated the wear mechanisms of carbide tools under high-pressure cooling. Advanced cooling techniques (HP coolant, cryogenic coolant, MQL and MQL with nanofluids) were compared for the machining of Inconel 718 in terms of wear, forces and surface finish [18]. Fang and Obikawa [19] studied the effects of flank and rake-face channel designs on indexable inserts under a pressure of 13 MPa and at a flow rate of 9.2 L/min HPJA and found less wear. Alagan et al. [20–22] investigated the influence of high-pressure coolant (up to 16 MPa) and changes in tool design when turning Inconel 718. Their results showed that different coolant pressures on the flank and rake faces result in different wear behaviors. They also proved that the use of microtextured tools increases tool life under HPJA conditions and identified a new wear mechanism—cavitation wear—caused by the boiling of the coolant during HPJA machining. In another study by Suárez et al. [23], a reduction in flank wear of more than 30% and a reduction in cutting force of more than 10% were observed during face turning at pressures of 8–16 MPa. Khochtali et al. [24] reported an improved tool life of coated carbide tools with high-pressure coolant. Polvorosa et al. [25] found reduced flank wear in Inconel 718 and Waspaloy with a high-pressure coolant (8 MPa) compared to a conventional coolant (0.6 MPa). Nasr et al. [26] investigated the mechanisms of tool wear during HPJA machining of Inconel 625, and Hoier et al. [27] achieved a 45% reduction in flank wear by combining HPJA with tool-surface modifications. Li et al. [28] studied the influence of HPJA (8–11 MPa) on the performance of PCBN tools when turning GH4169. Díaz-Álvarez et al. [29] evaluated tool wear, forces and surface finish when machining Inconel 718 and Haynes 282 with coated carbide tools using HPJA.

As discussed in the previous section, HPJA machining has proven to be remarkably effective in extending tool life when machining nickel-based superalloys. This method enables the machining of difficult-to-cut materials at established cutting speeds with low-cost coated carbide tools. However, the presented overview of the research on applications of this technique shows that HPJA machining uses lower coolant pressures (up to 45 MPa) and very high flow rates (up to 55 L/min), with a larger nozzle diameter. Such commercially available nozzles tend to generate scattered jets, so not all of the coolant volume is used for cooling/lubricating function in the cutting zone. It is therefore interesting to investigate tool life when machining Inconel 718 with ultra-high pressures (in the range of 50–130 MPa) and very low flow rates (below 3 L/min), as is done in the present study with very small,

sharp-edged sapphire waterjet nozzles. In addition, the influence of the nozzle parameters was also investigated. The authors have conducted several studies on HPJA machining in such pressure/flow ranges. One article [4] presents a multicriteria optimization of the HPJA process, focusing on cutting power, power required to operate the HP pump, MRR (material-removal rate), surface roughness, cutting temperatures and chip shape. A preliminary study comparing tool wear between conventional turning and HPJA is presented in [7]. The main focus of the study is on the comparison of the two processes (conventional and HPJA turning) with regard to machinability, as well as environmental and sustainability aspects. The machinability of Inconel 718 under the different conditions (cutting forces, chip-tool contact length, chip formation, surface finish, heat generation) is also discussed by the authors [30]. Cutting-tool utilization is one of the most important performance indicators in machining processes in terms of direct effects on manufacturing costs. Therefore, the aim of the present study is to investigate the influence of high-pressure-jet parameters (nozzle diameter, jet impact distance and jet pressure) and conventional cutting parameters (cutting speed and feed rate) on tool life during semi-finish turning of Inconel 718 with coated carbide tools. There are several recommendations made by cutting-tool manufacturers for the semi-finish machining of nickel-based alloys. They all assume conventional machining under flooding conditions at high cutting-fluid flow rates. However, there is a lack of scientific literature that addresses the recommendations for semi-finishing a particular material with HPJA. Better utilization of the cutting tools with a reduced coolant quantity can significantly increase the sustainability and coolant management of the machining process. Therefore, the biogeography-based optimization (BBO) algorithm was employed to determine the optimal machining conditions for maximum tool life. Finally, the reliability of the proposed model was verified in a confirmation experiment.

2. Experimental Procedures

The experimental procedure consisted of two steps. In the first step, a series of preliminary experiments was carried out to investigate the effects of conventional flood cooling and HPJA machining on tool life when turning the difficult-to-cut alloy Inconel 718. In the second step, the main experiment, a detailed analysis was carried out, examining the effects on the tool of the geometric parameters of the nozzle (nozzle diameter and impact distance of the jet), the operating conditions of the HPJA system (pressure of the jet) and two fundamental cutting parameters (cutting speed and feed rate).

2.1. Workpiece Material, Machine Tool, and Cutting Tool

In this work, cylindrical rods made of the nickel-based superalloy Inconel 718 with the dimensions Ø120 × 300 mm were used as workpiece material. The longitudinal turning operations were carried out with a CNC lathe equipped with an additional high-pressure plunger pump with a flow rate of 8 L/min, delivering a maximum pressure of 150 MPa (Figure 1). A vegetable-oil-based emulsion with a concentration of 5.5% was used as the cooling lubricant. The high-pressure coolant was supplied through sapphire nozzles. These nozzles, which are commonly used in waterjet applications, were mounted in a customized tool holder that allows precise adjustment of the jet. Such nozzles generate a coherent, non-dispersed jet, which, unlike the commercially available nozzles for HPJA applications, allows the jet to be correctly directed onto the rake face of the cutting insert. The distance between the nozzle and the tip of the cutting tool was kept at 22 mm. The high-pressure coolant jet was directed at a small angle (approximately 5–6°) onto the rake face of the cutting insert, perpendicular to the cutting edge. Commercially available PVD TiAlN-coated carbide inserts with ISO 13399-1 specification [31] SNMG 120408-23 with chip-breaker geometry from Sandvik were used for all the experiments. The selected insert

is an interchangeable type and offers eight working edges. The insert was clamped in a Sandvik PSBNR 2020K 12 tool holder.

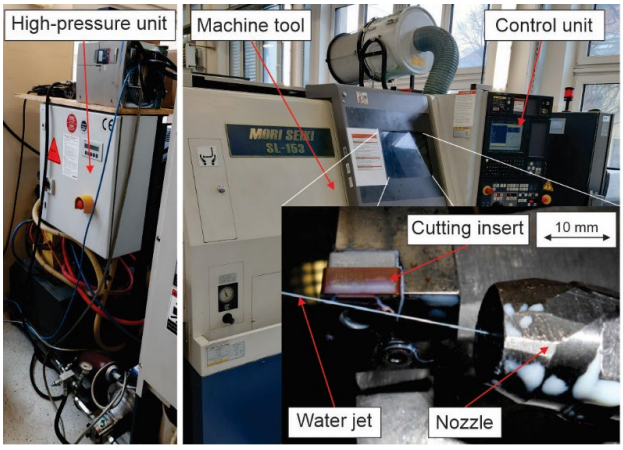

Figure 1. Experimental set-up.

2.2. Preliminary Experiments

In addition to HPJA machining, conventional flood cooling was used as a reference to evaluate HPJA performance when machining the difficult-to-cut alloy Inconel 718. The variation in tool flank wear was measured for both cooling methods. A constant depth of cut of a_p = 2 mm, a constant feed rate of f = 0.25 mm/rev and four different cutting speeds of 30, 50, 70 and 90 m/min were used in the tests. The coolant was fed into the cutting zone at a flow rate of 6 L/min and a pressure of 0.4 MPa. The pressure of the high-pressure coolant supply was 50 MPa, and the average flow rate was 0.8 L/min when a nozzle with a diameter of 0.3 mm was used.

2.3. Design of Main Experiments

Traditional experimental design is very complex and difficult to carry out. In particular, the number of experiments increases considerably with the number of process parameters. To solve this problem, Taguchi developed a simple and efficient approach based on the design of experiments with orthogonal arrays (OAs), which enables the independent and simultaneous investigation of quality characteristics with a small number of experiments. The OAs make the experimental design very simple and drastically reduce the number of experiments, as well as the time and cost of the experimentation. In addition, the proposed experimental design provides information about the effects of each process parameter, as well as information about their interactions. Therefore, this approach has achieved considerable success and justified popularity in the scientific community.

In this research, the orthogonal array L_{27} was selected for the experimental design. The nozzle diameter (D), the jet impact distance (s), the jet pressure (p), the cutting speed (v_c) and the feed rate (f) were investigated as control parameters for tool life. The jet impact distance was defined as the distance between the target point of the jet on the rake face and the cutting edge. If the distance is 0 mm, the jet is aimed directly at the edge. The depth of cut was kept constant at 2 mm. The control factors and their levels are listed in Table 1. A total of 27 experiments were carried out with the defined control factors and their values (see Table 2).

Table 1. Design factors and their levels.

Machining Parameters	Level		
	1	**2**	**3**
Nozzle diameter, D (mm)	0.25	0.3	0.4
Jet impact distance, s (mm)	0	1.5	3
Pressure of the jet, p (MPa)	50	90	130
Cutting speed, v_c (m/min)	46	57	74
Feed rate, f (mm/rev)	0.2	0.224	0.25

Table 2. Input parameters and experimental results for tool life.

No.	Machining Parameters					Tool Life (min)
	D (mm)	s (mm)	p (MPa)	v_c (m/min)	f (mm/rev)	
1.	0.25	0	50	46	0.2	10.54
2.	0.25	0	90	57	0.224	8.77
3.	0.25	0	130	74	0.25	1.76
4.	0.25	1.5	50	46	0.25	10.20
5.	0.25	1.5	90	57	0.2	9.79
6.	0.25	1.5	130	74	0.224	2.26
7.	0.25	3	50	46	0.224	8.75
8.	0.25	3	90	57	0.25	5.75
9.	0.25	3	130	74	0.2	3.52
10.	0.3	0	50	57	0.2	11.55
11.	0.3	0	90	74	0.224	3.07
12.	0.3	0	130	46	0.25	7.15
13.	0.3	1.5	50	57	0.25	8.08
14.	0.3	1.5	90	74	0.2	3.50
15.	0.3	1.5	130	46	0.224	7.35
16.	0.3	3	50	57	0.224	9.51
17.	0.3	3	90	74	0.25	2.14
18.	0.3	3	130	46	0.2	10.10
19.	0.4	0	50	74	0.2	3.93
20.	0.4	0	90	46	0.224	12.88
21.	0.4	0	130	57	0.25	6.25
22.	0.4	1.5	50	74	0.25	2.88
23.	0.4	1.5	90	46	0.2	11.00
24.	0.4	1.5	130	57	0.224	8.05
25.	0.4	3	50	74	0.224	3.32
26.	0.4	3	90	46	0.25	8.58
27.	0.4	3	130	57	0.2	6.99

2.4. Measurements

According to orthogonal array L_{27}, experiments were carried out to monitor and analyze the evolution of tool wear during HPJA machining. The Mitutoyo TM-505 tool microscope was used to measure wear on the cutting edge at 20× to 50× magnification and with a resolution of 0.001 mm. According to ISO 3685 [32], the most commonly used measures of tool life are the average (VB) and maximum width (VB_{max}) of flank wear. In this study, the end of tool life was defined as a VB of 0.3 mm. This permissible value is most commonly used in the scientific literature for semi-finish machining. At this value, the probability of tool breakage is still relatively low. The tool flank wear was measured individually for each experiment. After a cut of 30 mm in the feed direction, the turning process was stopped and the tool wear measured. This was repeated until the above-mentioned value VB = 0.3 mm was reached. Tool life was then recorded in

units of time (in seconds). Table 2 shows the tool-life results for different combinations of machining parameters.

3. Experimental Results and Data Analysis

The results of preliminary experiments showing the difference in machinability of Inconel 718 in terms of tool wear between conventional flooding and HPJA technology are presented at the beginning of Section 3.1. The same chapter, based on the results obtained in the main experiment, discusses the importance of analyzing the influence of the process parameters of HPJA technology on tool life. For this purpose, Section 3.2. presents an ANOVA for the influence of the individual parameters and an empirical model in the form of a reduced quadratic polynomial. In Section 3.3, these influences are presented in graphical form using RSM diagrams and explained in more detail.

3.1. Tool Life Under HPJA and Flood Coolant–Lubricant Conditions

Figure 2 shows the effects of cooling/lubrication technique and cutting speed on tool life. The results show that HPJA machining significantly improves tool life at any combination of cutting speeds compared to flood cooling. HPJA machining increases tool life by 135.3%, 117.8%, 238.7% and 215.5% compared to flood cooling at cutting speeds of 30, 50, 70 and 90 m/min, respectively. This is due to the coolant penetrating better into the cutting zone, reducing the temperature and friction of the cutting tool and thus resulting in a longer tool life. The results also show that cutting speed significantly affects tool life for both cooling conditions. As expected, tool life is significantly shorter at higher cutting speeds. In fact, with flood cooling, the combination of very high temperatures and high cutting forces leads to a softening of the cutting edge and accelerated tool wear, especially at high cutting speeds.

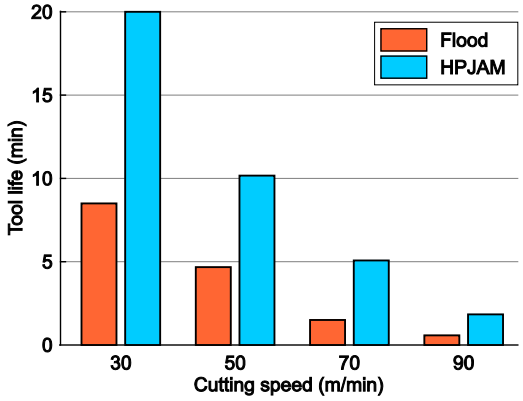

Figure 2. Effects of cooling conditions and cutting speed on tool life.

The average flank wear (VB) as a function of cutting time at v_c = 50 m/min under both cooling conditions is shown in Figure 3. Tool-life curves show typical phases: initial wear, uniform wear and severe (rapid) wear. A tool life of 4.67 min was determined for flood cooling; this value was greater, at 10.17 min, for HPJA machining. It can therefore be concluded that HPJA machining can increase tool life by almost 2.5 times compared to flood cooling due to the effects of improved cooling and lubrication. It can also be observed that the development of flank wear is much more uniform with HPJA machining. A rapid increase in the tool wear rate was observed with flood cooling. With flood cooling, the wear rate is higher than with HPJA machining, as many wear mechanisms are activated. Flank wear increases almost linearly with time, from 0.14 to 0.30 mm.

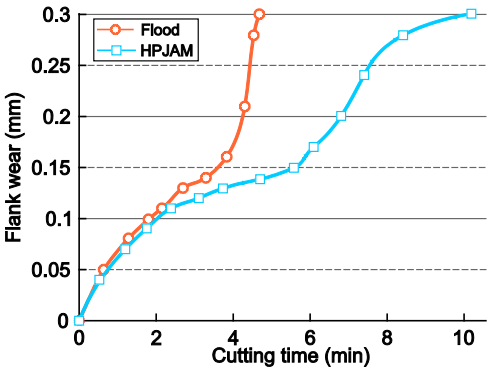

Figure 3. Tool life when under flood and HPJA machining conditions.

Tool life in HPJA machining is a dynamic process that is influenced by different parameters, namely, both the high-pressure jet and cutting parameters. The tool-life results for different combinations of process parameters in high-pressure jet-assisted turning of Inconel 718 are shown in Table 2. These results from the experimental trials show that tool life is significantly influenced by the machining conditions. For example, the longest tool life, 12.88 min, was achieved with the following combination of machining parameters: D = 0.4 mm, s = 0 mm, p = 90 MPa, v_c = 46 m/min and f = 0.224 mm/rev (experiment No. 20). The shortest tool life (1.76 min) was observed for run No. 3: D = 0.25 mm, s = 0 mm, p = 130 MPa, v_c = 74 m/min, and f = 0.25 mm/rev. The increase in flank wear (VB) observed for this combination of parameters with increasing cutting time when machining Inconel 718 is shown in Figure 4. This drastic reduction in tool life, by a factor of 7.3 (from 12.88 min to 1.76 min), shows that tool wear is significantly influenced by the cutting conditions. Based on these results, further analyses are required to investigate the effects of the individual process parameters and to determine the optimum machining conditions for achieving maximum tool life.

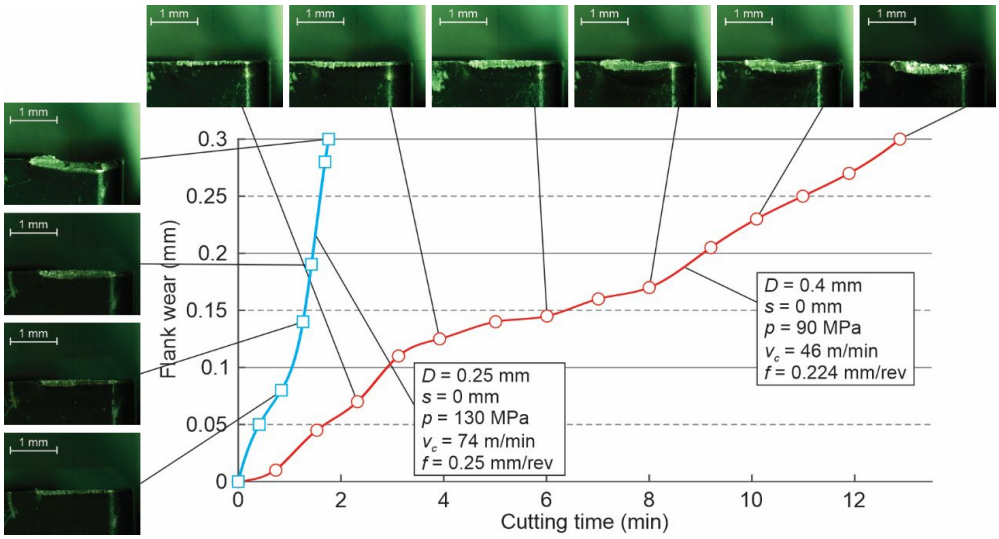

Figure 4. Tool-life curves for experimental trials: No. 3 (blue) and No. 20 (red).

3.2. Analysis of Variance

A statistical analysis of variance (ANOVA) was performed to investigate the significance of the effect of each machining parameter on tool life in HPJA turning of Inconel 718 (Table 3). In order to better discuss the results obtained by ANOVA, a Pareto diagram was also created (Figure 5). This tool makes it possible to determine the influence of the individual input parameters in ascending order according to the Fisher test (F-value). The

statistical analysis of the test data shows that cutting speed has the greatest influence on variance in tool life (approx. 73.5%). The term with the next-greatest effect on tool life is the pressure of the jet, followed by the feed rate and the jet impact distance, which contributes only slightly. Nozzle diameter has an nonsignificant influence on tool life. The terms $D \times v_c$ and ${v_c}^2$ were also significant. This result indicates that both the main cutting parameters (cutting speed and feed rate) and the high-pressure-jet parameters, i.e., jet pressure and nozzle distance, have significant effects on tool life.

Table 3. Results of the ANOVA.

Source	DOF	SS	MS	*F*-Value	*p*-Value
Model	8	270.97	33.87	46.08	<0.0001
D	1	0.084	0.084	0.11	0.7395
s	1	5.20	5.20	7.08	0.0159
p	1	21.33	21.33	29.02	<0.0001
v_c	1	208.96	208.96	284.26	<0.0001
f	1	18.36	18.36	24.98	<0.0001
$D \times v_c$	1	8.08	8.08	11	0.0038
$p \times f$	1	2.32	2.32	3.16	0.0923
${v_c}^2$	1	10.21	10.21	13.89	0.0015
Residual	18	13.23	0.74		
Total	26	284.2			
Std. dev.	0.86	R^2	0.9534		
Mean	6.95	R^2_{Adj}	0.9328		
S/N ratio	20.905	R^2_{Pred}	0.8903		

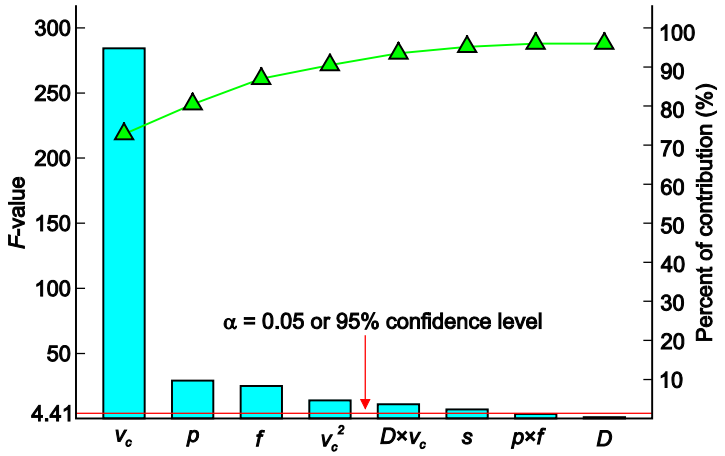

Figure 5. Pareto diagram of machining parameters effect on tool life.

The empirical model of tool life in HPJA machining of Inconel 718 was formulated using Response Surface Methodology (RSM). The RSM model, which relates tool life to the process parameters under consideration, was developed using ANOVA in the form of a reduced second-order (quadratic) model. The significance of the model and the effects of the parameters were established based on the *F*-value and the *p*-value. The model *F*-value of 46.08 means that the model is significant (Table 3). There is practically no influence (0.01%) of noise on the developed model. The model was developed for a confidence level of 95%. Therefore, *p*-values below 0.05 indicate significant model terms. The analysis of the *p*-value reveals that the parameters s, p, v_c and f, the product $D \times v_c$ and the quadratic term ${v_c}^2$ are significant model terms. However, since the model (for statistical purposes) also contains subsets of all possible effects that maintain the hierarchy, significance is not

given. The signal-to-noise ratio (S/N) of 20.91 and the coefficient of determination (R^2) of 0.9534 indicate that the model is suitable for representing a relationship between tool life and the process parameters under consideration. The $R^2{}_{Pred}$ of 0.8903 is in reasonable agreement with the $R^2{}_{Adj}$ of 0.9328. In the present work, the mathematical relationship of the response equations for tool life (T), expressed in terms of actual factors, is given as follows:

$$T = -19.9 + 57.4 \cdot D - 0.45 \cdot s + 0.0906 \cdot p + 0.903 \cdot v_c + 9.3 \cdot f - 0.941 \cdot D \cdot v_c - 0.552 \cdot p \cdot f - 0.00703 \cdot v_c^2 \quad (1)$$

3.3. Response Surface Graphic Analysis

In the following section, three-dimensional (3D) response surface plots were created to investigate the effects of the input machining parameters on tool life. These plots were generated using the developed RSM model and by varying two parameters at a time while holding the other parameters constant at their mean values.

Figure 6 shows the influence of nozzle diameter and cutting speed on tool life. As expected, tool life decreases significantly with increasing cutting speed. This can be attributed to the reduction in the contact length between the cutting tool and the chip, which leads to higher heat generation. In addition, an increase in cutting speed is also associated with an increase in normal and shear stresses in the area of the tool tip. It can also be seen that tool life increases with greater nozzle diameters. This effect is related to minimizing the formation of a built-up edge by reducing adhesion phenomena, especially at low cutting speeds [30]. Figure 6 also shows that tool life can be increased by around 6.8 min at low cutting speeds by increasing the nozzle diameter.

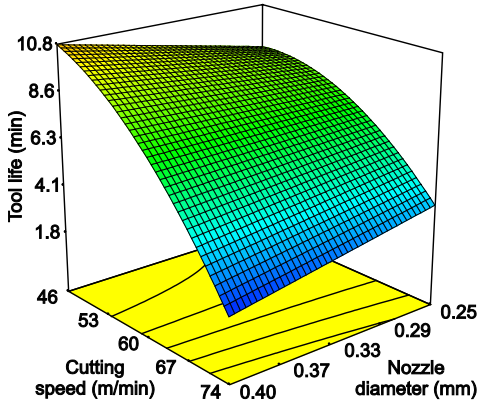

Figure 6. Effect of nozzle diameter and cutting speed on tool life.

The effect of impact distance and cutting speed on tool life when the other parameters are kept constant at their mean values is shown in the surface plot (Figure 7). The response surface plot shows that the cutting speed has a very strong influence on variability in tool life. Turning Inconel 718 at higher cutting speeds leads to higher temperatures in the contact zone and thus accelerates the thermally induced tool-wear mechanisms. Therefore, lower cutting speeds are generally required to improve tool life. It can also be seen from Figure 7 that tool life increases as the impact distance is reduced to an optimum point.

The influence of jet pressure and cutting speed on tool life is shown in Figure 8. It clearly shows a significant change in the response surface when the cutting speed is changed from low to high values. In addition to the significant influence of the cutting speed, tool life is also influenced by the pressure of the jet. Figure 8 shows that tool life increases as the jet pressure decreases. Higher pressure values increase the jet velocity, which may reduce the duration of the cooling/lubricating effect so that the coolant/lubricant cannot

reach the contact surface between the tool and the chip and consequently does not prevent accelerating wear [33]. In addition, it can be observed that tool life can be increased by almost 10 min at low cutting speed by reducing the jet pressure.

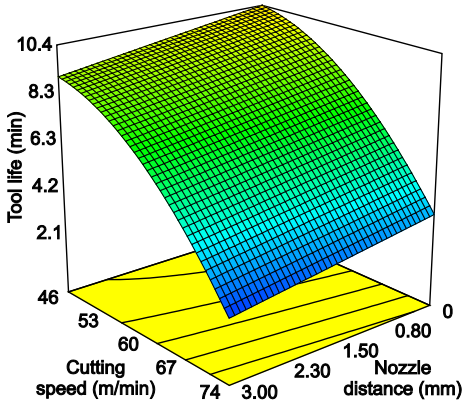

Figure 7. Effect of impact distance and cutting speed on tool life.

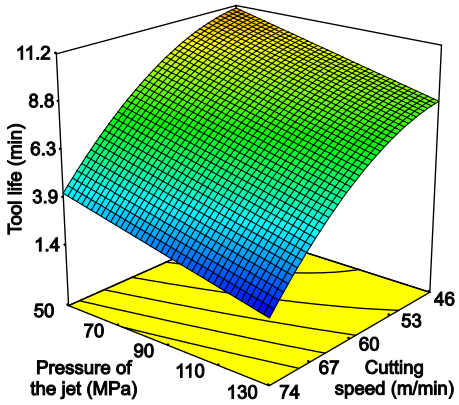

Figure 8. Effect of the pressure of the jet and cutting speed on tool life.

The effect of jet pressure and feed rate on tool life is shown in Figure 9. It illustrates that tool life increases as the feed rate decreases. The reason for this is that as the feed rate increases, the cutting forces also increase and additional heat is generated in the cutting area. Excessive heat development accelerates the mechanisms of tool wear. Although feed rate is normally associated with notch wear, this factor has also been shown to influence flank wear. It is also clear that an increase in the jet pressure leads to a reduction in tool life, especially when the feed rate is increased.

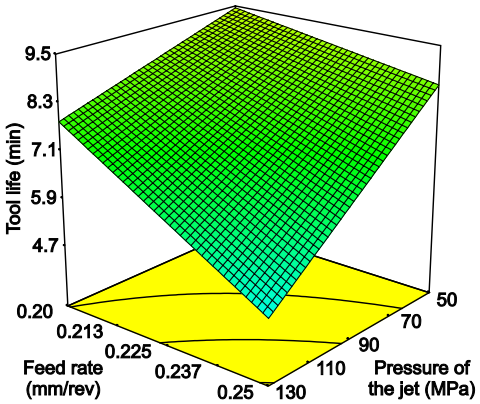

Figure 9. Effect of the pressure of the jet and feed rate on tool life.

Figure 10 illustrates the evolution of tool life as a function of cutting speed and feed rate when the other parameters are kept constant at their mean values. The analysis of the 3D surface plot shows that a reduction in cutting speed leads to a significant increase in tool life, which is consistent with the previous result. The response surface plot reveals that the feed rate has a moderate influence on tool life. As the feed rate increases, tool life decreases. Therefore, lower cutting speeds and feed rates are required to achieve an increase in tool life. Furthermore, Figure 10 shows that it is possible to increase tool life by 10 min when cutting speed and feed rate are at their lowest values.

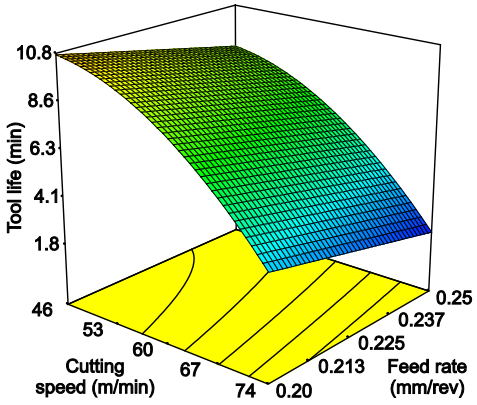

Figure 10. Effect of cutting speed and feed rate on tool life.

4. Optimization

4.1. Biogeography-Based Optimization

Based on the results presented in the previous section, it is clear that the selected control parameters have a significant impact on tool life during HPJA machining of Inconel 718. In recent decades, various artificial intelligence (AI)-based methods have become preferred and are applied by most researchers to optimize machining processes. Although a large number of efficient AI methods have been proposed for the optimization of machining processes, the biogeographic optimization (BBO) algorithm has been successfully applied in a variety of engineering disciplines due to its ease of implementation, simplicity, robustness and fast convergence. Therefore, in this part of the study, the BBO algorithm was employed to determine the optimal value of each machining parameter for optimum tool performance.

The BBO algorithm is a relatively new metaheuristic algorithm based on the theory of biogeography, which studies the distribution, migration and extinction of biological entities in habitats [34]. In biogeography-based optimization, in a process analogous to other population-based optimization methods, optimization starts with a set of solution sets, which are called habitats and can be represented as vectors of integers. In the BBO algorithm, a quantitative performance index, the habitat suitability index (HSI), is employed to indicate the performance level, which is comparable to the fitness function of other population-based optimization techniques. Each variable that characterizes a habitat feature is considered a suitability index variable (SIV). In the optimization problem, habitats with a high HSI value represent desirable solutions and vice versa. The basic idea of the BBO is that solutions with high-fitness solutions tend to share their features with other solutions and that solutions with low-fitness solutions acquire new features. Therefore, the migration operator, which includes both emigration and immigration, is used to evolve the population and obtain a global optimal solution.

In the BBO algorithm, migration is a probabilistic operator used to share features between solutions. To improve a solution to an optimization problem, individuals have their own immigration (colonization) rates (λ) and emigration (extinction) rates (μ). These rates

are functions of the number of species in the habitat, i.e., the immigration rate decreases and the emigration rate increases as the number of species increases. Both the emigration rate and the immigration rate for each solution are employed to exchange information between habitats in a probabilistic way. The higher the fitness of the solution, the higher the emigration rate and the lower the immigration rate. Poor solutions (i.e., habitat with few species) receive many new features from good solutions (i.e., habitat with many species), and these features improve the usability of the BBO algorithm. The immigration and emigration rates can be calculated as follows:

$$\chi_S = I\left(1 - \frac{S}{S_{\max}}\right) \tag{2}$$

$$\mu_S = E\left(\frac{S}{S_{\max}}\right) \tag{3}$$

where I is the maximum immigration rate, S is the number of species, $Smax$ is the maximum number of species and E is the maximum emigration rate.

In addition to migration, the BBO algorithm is also based on mutation, which is employed to increase diversity in the population. The probability associated with a given number of species can be calculated as follows:

$$\dot{P}_S = \begin{cases} -(\lambda_S + \mu_S)P_S + \mu_{S+1}P_{S+1}, & S = 0 \\ -(\lambda_S + \mu_S)P_S + \lambda_{S-1}P_{S-1} + \mu_{S+1}P_{S+1}, & 1 \le S \le S_{\max} - 1 \\ -(\lambda_S + \mu_S)P_S + \lambda_{S-1}P_{S-1}, & S = S_{\max} \end{cases} \tag{4}$$

where P_{S-1}, P_S and P_{S+1} are the counting probabilities of the species; λ_{S-1}, λ_S, λ_{S+1} are the immigration rates and μ_{S-1}, μ_S, μ_{S+1} are the emigration rates of a habitat with $S-1$, S and $S+1$ species.

In the BBO algorithm, the mutation rate is inversely proportional to the solution probability, i.e., solutions with a lower probability are more likely to mutate to other solutions, while solutions with a higher probability are less likely to mutate. The mutation rate for each solution set can therefore be determined as follows:

$$m(S) = m_{\max}\left(\frac{1 - P_S}{P_{\max}}\right) \tag{5}$$

where $m_{\max}$ is a user-defined maximum mutation rate and $P_{\max}$ the maximum probability.

Prior to the optimization process, it is necessary to establish relationships between the process parameters (nozzle diameter, jet impact distance, jet pressure, cutting speed and feed rate) and the target or fitness function (tool life). For this purpose, the model for predicting tool life, Equation (1), was used as the fitness or objective function. The optimum values of the machining parameters that contribute to the longest possible tool life were assumed to be the objective of the optimization process. In addition to identifying the machining parameters to be optimized and expressing the objective functions, the formulation of an optimization model also involves defining the limits (constraints) of the values for the machining conditions. The range of values of the experimental machining conditions in Table 1 was selected to represent the limits of the optimization problem. Thus, the optimization problem of HPJA turning of Inconel 718 is as follows:

Find $X = [D, s, p, v_c, f]$
Maximize $T(X)$
Subject the putative solution to the constraints, as follows: $0.25 \le D \le 0.4$, $0 \le s \le 3$, $50 \le p \le 130$, $46 \le v_c \le 74$, $0.2 \le f \le 0.25$.

The developed model was optimized using the BBO algorithm.

In order to perform a comprehensive search for the optimal machining parameters in the predefined search space, the commonly used parameters of the BBO algorithm were considered and analyzed. Based on the convergence results, a habitat-change probability of 1, a mutation probability of 0.1, a maximum number of iterations of 500, a number of habitats of 50, a maximum immigration rate of 1, a maximum emigration rate of 1 and an elitism parameter of 2 were selected as optimal values. The set values of the machining conditions that led to the maximum tool life value of 13.25 min were 0.4 mm for the nozzle diameter, 0 mm for the distance between the impact point of the jet and the cutting edge, 50 MPa for the pressure of the jet, 46 m/min for the cutting speed and 0.02 mm/rev for the feed rate. It was also found that the optimal solution was achieved in the 19th generation (iteration) of the BBO algorithm. To verify the performance of this algorithm, the BBO algorithm was compared with several popular metaheuristic algorithms such as the genetic algorithm, particle swarm optimization, and grey wolf optimization. It has been observed that the proposed BBO algorithm yields same values for optimal process parameters that other optimization techniques do. Figure 11 shows the convergence of the BBO algorithm.

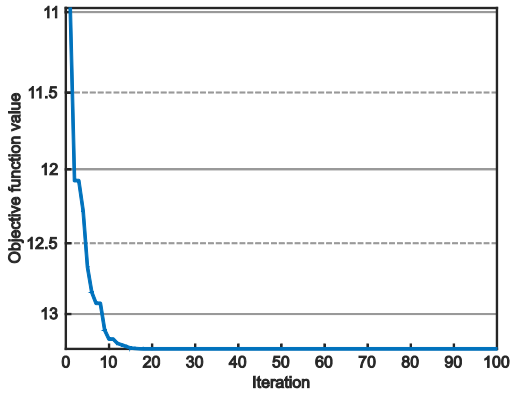

Figure 11. The convergence of the BBO algorithm as a function of iteration step.

4.2. Confirmation Experiment

In order to validate the optimum machining parameters obtained from the BBO algorithm, a confirmation experiment was carried out under controlled conditions. The results of the confirmation experiment with the optimum factor values are shown in Table 4. The combination of machining parameters for the experimental run with the longest tool life (experiment No. 20) was selected for the initial parameter values. With the machining parameters determined before and after optimization, tool life was increased by approximately 8.4%, from 12.88 to 13.96 min. This confirmation test provided satisfactory results and showed that the proposed BBO algorithm improved tool life in high-pressure jet turning of Inconel 718, a nickel-based superalloy.

Table 4. Results of the confirmation experiment with the optimal factor values.

Parameter Settings	Machining Parameters					Tool Life (min)	Improvement (%)
	D (mm)	s (mm)	p (MPa)	v_c (m/min)	f (mm/rev)		
Initial	0.40	0	90	46	0.224	12.88	8.4
BBO	0.40	0	50	46	0.2	13.96	

5. Discussion

Since the analysis of tool life is a time-consuming experiment—tool life is defined as the time until the tool is completely worn out and needs to be replaced, so its study

consumes large amounts of material in addition to the tools—there is a lack of studies in the scientific literature on optimizing the HPJA turning process in terms of tool wear. However, various articles can be found that examine this technology and compare it with conventional turning. In most cases, various authors [6,9–17,19–29] use lower pressures (up to 50 MPa) and higher coolant-flow rates (up to 50 L/min), as much larger nozzles are used.

In the present study, a wider range of pressures (above 50 MPa) and flow rates (nozzle diameter size) are analyzed, as is the position of the jet at the cutting edge, and the influence of these so-called hydraulic parameters on tool life is investigated. From a practical point of view, the results provide information on the selection and optimization of hydraulic parameters in HPJA turning, as no comparable study exists to the authors' knowledge.

A preliminary experiment compares conventional turning of Inconel 718 with flooding and HPJA turning. The analysis shows an improvement in tool life of almost 2.5 times in the case of HPJA. Some other authors [6] report even better improvements in tool life with HPJA (even up to seven times), but these studies used different hydraulic parameters or settings (lower pressures at significantly higher flow rates). When a high-pressure jet is used at flow rates of several tens of liters per minute or almost one liter per second, the application of such a system is limited, as the tightness of the machine must be guaranteed. In addition, the management of the cutting fluid is more demanding under such conditions. In our experiments, the flow rate of the cutting fluid ranged from a few dcl to several liters per minute.

The main experiment is a comprehensive study of the influence of HPJA turning process parameters on tool life. The results show that the cutting speed has the greatest influence. This is not surprising, as it is known from machining theory that this parameter has the greatest influence on heat generation, which in turn has a negative effect on tool durability due to a decrease in hardness. The effects of the other parameters are more interesting. The results show that the applied pressure also has a significant influence on tool life. Increasing the pressure above 50 MPa does not bring any improvements; instead, the reverse is true. The authors believe that higher pressures generate a higher jet velocity, which leads to shorter interaction times for the cutting fluid and the cutting zone. However, pressures below 50 MPa do not provide sufficient flow of cutting fluid for effective cooling when such nozzles are used, as was shown in one of our earlier studies [4]. Based on the empirical model obtained with ANOVA, process optimization was performed with a single objective or criterion: the longest tool life. This model output was optimized when the lowest cutting speed was used in the experiment. This speed is relatively low compared to the recommended values and the results from the evaluated literature, but it leads to a significantly longer tool life. The aim of such an optimization was to achieve a longer tool life for real continuous operations of more than 12 min with a relatively high rate of material removal.

In all cases of HPJA application presented in this study, favorable conditions for chip breaking were created, resulting in acceptable chip shapes. In another paper [30], the authors present a study on chip breaking. In conventional turning, chip breaking is very difficult to control when turning this material. In most cases, long, spiral-shaped chips of unacceptable shape are produced.

6. Conclusions

In this study, tool life during HPJA turning of Inconel 718 is experimentally investigated. A preliminary comparison is made between conventional flooding and HPJA. In the main experiment, an orthogonal L27 array is used to optimize tool life as a function of five machining parameters: nozzle diameter, jet distance, pressure, cutting speed and

feed rate, each at three levels. The influence of these parameters on tool life is analyzed in order to improve the efficiency of the cutting tool. The most important results are summarized below:

- HPJA machining is undoubtedly capable of creating machining conditions that extend tool life compared to conventional flood cooling when turning difficult-to-machine materials, namely the nickel-based alloy Inconel 718, with carbide inserts.
- The results show that the dominant factor influencing tool life is cutting speed, which accounted for almost 74% of the total variability of the model. Other factors that have a significant influence on tool life are, in descending order, the pressure of the jet, the feed rate and the distance of jet impact. The results show that the nozzle diameter has an influence on tool life only in interaction with the cutting speed. The product (v_c^2) also appears to be significant. The results revealed that a significant increase in tool life can be achieved when the cutting speed is reduced. According to the results presented, tool life increases with a reduction in jet pressure. The results also show that the lower the feed rate and the jet impact distance, the longer the tool life, while the smaller the nozzle diameter, the shorter the tool life.
- Jet pressures above 50 MPa do not improve tool life; in fact, they reduce it due to the shorter coolant-interaction time caused by higher jet velocities.
- Non-dispersed water-jet nozzles enable precise targeting and effective cooling/lubrication with lower flow rates, improving tool life compared to standard HPJA systems.
- A mathematical model for tool-life prediction in HPJA machining of Inconel 718 was developed based on RSM. The formulated mathematical model is statistically significant and very useful for prediction purposes.
- Based on the BBO algorithm, the optimum parameter combination for tool life was determined to be D = 0.4 mm, s = 0 mm, p = 50 MPa, v_c = 46 m/min and f = 0.2 mm/rev.
- A confirmation test validated the results of the optimization and showed an improvement in tool life of 8.4% under optimal conditions compared to the best result of the 27 experimental runs.

Author Contributions: Conceptualization, D.K. and D.C.; methodology, D.K. and D.C.; validation, D.K. and D.C.; formal analysis, D.K. and D.C.; investigation, D.K. and D.C.; resources, D.K.; data curation, D.K.; writing—original draft preparation, D.K. and D.C.; writing—review and editing, D.K. and D.C.; visualization, D.C.; supervision, D.K. All authors have read and agreed to the published version of the manuscript.

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