

Article

Influence of Coolant Properties and Chip Former Geometry on Tool Life in Deep Drilling

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Abstract: The aim of the article is to find a correlation between a change in the properties of the cooling agent and a change in the geometry of the chipformer, as both are reflected in the service life of the tool after deep drilling. The reason for carrying out the research is the requirement of practice to obtain the economic efficiency of the production of such a demanding process as deep drilling. When applying the latest designs of gun drills, it is very important to correctly set the technological parameters to maintain the stability of the cutting process. One of the most important parameters is the correct removal of heat from the cutting site, and this will be ensured by the stability of pressure, temperature, and percentage of emulsion in the cooling medium, as well as the adjustment of the geometry of the chip former. On this basis, a large number of tests were carried out, consisting of testing the number of drilling cycles carried out by new, unfluted gun drills at constant feed rates and spindle rotation frequencies. After testing, it is possible to modify and supplement the existing methodology of deep drilling technology in terms of managing the cooling emulsion and chip-forming geometry. The tests were aimed at increasing the service life and the number of possible re-grindings of the gun drills depending on changes in the percentage of the emulsion concentration, the pressure and temperature of the cooling agent, and the associated chipformer geometry.

Keywords: chipformer geometry; deep drilling; tool life; feed rate; spindle speed; emulsion concentration; cooling agent



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1. Introduction

The current time in the engineering industry places great demands on the reduction of the time needed for production preparation, preferably by rationalizing the process by applying new methods and techniques in the development process. One such technology is the process of deep drilling, where it is necessary to create holes up to ten times deeper than their diameters. Deep drilling is most often used in the automotive industry, utility vehicles, aerospace, medicine, and, of course, mechanical engineering manufacturing.

Standard drilling tools demonstrate low service life in deep holes and do not meet the necessary cutting conditions. Their design does not satisfy the conditions for a sufficient supply of cooling agent, which is also associated with heat dissipation from the site of the cut, as well as insufficient chip removal, which is one of the most important principles in drilling deep holes. Conventional machines can be applied to deep drilling technology. Making holes of greater lengths is, however, limited by their design, and, therefore, for maximum depth and productivity, special machines are developed, the design and properties of which are tailored to deep drilling.

Drilling is defined as a technological process resulting in holes of circular cross-section. Their depth depends on the design requirements, and it is often necessary to drill holes five times the depth of their diameter. This operation is called deep drilling. The deep drilling

technology is much more demanding on the cutting process than the drilling of standard holes of less than $5xD$. In the past, holes with a length-to-diameter ratio greater than $3\text{--}5xD$ were considered deep holes, but nowadays, thanks to modern procedures and technologies, we consider holes with a diameter of up to $10xD$ to be deep holes.

The constant effort to streamline production forces engineering companies involved in the development of drill bits to come up with new solutions for conventional helical drill bits capable of drilling holes that have a length-to-diameter ratio of up to 30 mm.

Monolithic long screw drill bits, STS 22 1130 and STS 22 1150, or drill bits with internal cooling, STS 22 1154, are used for drilling deep holes. Because the drill bits' flutes are quickly filled with chips, the drill bits are pulled out of the cutting holes to cool and remove the chips. Such drilling is called intermittent work cycle drilling. Solid carbide (TK) drill bits work similarly to HSS drill bits. These are produced up to a maximum length of $30xD$ and always come with internal cooling. Thanks to the drill bit's internal cooling, an intermittent work cycle need not be applied. In order to be able to drill in one cycle, it is necessary to pre-drill a pilot hole, the depth of which must be at least $3xD$. Since monolithic solid carbide drill bits are quite expensive and the solid carbide body is fragile and does not allow for application under any conditions, e.g., in older machines with increased vibration or with the product itself prone to vibration, it is possible to use a drill bit with a replaceable tip. The solid body of such a drill bit can withstand higher vibrations, but at the cost of reduced machining conditions. Another advantage is the simple replacement of the worn tip without further tool alignment.

The gun drill is a tool with one cutting edge that contains internal flushing and external chip removal. It contains an external, direct V-shaped pipe and, at the same time, an inner hole for the cooling medium. The fluid flows through the axis of the tool, circling the cutting blade and flushing the emerging chips through an external path out of the hole.

The gun drill has three basic parts: a drill head, a drill pipe, and a shank (Figure 1). The drill head is typically carved from carbide, but in the case of larger diameters, it can be composed of steel with carbide elements bonded thereto. The guide surfaces of the head are fluted along its circumference, and they are in contact with the drilled material in the course of drilling. For larger diameters, replaceable elements (plates and guide surfaces) are widely used nowadays.

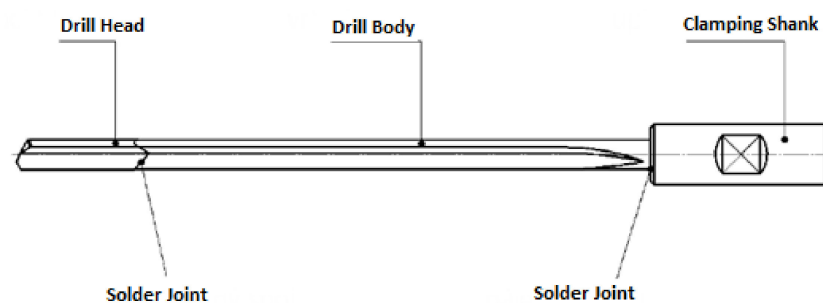


Figure 1. Description of the gun drill.

The drill pipe is typically composed of high-quality stainless steel with a V-shaped groove engraved into it for chip removal. The drill pipe is connected to the drill head with silver solder. All-carbide gun drills are produced for the smallest diameters. Their head and pipe are composed of a single piece of carbide. This instrument has significantly higher stiffness. Only the invention of the all-carbide gun drill made it possible to produce gun drills with a diameter of less than 2 mm and allowed the use of higher feed rates. The fastening shank is used to clamp the tool in the holder. The fastening of the gun drill depends mostly on the type of machine tool used. In conventional machines, the milling cutter-lathe's greatest advantage is ensured by using hydrostatic clamping, in which the fastening shank is smooth and facilitates quick replacement while maintaining the best stiffness and clamping force.

Long-term research in this area shows that the main parameters that significantly affect the tool life in the deep drilling process are the type of tool, the machine used, the material of the machined part, the geometry of the tool, and the cooling medium used. It is the last two parameters that are the subject of our research, as the manufacturers provide a fairly wide range of recommended values for the parameters of the cooling medium, such as concentration, pressure value, and temperature of the cooling medium. The goal is to find the optimal parameter of these parameters in order to obtain the maximum service life of the tool while maintaining the high economic efficiency of the deep drilling process. The request to carry out the research came from the tool sellers themselves, in order to supplement the methodology of the deep drilling process and maximize the life of the tools used.

2. State of the Art

Deep drilling is currently used in various industries, such as mechanical engineering, construction, geological surveying, etc. The main task of this technology of drilling is to correctly determine the drilling process parameters and the correct selection of the tool [1,2].

The most important parameters are rotational speed, torque, and contact force. The correct choice of parameters depends on the strength of the drilled material, the diameter of the drilled hole, and the force exerted in the process of the hole-drilling [3–5]. The correct selection of parameters with optimal settings can be monitored in real time by a suitably selected sensor involved in the drilling process [6,7].

The paper by Biermann D. et al. presents an overview of several methods applied to the creation of holes with a large length-to-diameter ratio of the tool. The authors focused on the description of the basic principles of hole formation using deep drilling technology with regard to the quality of the drilled hole when using different types of workpiece materials. In conclusion, they summarized the results of the development of the deep drilling process and the production of tools around the world [8].

Deep holes are formed by conventional or unconventional methods. The article by Chandar J.B. et al. compares the methods of this drilling process based on the results achieved in research by several authors from around the world who investigate this area. These are conventional methods of drilling deep holes, such as, e.g., Gun Drilling (GD), Boring and Trepanning Association (BTA) deep-hole drilling, and Single Lip Drilling (SLD), and unconventional methods such as Electro-Chemical Machining (ECM), Laser Beam Machining (LBM), Electro Discharge Machining (EDM), and Abrasive Water Jet Machining (AWJM). They elaborated and described in detail the parameters entering the drilling process under individual methods and the direction of the research activity in this area of hole formation technology [9].

In their paper, the authors of Hoang T.D. et al. focused on the description of a new lubrication method in the process of deep drilling stainless steel AISI SUS 304. The new lubrication method consisted of creating a “nanofluid” by adding a graphene nanolayer to the soluble emulsion and then mixing the two substances with water. The results showed that the created nanofluid provides a 4.4-fold reduction in drilling torque, resulting in a 20-fold increase in the life of the cutting tool compared with the use of a conventional emulsion lubricant. Furthermore, the authors dealt with the optimal setting of cutting parameters using the Taguchi L9 experiments, the results of which they presented and which are suitable for further exploration of this hole production technology [10].

The authors, Oezkaya E. et al., used combined simulation methods to analyze the behavior of cutting fluids for tool cooling and chip removal. The analysis pointed to the need to adjust the cross-sectional area of the internal cooling channel as well as the internal and external angles of the cutting edge. As a result, the drilling process was optimized by 40% by adjusting the cutting fluid speed and by 60% in terms of chip removal [11].

Authors Yu D.G. et al. studied the reduction in deviations emerging in deep hole drilling through the proposed hydrodynamic lubrication. They designed a centering device with Archimedes spirals that was fastened between the drill tool and the drill pipe to create three wedge oil films to prevent the drilling system from deflecting [12].

A study by Baumann A. et al. looked at the distribution of cutting fluid and chip removal during microcurvature drilling of deep holes using 3D multi-physical simulation methods [13].

The authors, Oezkaya E. et al., dealt with the mechanical load and the formation of chips when drilling deep holes using various cooling agents. In the experiments, they drew on changes in the settings of the feed force, torque, quality of the hole created, and tool wear. In the simulation they proposed, they presented an optimal passage of the cooling lubricant during the drilling process for the needs of chip formation in the drilling process with reference to its final shape [14].

The authors, Nomura M. et al., dealt with the description of small-diameter deep hole drilling into thermoplastic PEEK resin. The study looked at the effect of heat in the absence of stepwise drilling of holes into plastic materials with lower thermal conductivity than that of a drilling tool composed of metal, which eliminated the need for cooling of the drilled hole in the form of a cold gas used to ensure the required accuracy of the hole formed [15].

3. The Importance of Coolant in Deep Drilling Technology Using a Gun Drill

The basic function of the cutting fluid in deep drilling is to reduce wear and extend the life of the tool. When drilling deep holes, cooling fluids and their correct selection for a particular workpiece material are extremely important. For example, if we were to drill into steel, the main requirement for cutting fluid would be its cooling ability, while in drilling into aluminum, the main requirement is lubrication. On special drilling machines, cutting oil is used, which is the best cooling agent. As a rule, mineral oil is used with additives that enhance its parameters. The main requirements for the cutting fluid function are the following:

- Cooling of the cutting part of the tool;
- Reducing friction between the tool and the workpiece, thereby reducing torque values;
- Reliable chip removal from the drilled hole;
- Avoidance of expansion on the cutting part of the tool, thereby favorably affecting the roughness of the drilled hole;
- Damping of the tool's vibration.

On conventional machines, oil and synthetic emulsions are used for gun drilling. The emulsion should account for between 10 and 15% since water does not have a good lubricating effect, which is very important for the guide surfaces.

Another option is to use compressed air with oil aerosol (MQL). This method is the least effective, but it also allows for application in machines that are not equipped for internal cooling and do not have the necessary cladding for the work area. The air under pressure carries tiny droplets of oil into the cutting process, which ensures lubrication and, at the same time, performs the chip flushing function. The effect of the cutting fluid is enhanced if it is fed to the site of cutting under higher pressure. When drilling deep holes, cutting oils are used in some drilling operations. For drilling stability and tool life, the pressure and flow of the coolant are also important. The individual pressure values depend on the diameter of the hole and the hole's length. The recommended values are given in Figures 2 and 3.

For oils and emulsions, filtration is also very important, as it is also involved in increasing the durability of the tool. It should be able to capture particles of 5–10 µm in size, usually by centrifuge or magnet.

The correct geometry of the tool is also important for the efficient supply of coolant to the site of cutting. The cutting speed acting on the cutting blade decreases from the circumference towards the axis of rotation. In the middle, the speed is zero, which poses a disadvantage for the tool. A classic two-point drill bit is significantly stressed in the place of the transverse blade. These adverse effects are reduced in a gun drill through its asymmetrical geometry, as it is a single-pointed tool, and the tip of the drill bit does not lie on the axis of rotation but, as a rule, in 1/4 of the diameter. As a result, the distribution of cutting forces (Figure 4) is unbalanced, and the resultant forces have a significant radial component that acts in the direction of the first guide surface.

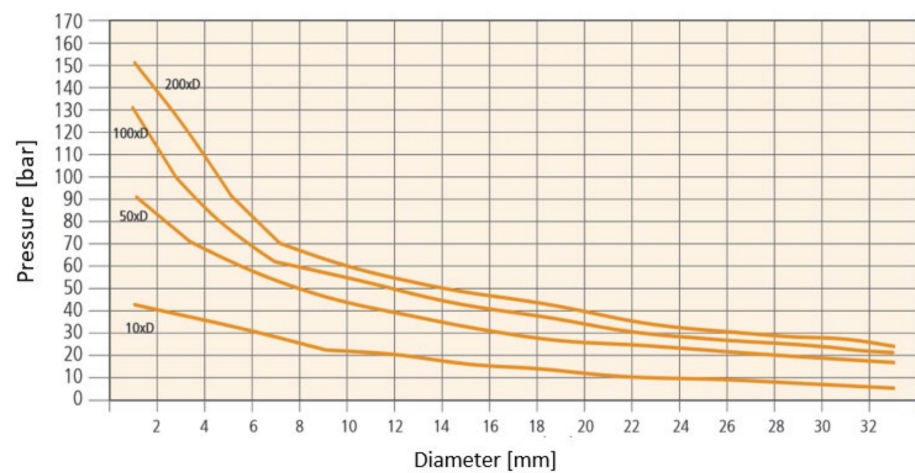


Figure 2. Coolant pressure.

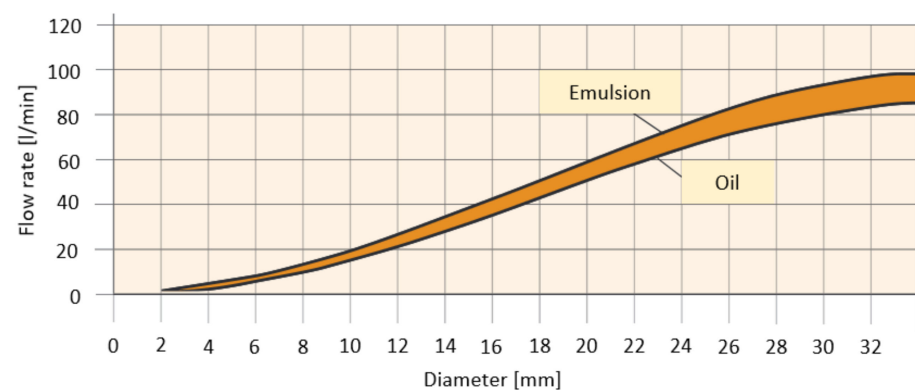


Figure 3. Coolant flow rate.

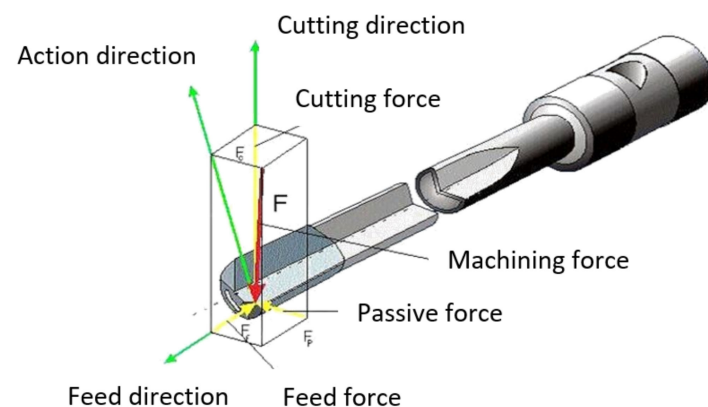


Figure 4. Distribution of cutting forces.

If it is necessary to reduce the vibration of the tool or improve the surface machining, it is necessary to increase the pressure on the guide surfaces, which can be achieved by grinding the damping flute slightly beveled on the outside or by moving the tip of the drill bit closer to the axis of the drill. Another adjusting option is to create a deeper oil flute in the stainless steel part of the tool. This will increase the space for the coolant to pass into the flush groove and improve chip removal. On the other hand, this will reduce the flow of fluid through the inner part of the cutting blade. In cases of chip-forming problems, a longitudinal or transverse chip-forming device is used. The longitudinal chip-forming device is sanded directly by the manufacturer and does not need to be adjusted during re-grinding. The transverse chip-forming device must be sanded with each re-grinding.

The setting of cutting parameters is subject to many factors, such as the material drilled, the type of gun drill used, the use of coolant, the stability of the cutting process, the clearance in the machine, the subsequent vibration, etc. Our choice of cutting parameters also influences the resulting machining time, which is directly related to the tool life. If the cutting parameters are increased due to the need to meet production plans, the life of the drill bit decreases. Therefore, a series of tests is usually carried out in practice to determine the parameters that correspond to the production plans but, at the same time, maximize the service life of the tool.

4. Testing the Impact of Changing the Coolant Parameters on the Service Life of the Gun Drill

The testing was carried out directly in the production plant, with a focus on the production of automotive components. The production machine used for testing in the real production process was the aligning and boring machine with a portal loader by CZ-Tech Celakovice, the ZAH620. Two heads were used on the ZAH720, the right head for VDI clamping and the other for Bolt-one, and the tool holders themselves are from ALGRA. The tool was clamped with an extremely short Tendo EC clamp. As a result, the highest clamping forces are available for the transmission of higher torques, as well as more space in the machining area of the machine.

The life of the tool was tested on a TBT cannon drill designated TBT 10.5×380 K15, with a diameter of 10.5 mm and a total length of 380 mm. The tool head is composed of carbide and coated with TiAlN coating in order to increase the life of the tool.

The shaft of a 6-speed gearbox was used as a test product. The semi-finished product for performing the test is a forging composed of the material STN EN 14220, EN 10084-94, or EN 84-70 16CrMo5. The drilling process consisted of drilling a hole in the shaft with a diameter of 10.5 mm and a depth of 240 mm. This opening serves the final product as an opening for lubrication and, at the same time, reduces its final weight. At the end of the shaft, there is a lubrication hole with a diameter of 3 mm. In order to prevent the formation of sharp points, the following technological procedure for the creation of the hole was proposed: In the first step, drilling with a diameter of 10.5 mm is carried out to the full required depth. In the second step, a perpendicular hole with a diameter of 3 mm is drilled. In the last step, the drilling cycle from the first step is repeated, which aims to remove the chips from the second step. It should be emphasized that during the last step there is increased wear of the side cutting edge of the gun drill, as in this case it is an interrupted cut.

To carry out the tests, it was necessary to create a guide pilot hole where a hole with a diameter of 10.5 mm and a depth of 14.5 mm was pre-drilled with a K40UF carbide drill from Konrad Friedrichs. The test of the deep drilling process took place at a constant feed rate of 0.04 mm^{-1} and a constant spindle speed of 2600 rpm.

4.1. Applied Coolant

The main function of the cutting fluid is efficient heat dissipation from the site of cutting by perfect cooling or lubrication to reduce internal and external friction through consistent means such as powder lubricants, which reduce friction but do not allow for intensive heat dissipation from the site of the cut. These means are rarely used, for example, in thread cutting or in some special machining operations. In addition to the cooling and lubrication effects, the cooling fluids also have a cleaning function, but they must not corrode the machine or pose a hazard to health. The choice of coolant is assessed according to

- The quality requirements for the component machining;
- Chip-forming mechanism;
- The characteristics of the material being machined;
- The characteristics of the tool material used.

The Quaker 3755 BIO KS coolant was used in the testing, representing a versatile, polysynthetic, cutting, and abrasive fluid that is suitable for use in a wide range of metalworking operations for aluminum and iron alloys. The QUAKER 3755 BIO coolant is diluted with water in concentrations ranging from 2–10% to produce a milky cooling emulsion. The exact concentration required will depend on the intensity of the application. The product is suitable for use with water with a hardness of up to 300 ppm CaCO_3 .

The advantages of cooling emulsion prepared in this way are as follows:

- Stable lubrication for high-quality surface treatment;
- Excellent corrosion protection for machined parts;
- No sticky residues on the workpiece;
- Phosphate-, sulfur-, or chlorine-free;
- It is biostatic and free of triazine.

The cooling of the tool in the machining device is ensured by a system of devices consisting of a low-pressure pump, a high-pressure pump, a filter, and a magnetic filter for small metal particles. The low-pressure pump provides the necessary pressure for standard cooling of the turning tools and the pilot drill bit, their lubrication, and de-chipping. In this case, a Wall Plus pump is used, which supplies the coolant at a pressure of 18 bar and a flow rate of 10.5 L/min. The pump used for standard cooling, the high-pressure pump, and the filter unit can be seen in Figure 5.



Figure 5. Standard cooling pump, high pressure pump, and Mahle filter unit.

To cool the gun drill, a Grundfos MTS high-pressure pump is used, the technical parameters of which are listed in Table 1. The Grundfos MTS high-pressure pump is a screw pump designed for pumping lubricants and cooling oils in machine tools, where the required pressure is about 40 bar. These pumps are designed to be mounted on top of the tank. They consist of two main elements, namely the engine and the hydraulic part.

Table 1. Parameters of the high-pressure pump used.

Pump Type	MTS 20–40
Flow	22.3 L/min
Pressure	40 bar
Power	2.4 kW
RPM	2900 min ^{−1}
Frequency	50 Hz
Viscosity	1 mm ² /s

During the drilling process, it is necessary to keep the coolant at the desired temperature. This is ensured by a cooling unit from JDK-WDE-S1K (up to 43 kW) with a plate evaporator of the box design, a built-in storage tank, and a pump.

4.2. Dependence of the Drill Bit Life on the Coolant Properties

The main function of the coolant is effective heat dissipation from the site of cutting and—through lubrication—to reduce internal and external friction. The main requirements for a coolant to be effective are pressure, emulsion percentage, temperature, and the cutting fluid flow rate. These parameters have been tested to determine their impact on tool life. The fluid flow rate has not been tested as the cooling equipment used does not allow it to be controlled and has been set to the constant flow rate of 22.3 L/mm, as recommended by the manufacturer. The testing was completed at the moment of damage to the drill bit, which can be seen in Figure 6.



Figure 6. Example of damage to the drill bit.

In general, the mechanism of wear of the drill bit mainly involves diffuse wear, adhesive wear, oxidative wear, and breakout. The cutting heat comes from the shear deformation of the materials, the friction between the contact surfaces, between the drill bit and the workpiece, and between the continuously removed chips. Heat formation increases above the melting point temperature of the alloy elements (for example, Co and W) and the hardness. The chemical resistance of the tip of the drill will decrease dramatically due to the peeling off of the alloy elements, too. Cyclic stress will cause mechanical and thermal shock during high-speed drilling. Mechanical shock subsequently gives rise to parallel cracks, and thermal shock gives rise to perpendicular or oblique cracks in the blade. These cracks expand, merge, and break the blade.

The first test was aimed at monitoring the life of the gun drill at different concentrations of cooling emulsion, namely 6%, 9%, 12%, and 15%, respectively, under a pressure of 35 bar. The resulting values of the gun drill life at different emulsion percentages are shown in Figure 7.

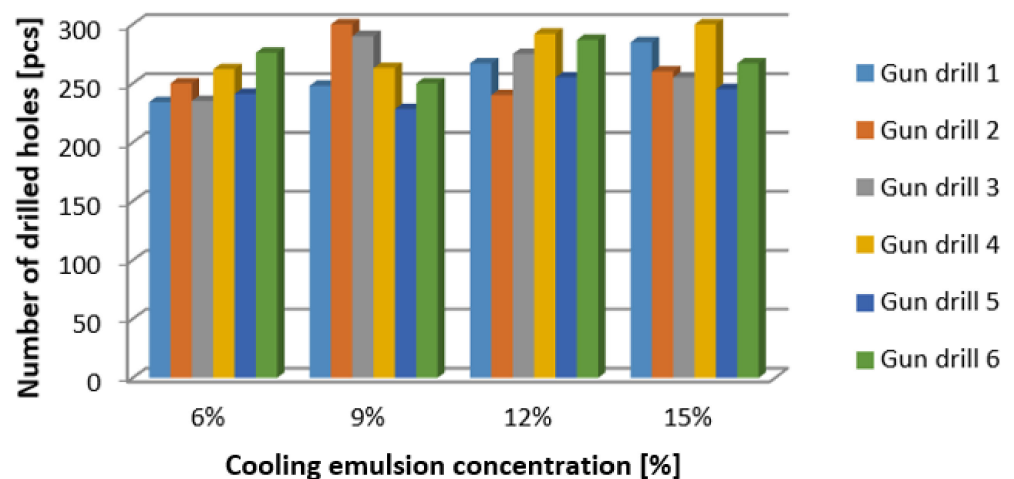


Figure 7. Plotted number of drilled holes up to the point of tool damage at different concentrations of the cooling emulsion.

Life values show a decreasing lifespan at an emulsion percentage below 9%. From the resulting life values, it is recommended to set the emulsion percentage value to 9%. The higher percentage of emulsion did not have a significant impact on the tool life.

The second test was aimed at monitoring the life of the gun drill under a change in pressure of the cooling emulsion ranging from 20 to 45 bar at its 9% concentration. The resulting values of the gun drill life under different emulsion pressures are shown in Figure 8.

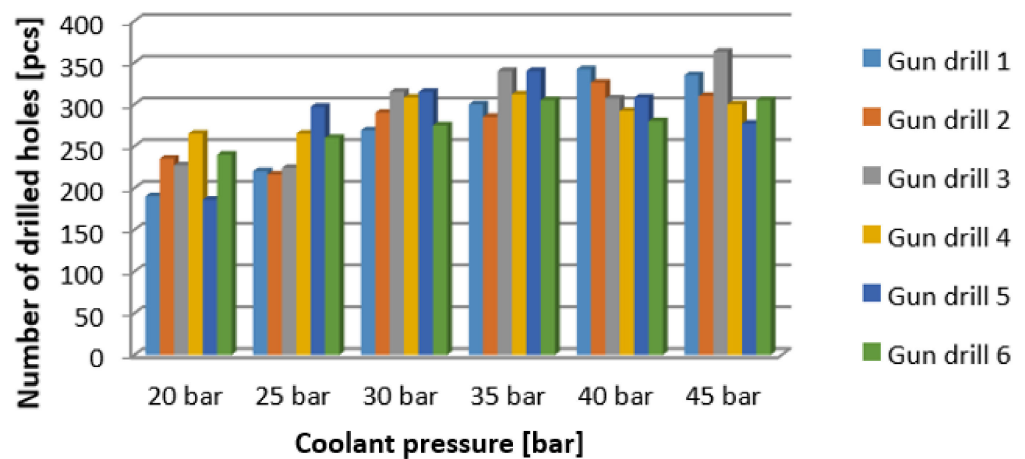


Figure 8. Plotted number of drilled holes up to the point of damage to the tool under different coolant pressures.

Tool life values show an increasing trend under emulsion pressure above 30 bar. From the resulting lifespan values, it is recommended to set the fluid pressure value to 35 bar. Higher emulsion pressure has only a small impact on the tool's life.

The last test was aimed at monitoring the life of the gun drill under a change in the temperature of the cooling emulsion ranging from 25–32 °C at 9% emulsion concentration and a constant pressure of 35 bar. The resulting values of the gun drill life under different temperatures are shown in Figure 9. The life values do not show an increased lifespan with the change in temperature that we were able to achieve on the refrigeration equipment.

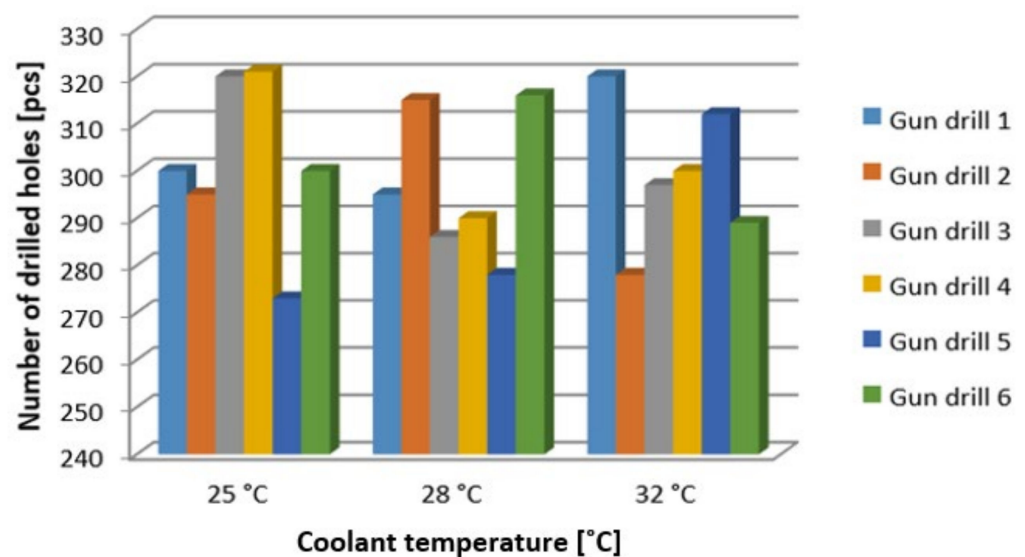


Figure 9. Plotted number of drilled holes up to the point of damage to the tool at different coolant temperatures.

During the testing, the influence of the pollution of the cooling medium was also manifested by adhesive damage on the guide surface of the gun drill. When it comes to adhesive damage (Figure 10) to the guide surface of the gun drill, it is necessary to immediately check the coolant filter and the percentage value of the cooling emulsion. This damage reduces the number of re-grindings of the drill bit and its reuse.

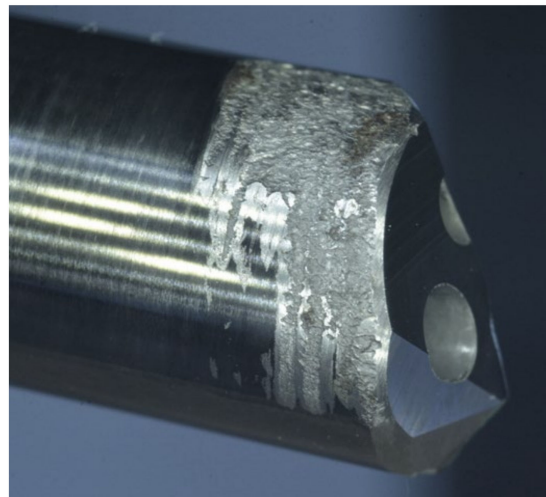


Figure 10. Adhesive damage to the drill bit.

Subsequently, the impact of changing the geometry of the chipformer on its service life was also examined. The wear of the cutting edge is largely manifested on its outer blade, which is exposed to the highest circumferential speed and the greatest torque force. At the same time, that part of the blade is compromised by the longitudinal chipformer, which contributes to the weakening of the outer tip of the cutting blade. Based on the findings, a solution was proposed consisting of a reduction of the blade shaper and thus the strengthening of the outer tip. The shapers are compared in Figure 11.

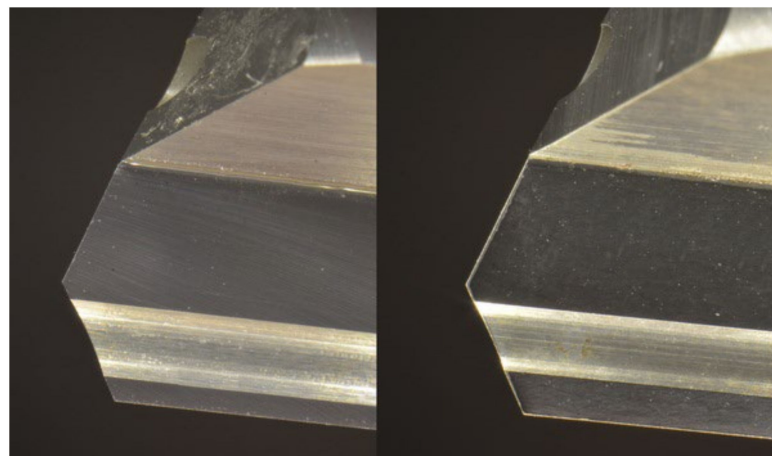


Figure 11. Gun drill with standard chipformer and gun drill with reduced chipformer.

The plotted representation of the service life of the gun drill's version with a standard chipformer and a gun drill's version with a reduced chipformer shown in Figure 12 makes it evident that the service life of the gun drill with a standard chipformer is significantly higher. The reduction in the chipformer caused a deterioration in chip formation and, consequently, a greater drill bit wear.

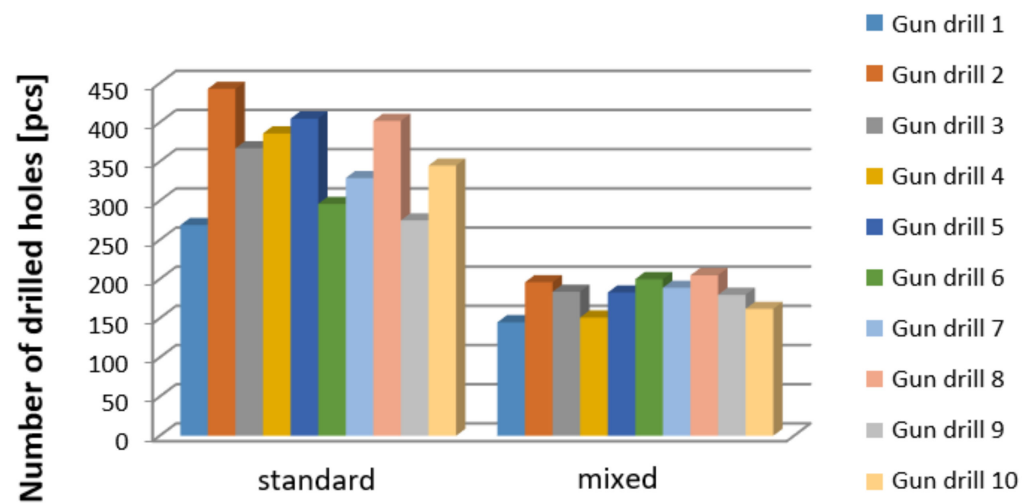


Figure 12. Plotted representation of the drill bit's life when geometry of the chipformer has been changed.

5. Statistical Evaluation of the Impact of the Cooling Agent Parameters on the Gun Drill Life

Mathematical statistics deals with mass phenomena and serves the purpose of objectively predicting their behavior, where statistical prediction is based on knowledge of the laws governing mass phenomena. On the basis of the data known about the previous course of development of a particular system, this will allow us to predict its future development to some extent.

The first statistical evaluation is that of monitoring the life of the gun drill at different concentrations of cooling emulsion, namely 6%, 9%, 12%, and 15%, respectively, at 35 bar pressure. A plotted comparison of the tool life in terms of the cooling emulsion concentration is shown in Figure 13.

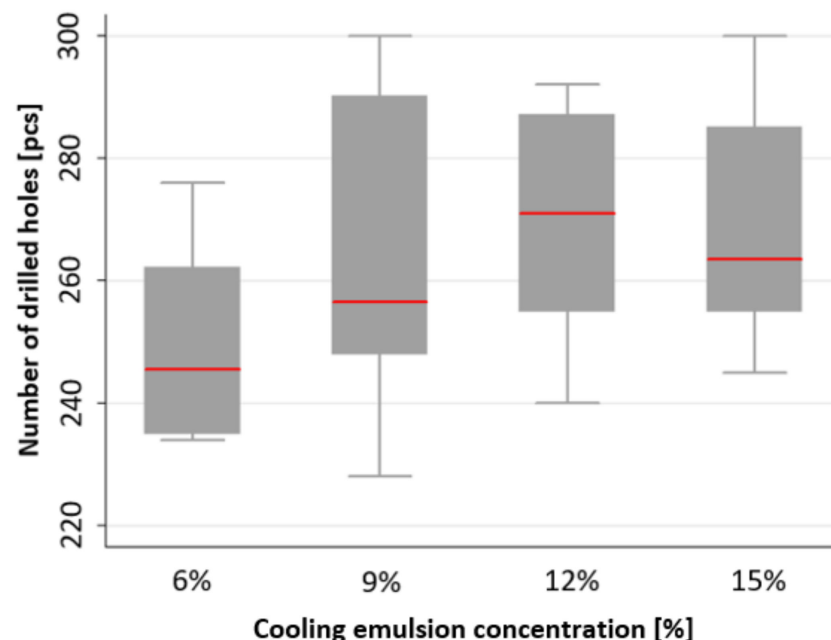


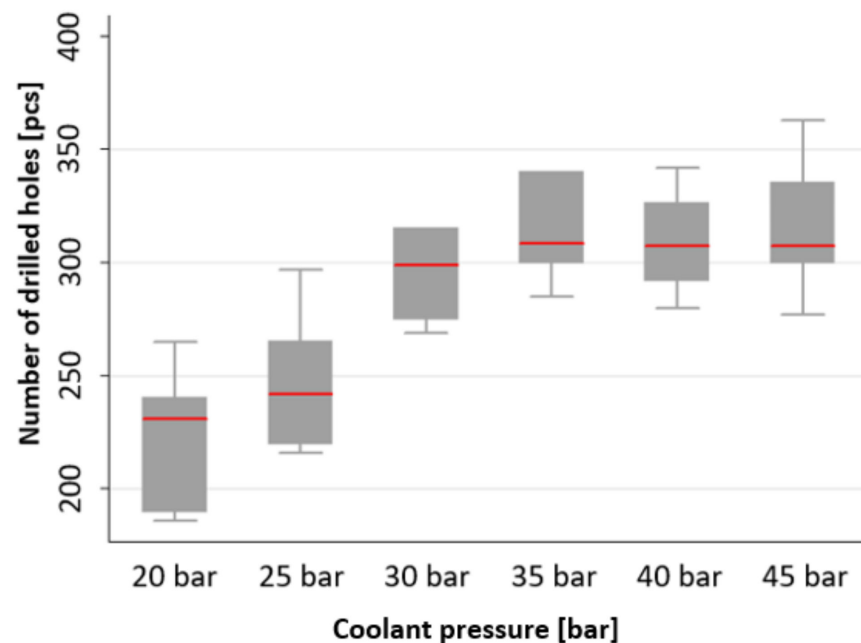
Figure 13. Plotted comparison of the tool life in terms of the cooling emulsion concentration.

From the value of the achieved level of significance of the Kruskal–Wallis scatter analysis ($p = 0.3522$), it can be concluded that there is no significant relationship between the concentration of the cooling emulsion and the tool life at the level of significance of 5%, as shown in Table 2.

Table 2. The result of the comparison of the tool life under different cooling emulsion concentrations.

Kruskal–Wallis ANOVA by Ranks; Drill Life (Analysis) Independent (Grouping) Variable: Emulsions of Cooling Liquid [%] Kruskal–Wallis Test: $H(3, N = 24) = 3.267349, p = 0.3522$				
	Code	Valid N	Sum of Ranks	Mean Rank
6%	1	6	49.50000	8.25000
9%	2	6	75.00000	12.50000
12%	3	6	89.00000	14.83333
15%	4	6	86.50000	14.41667

The second statistical evaluation is that of monitoring the gun drill life at different concentrations of cooling emulsion, namely 6%, 9%, 12%, and 15%, respectively, at 35 bar pressure. A plotted comparison of the tool life under the changed pressure of the cooling emulsion is shown in Figure 14.

**Figure 14.** Plotted comparison of the tool life under changing cooling emulsion pressures.

From the value of the achieved level of significance of the Kruskal–Wallis scatter analysis ($p = 0.0005$), it can be concluded that there is no significant relationship between the concentration of the cooling emulsion and the tool life at the level of significance of 5%, as shown in Table 3.

Table 3. The result of the comparison of the tool life under different coolant pressures.

Kruskal–Wallis ANOVA by Ranks. Tool Life (Analysis). Independent (Grouping) Variable: Coolant Pressure. Kruskal–Wallis Test: $H(5, N = 36) = 22.07260, p = 0.0005$				
	Code	Valid N	Sum of Ranks	Mean Rank
20 bar	1	6	34.5000	5.75000
25 bar	2	6	50.5000	8.41667
30 bar	3	6	126.5000	21.08333
35 bar	4	6	154.0000	25.66667
40 bar	5	6	148.5000	24.75000
45 bar	6	6	152.0000	25.33333

Table 4, showing multiple comparisons of the values, leads to the further conclusion that a statistically significant difference in tool life is observed at a cooling emulsion pressure of 35 bar, 40 bar, and 45 bar compared with 20 bar.

Table 4. Results of multiple comparisons of tool life values in terms of coolant pressure.

Multiple Comparisons: z' Values; Tool Life (Analysis). Independent (Grouping) Variable: Coolant Pressure.						
Kruskal–Wallis Test: H (5, N = 36) = 22.07260, $p = 0.0005$						
	20 bar R: 5.7500	25 bar R: 8.4167	30 bar R: 21.0830	35 bar R: 25.6670	40 bar R: 24.7500	45 bar R: 25.3330
20 bar		0.438397	2.520784	3.274280	3.123581	3.219480
25 bar	0.438397		2.082387	2.835883	2.685183	2.781083
30 bar	2.520784	2.082387		0.753495	0.602796	0.698696
35 bar	3.274280	2.835883	0.753495		0.150699	0.054800
40 bar	3.123581	2.685183	0.602796	0.150699		0.095899
45 bar	3.219480	2.781083	0.698696	0.054800	0.095899	

The third statistical evaluation is aimed at monitoring the service life of the gun drill at different temperatures of the cooling emulsion. A plotted comparison of the tool life is shown in Figure 15.

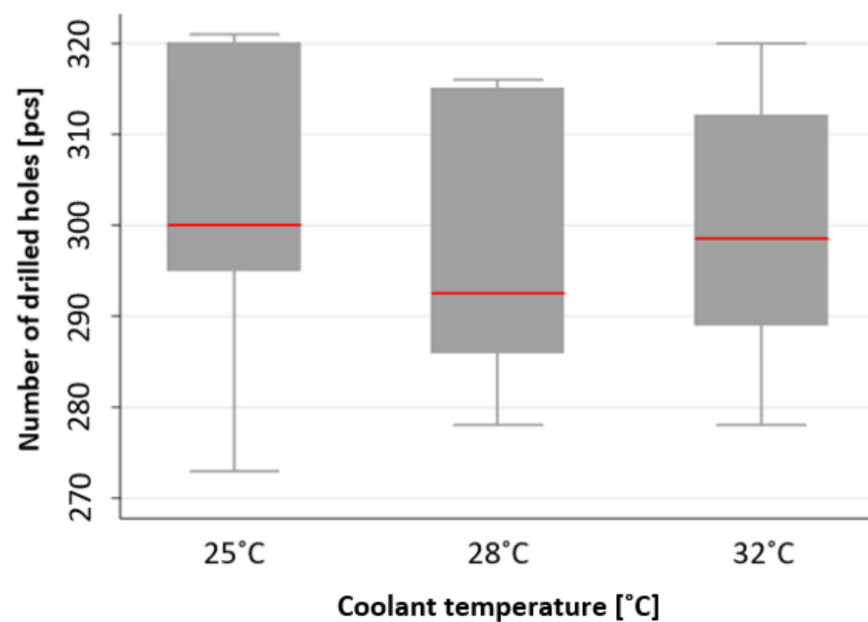


Figure 15. Plotted comparison of tool life in terms of coolant temperature.

From the value of the achieved level of significance of the Kruskal–Wallis scatter analysis ($p = 0.6859$), it can be concluded that there is no significant relationship between the temperature of the cooling emulsion and the tool life at the level of significance of 5%. The results of the comparison are shown in Table 5.

Table 5. The result of the tool life comparison in terms of the coolant temperature.

Kruskal–Wallis ANOVA by Ranks: Tool Life (Analysis) Independent (Grouping) Variable: Emulsion Temperature.				
Kruskal–Wallis Test: H (2, N = 18) = 0.7539848, $p = 0.6859$				
	Code	Valid N	Sum of Ranks	Mean Rank
25 °C	1	6	65.00000	10.83333
28 °C	2	6	49.00000	8.16667
32 °C	3	6	57.00000	9.50000

The last statistical evaluation is aimed at comparing the life of the drill bit under a changed chipformer geometry, which is shown in Figure 16.

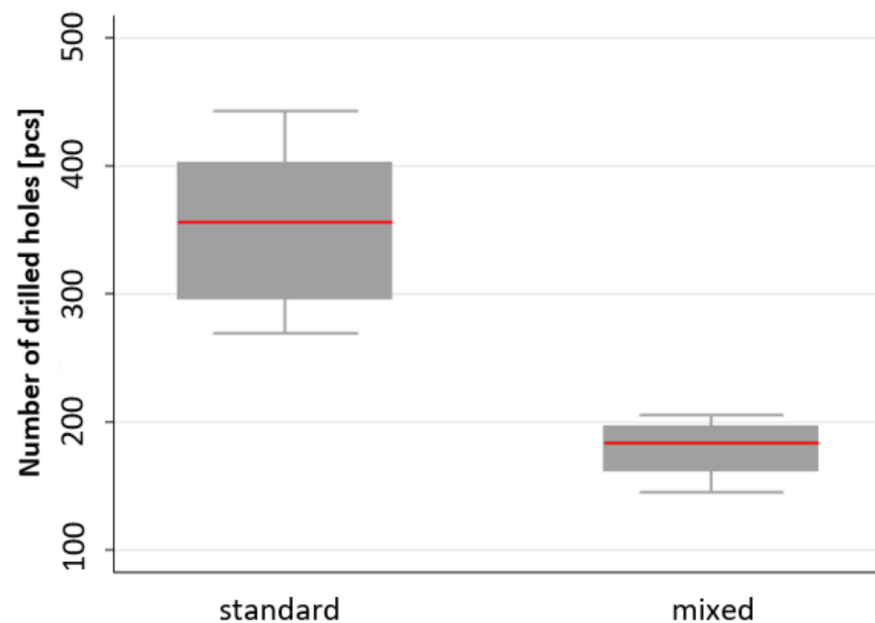


Figure 16. Plotted comparison of tool life in terms of the chipformer geometry.

Based on the significance level achieved in the nonparametric Mann–Whitney test ($p = 0.000183$), it can be concluded that there is a significant difference in tool life between the standard and the reduced tool at the significance level of 5%. The graph shown in Figure 16 makes it clear that the reduced tool has a shorter life than the standard tool. The overall result of the tool life comparison in terms of the chipformer geometry is presented in Table 6.

Table 6. The result of the tool life comparison in terms of the chipformer geometry.

Mann–Whitney U Test (w/Continuity Correction) (Analysis) By Variable Chipformer Geometry										
Marked Tests are Significant at $p < 0.05000$										
	Rank Sum Standard	Rank Sum Reduced	U	Z	p-Value	Z Adjusted	p-Value	Valid N Stand.	Valid N Reduced	2*1sided Exact p
Tool life	155.000	55.000	0.00	3.741848	0.000183	3.741848	0.000183	10	10	0.000011

6. Conclusions

Increasing the efficiency of production places new demands on companies to apply new concrete solutions and innovations for improving the usual procedures and methodology of product production. The arrival of new technological solutions and the current increase in consumer demands result in companies actively engaging in research and development tasks in the production of their products. Deep drilling technology is also one of the most important technological operations for the engineering industry. Despite this, there are no exact methodologies for the application of this technology; there are only recommendations from tool manufacturers for this technology, which only provide a wide variability of all technological parameters. Based on the requests from the companies, several research tasks devoted to the processing of the methodology, including its correlations, were carried out. Extensive tests were carried out directly on the premises of manufacturing companies, not in laboratory conditions.

On the basis of extensive tests and subsequent statistically processed data, the cooling agent parameters were correlated with the deep drilling technology. It can be stated that

in terms of the concentration of the coolant used, the sufficient percentage of emulsion is >9%, while the manufacturer recommends the coolant concentration be over 12%. Based on tests, the coolant pressure is recommended to be set at 30 bar. At the same time, it can be stated that the coolant temperature ranging between 25 and 32 °C did not have a significant impact on the change in the life of the gun drills. Due to the execution of longitudinal tests, it is possible to determine that the cleaning interval of the cooling agent filtration should happen at least once every 14 days and the cleaning of the magnetic filter should happen at least once every 7 days. In the event that adhesive damage is observed on the guide surface of the drill, an immediate check of the coolant filter is necessary, as is a check of compliance with the required percentage of the coolant emulsion.

In addition, it is recommended to use the standard geometry of the chipformer, as the reduced tool shows a significant reduction in tool life. In order to successfully increase the service life of gun drills, limit deviations from the prescribed properties and composition of the material being machined must be avoided. The service life of drill bits is also affected by the functional condition of the machine tools—spindle backlash, machine vibration, guide backlash, leaks in the fluid supply conduit, and the consequent loss of pressure.

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