Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(4), 156–170
https://doi.org/10.12913/22998624/195585
ISSN 2299-8624, License CC-BY 4.0

Received: 2024.10.11
Accepted: 2025.01.13
Published: 2025.02.19

The influence of cutting parameters and tool wear on the quality of holes in package sheets used in heat exchangers

Łukasz Wieczorek[1,2], Jerzy Józwik[3*], Piotr Niesłony[1], Kevin Moj[1]

[1] Opole University of Technology, ul Mikołajczyka 5, 45-271 Opole, Poland
[2] Kelvion Sp. z o.o., ul Kobaltowa 2, 45-641 Opole, Poland
[3] Lublin University of Technology, ul. Nadbystrzycka 38d, 20-618 Lublin, Poland
* Corresponding author's e-mail: j.jozwik@pollub.pl

ABSTRACT

The presented research aimed to obtain information on the effect of cutting parameters and tool wear on the quality of shaped holes in stainless steel package sheets. The testing was planned to allow evaluation of the impact of drilling technology. For this reason, verification tests were performed on a monolithic sheet of the same material grade and thickness equal to the package of four base sheets. It was noted that the double-insert drill is not qualified for use in this process, as it does not provide adequate hole quality (even 0.7 mm deviation in measured diameter from nominal value) and does not provide the expected tool life. Significantly better results were obtained for the monolithic and indexable head drills (IT8). In addition, it was observed that the burr formed when the drill exits the hole, in the case of the indexable double-insert drill, is also significantly larger (~1 mm) than for the other tools (less than 0.1 mm). Preliminary tests carried out in this way made it possible to select the tool with the best cutting capability and quality of the generated holes. It was decided to use a drill with an interchangeable head. Tests have shown that it is possible to produce up to 1.000 holes with a diameter of 18.5 mm in a sheet package of 316Ti material with a thickness of 40 mm while maintaining the assumed effective speed of the process (n=1200 rpm, f_n=0.18 mm/rev). In experimental testing, a significant effect of cutting speed on tool wear was noted. A correlation between coolant concentration and tool life was also identified – raising the concentration from 8% to 12% increased tool life by virtually 100%. Testing of hole roughness over a full tool life cycle showed that a drill bit with a completed break-in phase provides better hole roughness than a new drill bit. Measuring equipment and software were used for the research and processing of the results – Wenzel XO55, Hommel Etamic LV 17, WM Quartis R2021-1, Grapher 18.3.400, Autodsk Inventor Professional 2023.

Keywords: drilling process, cutting parameters, tool wear, hole accuracy, tolerances, dimensional and shape deviations.

INTRODUCTION

Drilling is one of the most common machining operations in the machining industry. Thanks to the use of modern tool materials and tool coatings, current machining techniques enable drilling with high productivity [1]. Faced with the need to remain competitive in the market, manufacturers are constantly optimizing their production processes using ever-newer machining techniques. Drilling the tubesheets is one of the basic manufacturing processes to produce high-efficiency heat exchangers. Tubesheets are built from various materials, such as carbon steels, acid-resistant steels, titanium alloys, cladded sheets, and many fundamentally different layers or even plastics [2]. The tubesheets in tubular heat exchangers usually have from tens to even thousands of holes, and the thickness of the tubesheets reaches, depending on the size and operating pressure of the exchanger, from several to several hundred millimeters. Regardless of the size of the tubesheets, the holes made in them must have high dimensional and shape quality, adequate surface quality or even defined characteristics of the outer edges of the holes.

The main methods of joining the bottom of the tubesheets to the exchange tubes are welding and rolling the tubes in the holes. Sometimes combined connections are used – welding together with re-rolling. If a hole is made with incorrect shape-dimensional parameters, there is a high probability of mechanical damage to the exchanger pipe during the production of the exchanger, that is, during its rolling or weld-in and its subsequent operation. Additionally, rolled joints have a high risk of unsealing.

A technology that affects the competitiveness of heat exchanger production and increases the efficiency of producing tubesheets, they are drilled in packages of several pieces. This is a solution which dramatically increases the speed and thus reduces the cost of manufacturing these components. However, drilling several sheets of metal at the same time also brings major technological challenges. In this type of process, there is a hindrance to its control for each layer of drilled sheets. Although the sheets are thoroughly joined together before machining with process welds, the individual layers tend to form micro-gaps between each other, which leads to inhomogeneity of the material in the cutting zone, and this can lead to a negative impact on the dimensional and shape quality of the holes by, for example, catching chips in the gaps and deforming the holes.

Additionally, such stratification of the material for each successive hole results in a kind of intermittent machining, and thus variable cutting forces and increased vibrations are generated. This negatively affects the tool life [3] and the shape-dimensional quality of the holes produced. An additional complication of conducting this type of process is the frequent use of acid-resistant steels for tubesheets, the processing of which affects the wear of the drill bit much more than carbon steel [4]. Harsh intermittent machining conditions can be compensated for with HPC [5], However, they are not available on every machine. Regardless of this, cooling when drilling acid-resistant steels is a key element and can significantly affect the course of the process [6]. An important factor in increasing the quality and efficiency of drilling is the use of appropriate coatings for drill bits [7], especially that the temperature during cutting of acid-resistant steel is up to twice as high as in the case of carbon steel [8]. The temperature during the process is also influenced by the geometrical parameters of the drill bits, and the right geometry selection can reduce the amount of heat introduced into the tool and reduce the forces during drilling [9, 10]. Regarding hole quality, cutting speed and feed rate have been shown to have the greatest impact in this regard [6]. Adjustment of process parameters does not depend only on the expected process performance but is also related to the requirements for adequate quality of hole surfaces. An interesting solution for improving the quality of surfaces when drilling acid-resistant steels is sheet annealing, but it is not always possible to carry out such a process [12].

These requirements, in addition to good practice, also derive from regulations on the construction of heat exchangers. Referencing the Tubular Exchanger Manufacturers Association [7], which is one of the primary organizations involved in setting guidelines for the design and manufacture of heat exchangers, holes in tubesheets must be within strict tolerances (Table 1).

As presented in Table 1, for diameters up to ϕ25.4 mm and the requirement to produce accurate holes, more than 96% of them must be within tolerance of +0, -0.05 mm. This standard clearly indicates that the internal edges of the tubesheet holes should be free of burrs to prevent damage to the tubes. Internal surfaces should also be finished to contain no sharp edges. Another key standard for designing and building heat exchangers such as industrial coolers is API document STANDARD 661 [8], which specifies the range of necessary hole tolerances for tubesheets. The maximum possible deviations are shown in Table 2.

Hole tolerances for the range up to ϕ 18 – ϕ 18.5 mm should be in the range of +0.05, - 0.05. Presented technological information and industry findings prove that the requirement for adequate dimensional and shape tolerance and surface quality in the holes of tubesheets is very important and independent of methods or techniques of their forming. A key element of novelty in the conducted testing was the processing of holes in package sheets. The genesis of this testing is related to the need for high quality holes in tubesheets used to manufacture high-efficiency heat exchangers. There is a lack of information about this type of process in the literature on the subject, and workshop practice yields information about problems in implementing this type of technological process. Thus, these requirements must be met both during production when drilling sheet metal individually and in package arrangements. Learning about the impact of drilling technology in package sheets on their quality and efficiency is therefore an important piece of engineering knowledge and information expected by the industry.

Table 1. Tolerances of holes in tubesheets according to TEMA

Nominal tube OD, mm	Nominal tube hole diameter and under tolerance, mm				Over tolerance; 96% of tube holes must meet value in column (c), mm. Remainder may not exceed value in column (d), mm	
	Standard FIT (a)		Special close fit (b)			
	Nominal diameter	Under tolerance	Nominal diameter	Under tolerance	(c)	(d)
6.40	6.58	0.10	6.53	0.05	0.05	0.18
9.50	9.75	0.10	9.70	0.05	0.05	0.18
12.70	12.95	0.10	12.90	0.05	0.05	0.20
15.90	16.13	0.10	16.08	0.05	0.05	0.25
19.10	19.30	0.10	19.25	0.05	0.05	0.25
22.20	22.48	0.10	22.43	0.05	0.05	0.25
25.40	25.70	0.10	25.65	0.05	0.05	0.25
31.80	32.11	0.15	32.03	0.08	0.08	0.25
38.10	38.56	0.18	38.46	0.08	0.08	0.25
50.80	51.36	0.18	51.26	0.08	0.08	0.25
63.50	64.20	0.25	64.07	0.10	0.10	0.25
76.20	77.04	0.30	76.89	0.11	0.11	0.25

Table 2. Nominal tolerances of holes in tubesheets according to API [8]

Nominal tube OD, mm	Standard fit		Special close fit		Over-tolerance, mm
	Nominal tube hole diameter, mm	Under-tolerance, mm	Nominal tube hole diameter, mm	Under-tolerance, mm	
19.05	19.30	0.10	19.25	0.05	0.05
25.40	25.70	0.10	25.65	0.05	0.05
31.75	32.11	0.15	32.03	0.08	0.08
38.10	38.56	0.18	38.46	0.08	0.08
50.80	51.36	0.18	51.26	0.08	0.08

MATERIALS AND METHODS

Based on information from tubesheet companies and information about cutting tool products, four types of drill bits with nominal diameters from ϕ 18 – ϕ 18.5 mm were selected. The dimension of the hole diameter is derived from the most common group of holes made in the tubesheets of heat exchangers in 10 mm to 40 mm thick stainless steel grades. Two indexable carbide head drills with diameters of ϕ 18.4 mm and ϕ 18.5 mm (Fig. 1a), an indexable double-insert drill with a diameter of ϕ 18.0 mm (Fig. 1b) and a monolithic drill (Fig. 3c) with a diameter of 18.5 mm were selected. All were characterized by an active working length of ~54 mm.

Two packages of four 10 mm thick grafted sheets of 316Ti material (Table 3) with dimensions of 400 × 200 mm were prepared for testing. To evaluate the differences in the processing of c, verification testing was conducted on a monolithic sheet of the same material grade with a 40 mm thickness corresponding to the thickness of a package of four sheets. The holes were drilled in a parallel arrangement, where the axes of the holes were spaced every 28 mm. This is one of the conventional spacing ranges used in designing the tubesheets of heat exchangers with tube diameters of ϕ 18 mm.

Drilling test were conducted on an AXA HSC 3DoSpi 3-axis twin-spindle machining center (Fig. 2). Horizontal drilling results in a better ability to evacuate the chip, and chips ejected from the hole go directly to the conveyor belt that leads them out of the machine, so they do not accumulate on the material. Coolant was supplied through the tool during machining. After analyzing the chemical composition of the processed material and estimating its machinability, Fuch Ecocool emulsion was used for cooling, applied at a pressure of 8 bar, in accordance with the manufacturer's

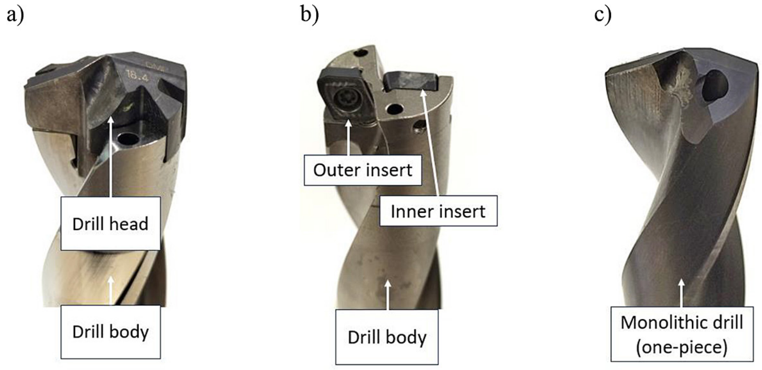


Figure 1. Type of tested drills, (a) indexable head drill, (b) Indexable insert drill, (c) Monolithic drill

Table 3. 316Ti steel characteristic

Steel 316Ti / 1.4571									
Chemical composition									
	C	Si	Mn	P	S	Cr	Mo	Ni	Ti
Min.						16.5	2.5	10.5	5xC
Max.	0.08	1	2	0.045	0.03	18.5	2.5	13.5	0.7
Properties									
Machinability	Medium 4 (1 = bad, 10 = good)								
Weldability	Excellent								
Corrosion resistance	Good								
Corrosion class	4 (0=bad, 5=good)								
Density	~8000 kg/m³								
Machinability	Medium 4 (1 = bad, 10 = good)								
Usable	up to 550 °C								
Tensile strength	500–700 N/mm²								

recommendations. The concentration of the emulsion solution was 8% with an increase to 12% in the later phase of testing due to its key effect on tool wear. To replicate the industrial conditions of tubesheet machining, the sample for drilling tests was supported and bolted to the machine table at its four extreme positions (Fig. 2), corresponding to the technological conditions of clamping during industrial machining.

The testing plan involved drilling tests for 4 different volumetric capacities. Individual capacities were obtained through a combination of adequate feed and cutting speed. A detailed testing plan is presented in Table 4.

The indexable head drills and the monolithic drill bit were identical for the different volumetric efficiencies, feed rates and cutting speeds. The indexable insert drills were used to achieve the same volumetric efficiency as the other drills at each trial operated at twice the cutting speed and twice the feed rate. This way of operation is due to its design. The full rotation of an indexable insert drill corresponds to half the rotation of a monolithic and indexable head drill.

RESULTS AND DISCUSSION

The quality of shaped holes with selected drills in the whole range of technological parameters was evaluated in terms of dimension and shape. The diameter of the holes drilled and its deviation from the nominal value were measured for the entire range of drilling depths. Drill wear testing was conducted using the Olympus SZ61 visualization system together with Olympus Stream Essentials software. The surface quality of the drilled holes was evaluated using parameters (*Ra, Rz*) as well as by analyzing the actual profiles of the internal surface of the hole.

Table 4. Configuration of cutting parameters

Drill type	Nominal diameter, mm	Insert type / carbide	*n*, rev/min	v_c, m/min	f_n, mm/ rev	Volumetric efficiency, Q_v, cm³/min	Tool ID
Indexable head drill	18.4	DrillMeister TID180F25-3 DMP184 - AH725	870	50.3	0.180	39.8	T1-A
					0.126	27.9	T1-B
			1200	69.4	0.180	55.0	T1-C
					0.126	38.5	T1-D
	18.5	DrillMeister TID180F25-3 DMP-185 - AH9130	870	50.3	0.180	39.8	T2-A
					0.126	27.9	T2-B
			1200	69.4	0.180	55.0	T2-C
					0.126	38.5	T2-D
Indexable insert drill	18	TungTwist TDX180F25-3 XPMT06X308R 6030	1740	98.4	0.090	39.8	T3-A
					0.063	27.9	T3-B
			2400	135.7	0.090	55.0	T3-C
					0.063	38.5	T3-D
Monolithic drill	18.5	WPC18.5 R3D IK	870	50.3	0.180	39.8	M-A
					0.126	27.9	M-B
			1200	69.4	0.180	55.0	M-C
					0.126	38.5	M-D

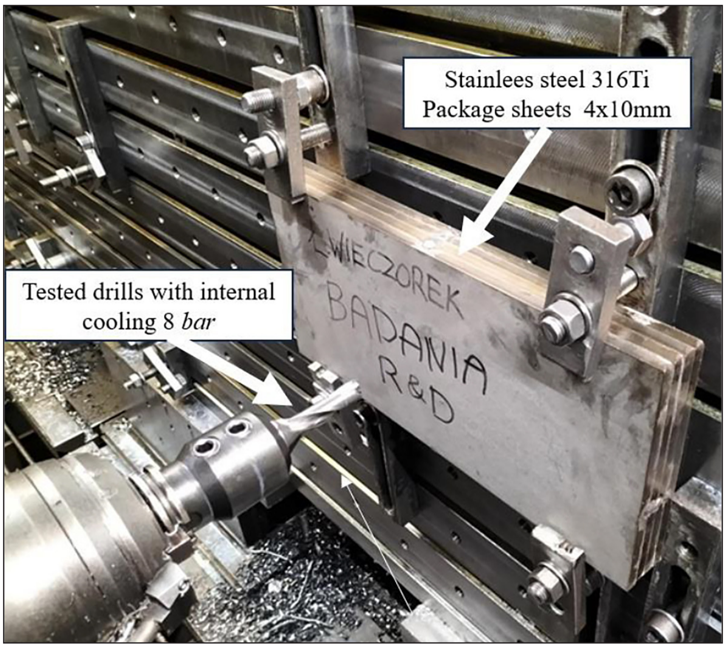


Figure 2. Test station

Dimensional and shape quality assessment of holes in package sheets

Dimensional and shape quality testing of the holes was conducted on a Wenzel XO 55 coordinate measuring machine and using WM Quartis R2021-1 software (Fig. 3 a, b). The measurement plan involved 5 measurements in the axial direction for each layer of the sheet metal package (a total of 20 measurements in the axial direction) and 20 measurement points at a given level to determine the circularity of the hole and determine its averaged diameter (Fig. 4). This configuration of the measurement plan makes it possible to acquire information on the basic dimension and shape parameters of the holes produced. To analyze the dimensional changes of the holes, the results of the measurements are presented in Figs.

a) b)

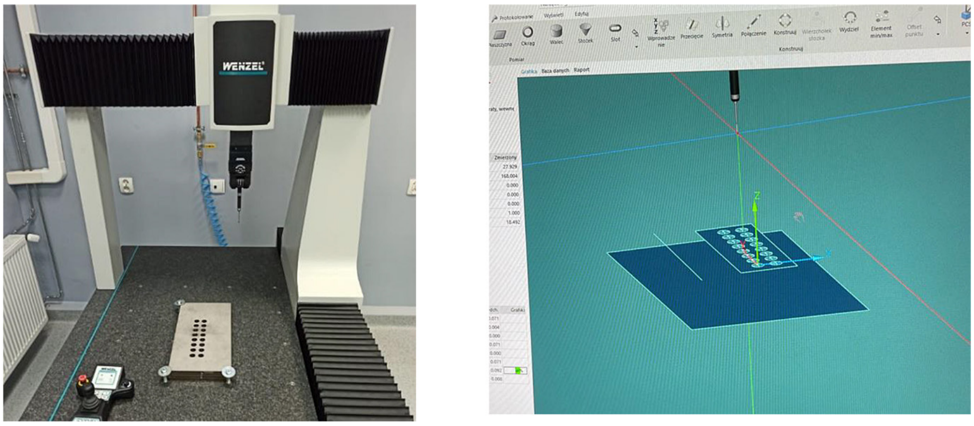


Figure 3. (a) Hole measurement station WENZEL XO 55, (b) measurement simulation

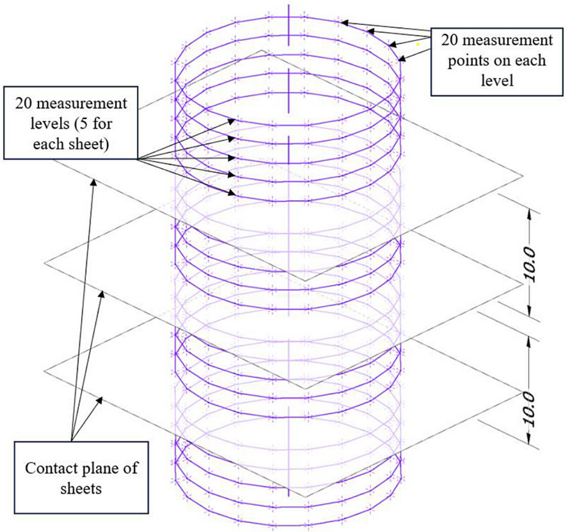


Figure 4. Measurement method

5–8, where the values of the difference in the dimension of the actual hole from its nominal diameter DN are presented for different volumetric efficiency of the process.

Authors observed that the double-insert drill is not qualified for precision drilling of package sheets. The first reason is the significant deviation of the actual dimension from the nominal dimension, reaching up to 0.7 mm. It should be noted that an important aspect is the lack of stability of the process. The difference between the minimum and maximum hole diameters reached even more than 0.4 mm, a result that is incomparably worse than for indexable head drills and monolithic drill, where the obtained range was adequately within 0.025 mm for indexable head drill and 0.05 mm for monolithic drill. During testing, it was also

a) b)

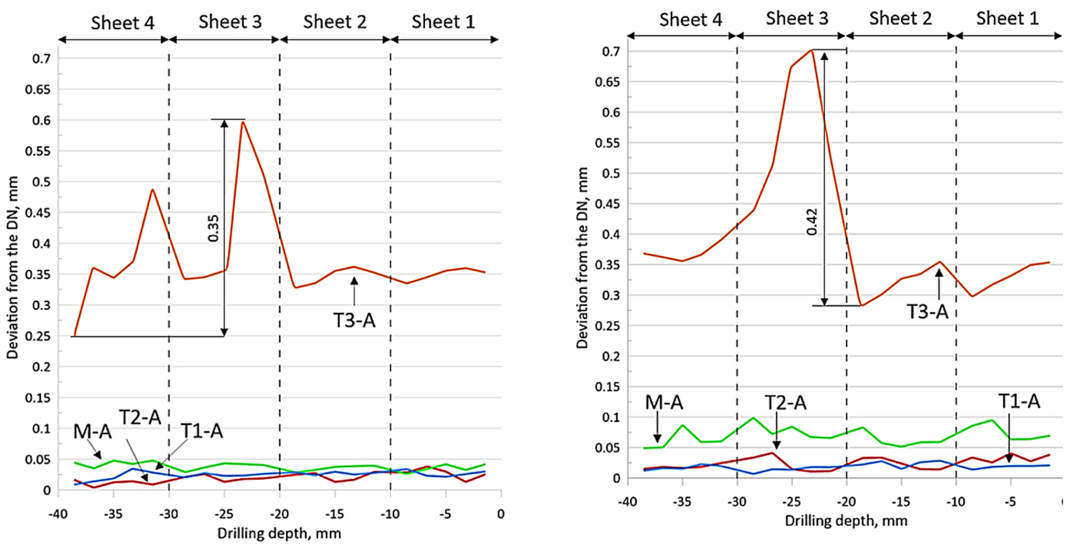


Figure 5. Deviation of actual diameter from nominal diameter. (a) configuration A in package sheet 1, (b) configuration A in package sheet 2; volumetric efficiency VE = 39.8 cm^3/min

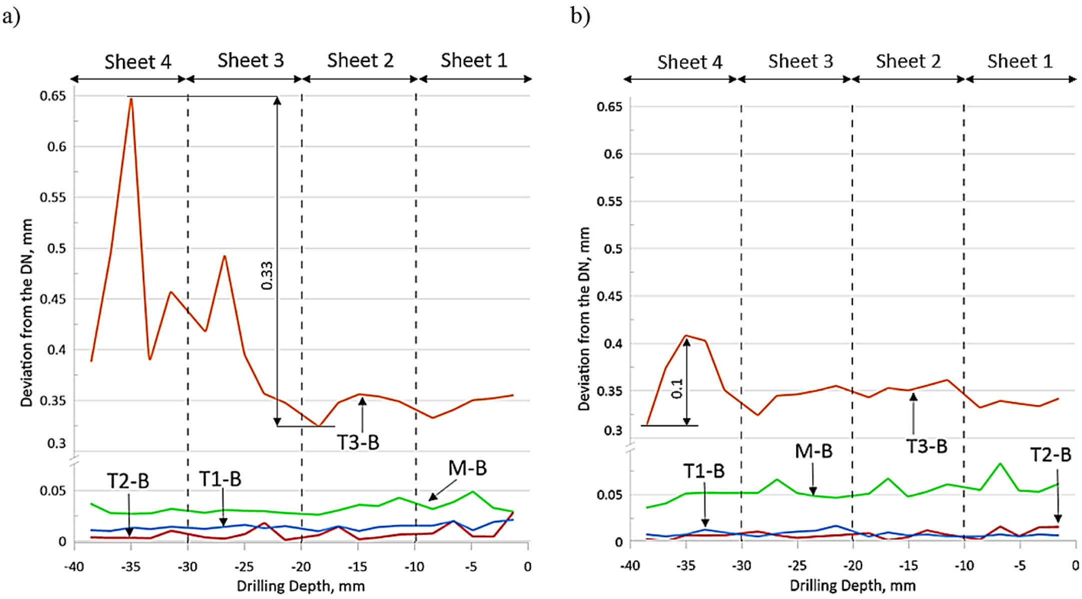


Figure 6. Deviation of actual diameter from nominal diameter. (a) configuration B in package sheet 1, (b) configuration B in package sheet 2; volumetric efficiency VE = 27.9 cm^3/min

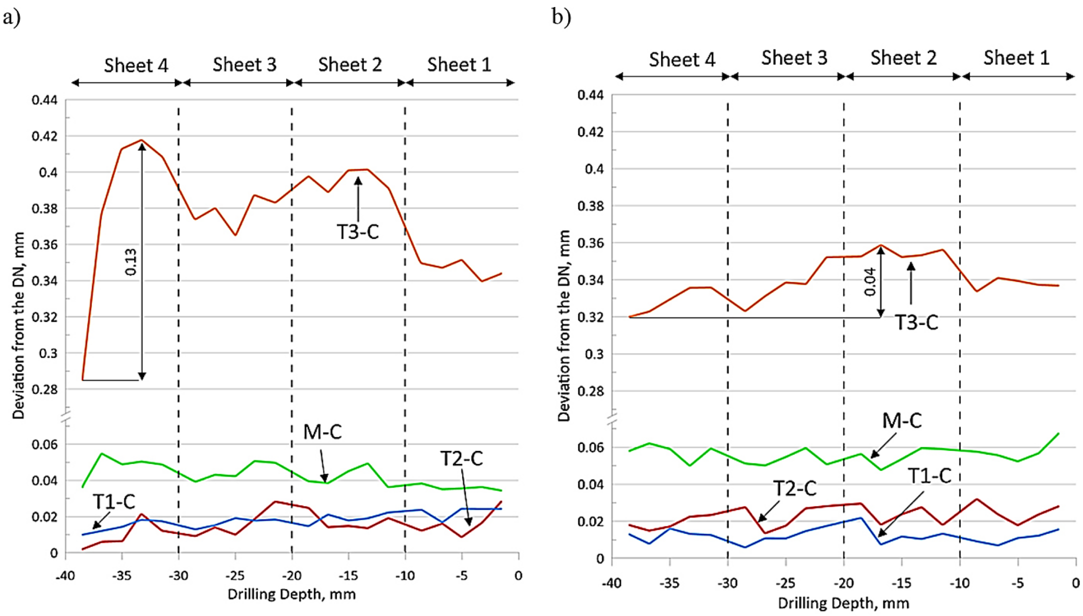


Figure 7. Deviation of actual diameter from nominal diameter. (a) configuration C in package sheet 1 (b) configuration C in package sheet 2; volumetric efficiency VE = 55.0 cm^3/min

noted that after 4 test holes were drilled, the cutting edges of the double-insert drill were chipped slightly (Fig 9).

The monolithic drill produced a relatively good quality hole, and the measured deviation from the nominal diameter occurred in the range of 0.025 to 0.1 mm. The most preferable result was obtained during the head drill test. The resulting deviation of the actual diameter from the nominal diameter ranged from 0 mm to 0.04 mm, which is an acceptable value and ensures that holes can be made in tubesheets using only drilling technology (without the need to use finishing tools such as reamers or boring bars). The worst deviation from the nominal dimension was obtained for a volumetric efficiency VE of 39.8 cm^3/min (up to 0.1 mm for the monolithic drill, 0.04 mm for the head drill and 0.7 mm for the indexable insert drill) (Fig. 5). Increasing the parameters to ensure a volumetric efficiency VE of 55 cm^3/min reduced

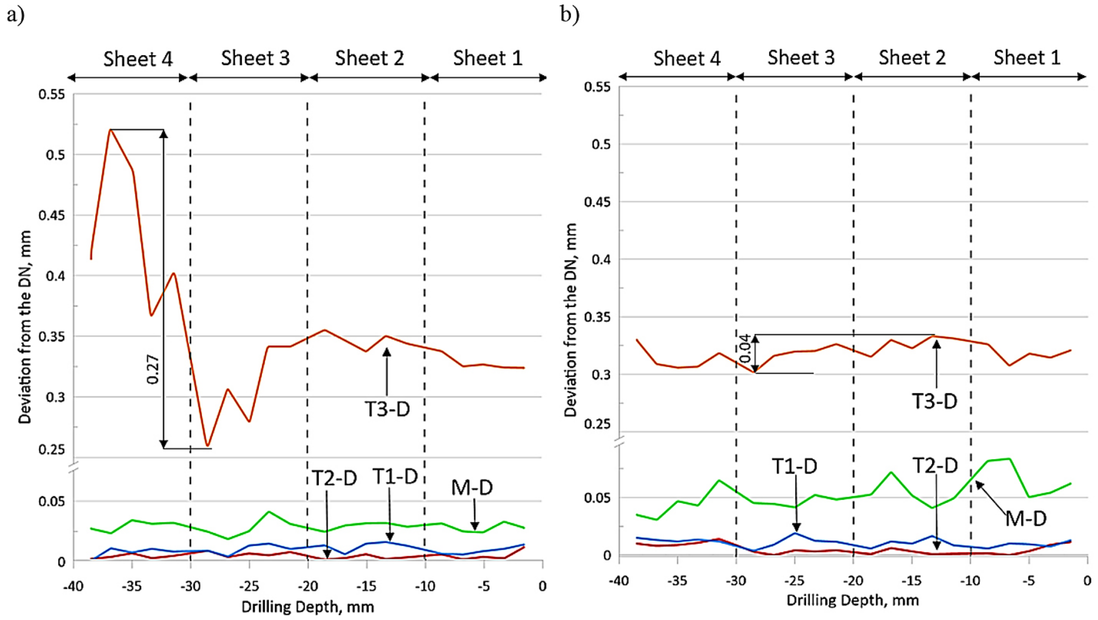


Figure 8. Deviation of actual diameter from nominal diameter: (a) configuration D in package sheet 1, (b) configuration D in package sheet 2; volumetric efficiency VE = 38.5 cm^3/min

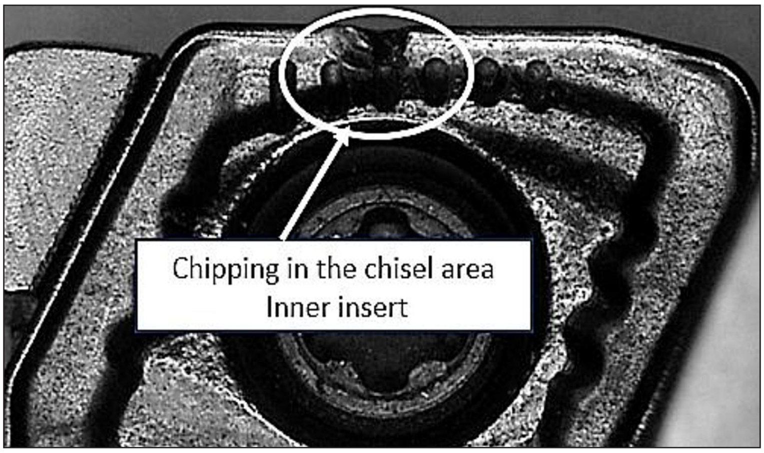


Figure 9. Damage of the insert

the deviation from the nominal diameter (to 0.7 mm for the monolithic drill, 0.03 for the head drill and 0.42 for the indexable insert drill).

Dimensional and shape quality assessment of holes in monolithic sheet

Comparative testing, prepared by authors to evaluate the impact of drilling in packaged sheets, was carried out on monolithic sheet metal of the same material grade and overall dimensions. The testing was carried out in accordance with an established testing plan, such as for package sheets.

The authors observed interesting effects. Testing showed that all drills achieved better results in monolithic sheet metal in terms of dimension and shape than when drilling in a sheet metal package. The largest deviation between the smallest and largest measured diameter was obtained for the T3 drill bit – 0.04 mm (Fig. 11 a), but in this case it is 90% smaller than for the same tool drilling a hole in a sheet metal package (Fig. 5b). The most noticeable difference with respect to drilling in a sheet metal package is that the T2 double-insert drill, despite a significant deviation from the nominal dimension, allowed to produce a hole with high stability of diameter dimensions along the drilling length – a spread of up to 0.02 mm (Fig. 11b), which cannot be said about drilling with this tool in packages (Fig. 5b). Also, the initial testing phase noticed no chipping of the drill's cutting edge. Thus, it can be considered that the double-insert drill is suitable for drilling monolithic sheets, where a hole with high dimensional and shape accuracy is not required, that is, at the level of IT8-10 (for DN ϕ 18.0 – ϕ 18.027/ϕ 17.973 for IT8 – ϕ 18.07/ϕ 17.93 for IT10). Monolithic drill bit M and head drills T1 and T2 obtained a dimension closer to the nominal dimension (Fig. 10, Fig. 11), and drilling was characterized by increased stability compared to package sheets. The deviation from the nominal value was less than 0.05 mm for the monolithic drill bit and less than 0.025 mm for the head drill bits, where after drilling into the plate pack, less than 0.1 and 0.04 mm were achieved adequately. In addition to the issue of measured diameters, as mentioned earlier, an important factor in evaluating the hole is the burr at the end of the hole. It was observed in both monolithic and package sheets. Holes made with a double-insert drill, in addition to the large diameter deviations visible to the naked eye inside the hole (Fig. 12a), are also characterized by a much larger burr with a height of even more than 1 mm, while head drills

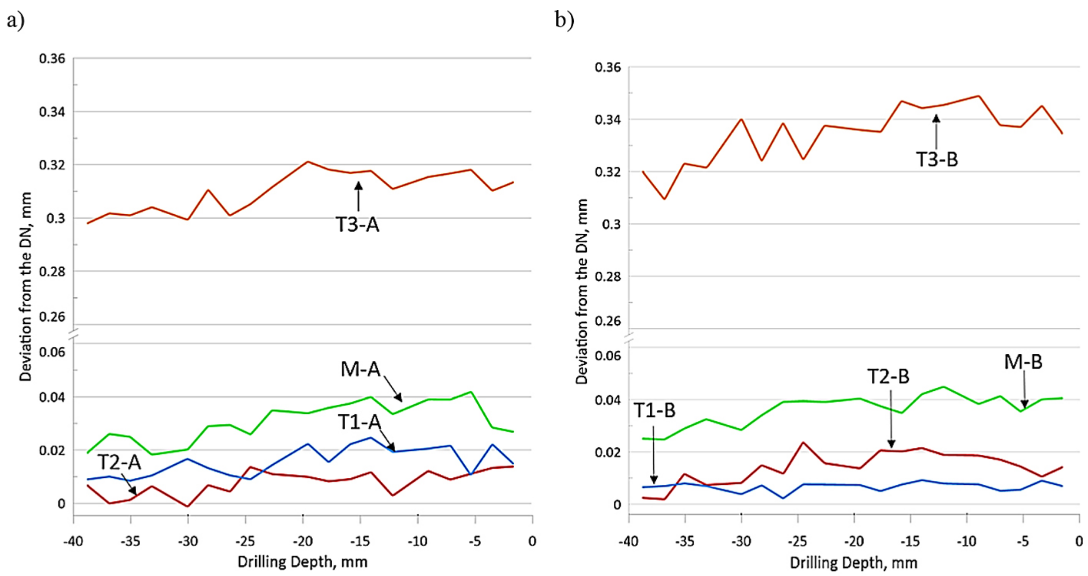


Figure 10. Obtained deviation at volumetric efficiency VE: (a) 39.8 cm³/min and (b) 27.9 cm³/min – monolithic sheet

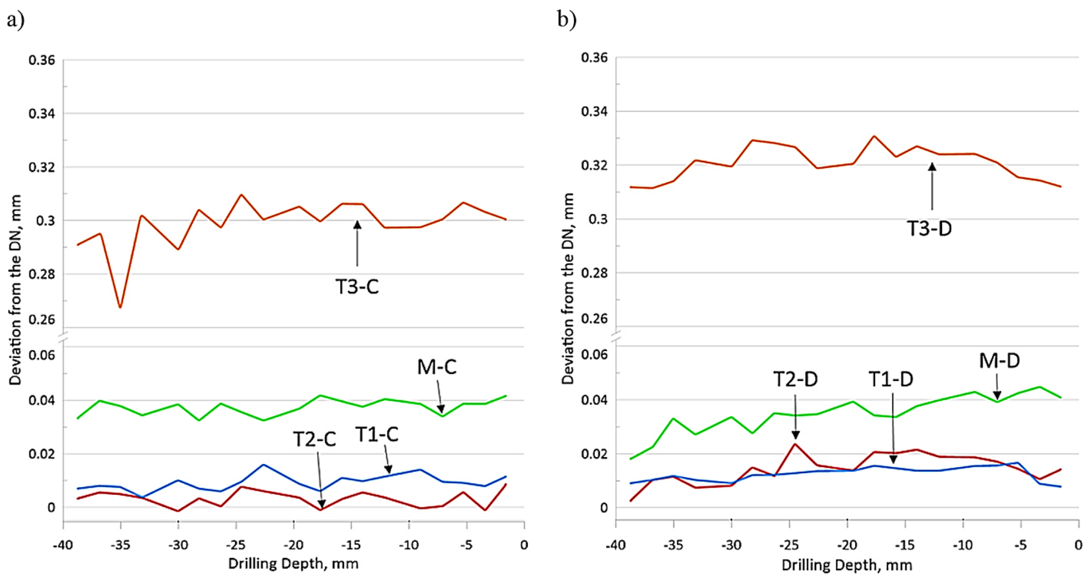


Figure 11. Obtained deviation at volumetric efficiency VE: (a) 55.0 cm³/min and (b) 38.5 cm³/min – monolithic sheet

have a burr of less than 0.1 mm. In all tube sheets, sharp edges must be completely eliminated. These operations are carried out either manually or by machine. Elimination of a crown burr is, in any case, longer and more complicated than a small even burr.

Tool wear

Tool wear testing was conducted on selected drills. Particularly noteworthy is that head drills obtained the best dimensional results. Nevertheless, from the results obtained in the test and production phase, the indexable head drill DMP185 made of AH9130 carbide was selected for further testing. This choice is because it has a different wear mechanism and, thus, the possibility of better process control in packet plates compared to AH725 carbide. It was observed that the chipping in the AH9130 head in the central part of the chisel edge (Fig. 13a), which should theoretically end the tool's service life, still allows the drilling process to be carried out correctly. During the tests performed, it was noted that the formation of small chips in the AH725 head (Fig. 13b) resulted in the inability to break the chip. Although this wear seems less critical, its formation prevented the process from running properly. This problem causes the chip to wind up on the drill bit at a later stage, making it necessary to stop the drilling cycle and manually remove the chip from the bit every 2 to 3 holes or so. Such solution is unacceptable to the industry because of the danger to the machine operator, as well as in terms of production automation and its cost-effectiveness. If the central part of the chisel edge is damaged, the problem of breaking and removing the chip from the tool does not occur (Fig. 13a). Based on the experience gained by authors in machining 316Ti material in package sheets with the AH9130 carbide head drill, it was found that the drill wear process is identical each time. It can be divided into 4 stages. The first

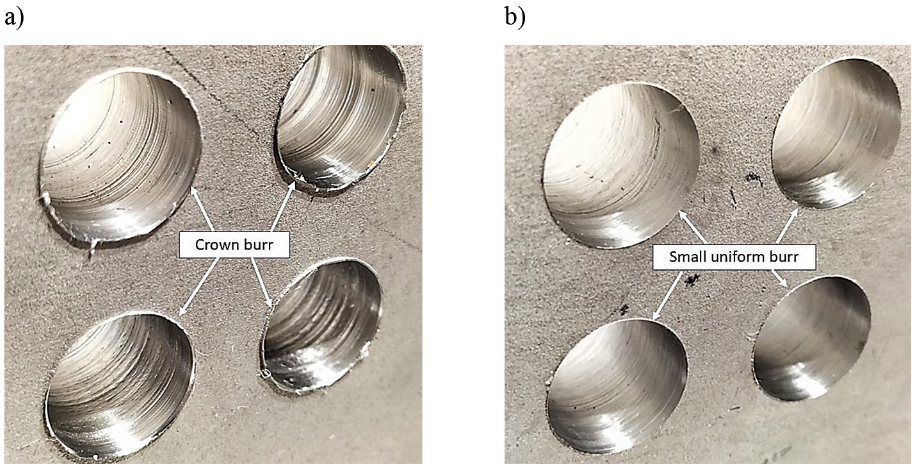


Figure 12. (a) Crown burr – double-insert drill bit, (b) small burr – head and monolithic drill bits

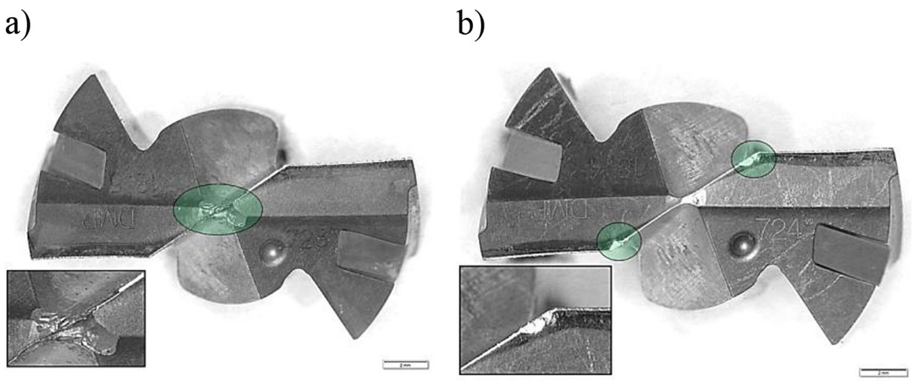


Figure 13. Breakage sites in carbides (a) AH9130, (b) AH725

is the lack of wear and tear and the start of the break-in process of the drill bit (Table 5, pos. I).

The second is abrasive wear in the chisel edge and cutting area (Table 5, pos. II). The third stage, which still allows drilling to proceed, is the chipping of the drill bit in the chisel edge area (Table 5, pos. III). The fourth last stage of drill bit wear, where the process proceeds rapidly, is the breakout or complete destruction of the drill bit (Table 5, pos. IV). A visualization of the stages of wear is presented in Table 5. Three trials of tool durability testing were conducted with the configurations presented in Table 6. Each trial used a feed rate of f_n=0.18 mm/rev, the highest used in the test stage. The tool speed (n = 870 rpm and n = 1200 rpm) and emulsion concentration were changed. As testing turned out, the last factor significantly impacted the tool's durability. In sample A, noticeable changes on the surface occurred after just 5 m of drill path, which mainly included coating wear. The first signs of phase III, i.e. chipping in the area (Table 4, pos. 3) of the chisel edge, were recorded

Table 5. Classification of stages of tool wear

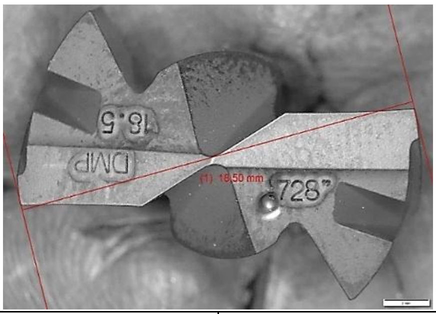
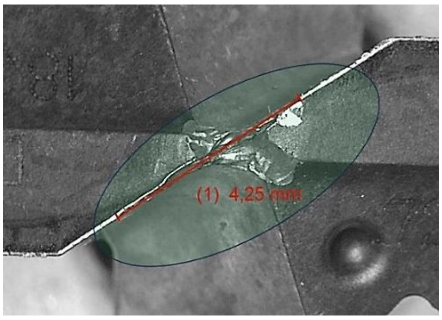
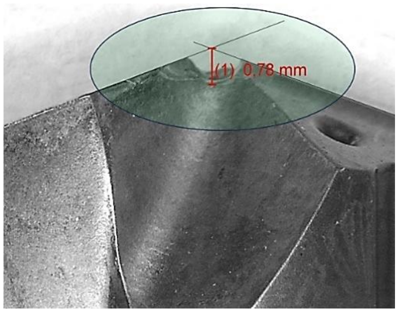
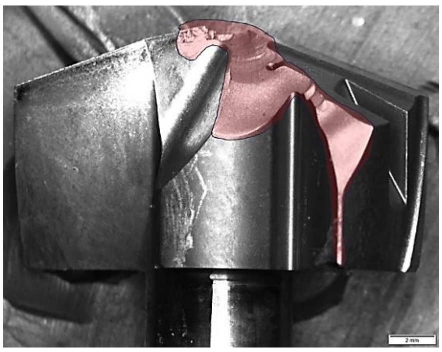
The degree of drill wear during testing		
I. No wear		
II. Abrasive wear in the chisel edge and cutting edge area		
III. Chipping in the chisel area		
IV. Breakage or complete destruction of the drill withdrawal of the drill from research		

Table 6. Machining parameters when checking tool wear

Machining parameters	Degree of wear and the moment of occurrence			
	I. No wear	II. Coating wear	III. Catastrophic wear in the chisel edge area	IV. Complete or almost complete destruction of the tool
A) Tool rotation - n = 870 rpm; Feed rate f_n = 0.18 mm/rpm; Coolant concentration cc = 8%	New drill	Gradually, throughout the operation period	20 m	25 m
B) Tool rotation - n = 1200 rpm; Feed rate f_n = 0.18 mm/rpm; Coolant concentration cc = 8%	New drill	Gradually, throughout the operation period	15 m	20 m
C) Tool rotation – n = 1200 rpm; Feed rate f_n = 0.18 mm/rpm; Coolant concentration cc = 12%	New drill	Gradually, throughout the operation period	30 m	42 m

after 20 m (500 holes) of the drill path in the material. A fragment measuring 2.9 × 0.82 mm was chipped. After 25 meters of drill path in the material, which corresponds to 625 holes drilled in a 40 mm pack, due to deepening deterioration, and the high risk of jamming the drill in the material, further drilling was stopped. Trial B, which was characterized by increased tool rotations, resulted in significantly lower drill life. Already after 15 m of road there was chipping in the chisel edge area, and after 20 m of path there was a large breakout, which had to result in withdrawal of the drill from testing. The last test sample conducted in the series of tool life tests was the C test. During this, the cutting parameters used were identical to those in Test B while the concentration of the cooling and lubricating emulsion was changed from 8% to 12%. An important difference from the B run is that the drill went into the third wear phase only after 30 m of drill path. After 40 meters were completed, further drilling was discontinued due to the high risk of complete destruction of the tool. Coating wear was noticeable on the edges. The width of deformation and chipping in the upper part of the drill was 4.25 mm and the depth was 0.78 mm (Table 4, pos. III). Based on the above information, it can be concluded that a higher cutting speed causes faster wear of the drill bit, while increasing the concentration of emulsion in the system from 8% to 12% elongates its life practically twice (from 20 m to 40 m of drill path in the material).

Testing of roughness and hole diameter in the tool wear cycle

Durability testing of the selected AH9130 carbide head drill bit was carried out in an intermittent cycle. The roughness of the holes was measured using a Hommel Etamic LV17 machine. The measurement in the sheet package and in the monolith was carried out in accordance with PN-ISO 4288. 16 measurements were taken in each hole (4 measurements, rotated in 90° increments for each layer of the package) (Fig. 14). In the form of a graph (Fig. 15a, b), the change in roughness of the hole is presented in relation to the quantity of holes which the drill has made. The results presented in the graph are the averaged value obtained from a given hole. The standard deviation ranged from 10 to 33%.

Testing of the surface quality of the holes made shows an interesting characteristic. It was observed that the holes made in the monolithic sheet and the sheet package have similar characteristics of roughness parameters evaluated by the parameter Ra (Fig. 15a). Most of the holes in the sheet metal package achieved a higher roughness value Ra than the monolithic sheet. A similar situation was observed analyzing the variation of the diameter deviation from the nominal value, with holes in monolithic sheet showing values closer to the nominal. In the initial phase (the first hole made with a new tool), you will always notice a higher Ra value. After the drilling of about 200 holes (cutting path equal to 5 m), the state of the drill goes to the second phase, when break-in of the cutting edges and margins occurs, leading to the most optimal cutting conditions in terms of the surface quality of the drilled holes. The physical result of such interaction of the machining system is a significant reduction in the roughness parameter Ra. A Ra of 1.05 μm was obtained for the monolithic sheet, where for the sheet package, the average Ra ranged from 1.2 to 0.92 μm, with a peak of the minimum value around the 16 m cutting path. A sharp increase

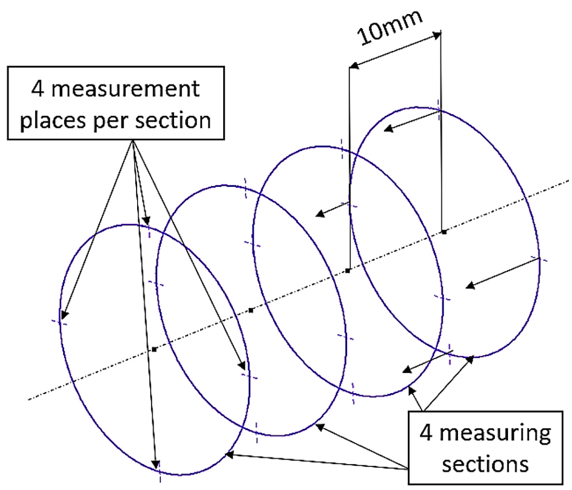


Figure 14. Method of measuring roughness

in roughness occurs in phase III. The cause of this phenomenon is chipping in the chisel edge area (Table 4, pos. 3). As a result of the resulting damage, the ability to keep the drill bit in the axis of the hole decreases, which can cause run-out and generate non-uniform machining marks affecting surface roughness. It is interesting to note that in Phase IV, just prior to the drill bit being taken out of service due to breakage, the roughness of the hole decreased, even though the condition of the tool's drill head deteriorated significantly. New cutting edges created by broken blades are likely responsible for this condition. Around the 1.000th hole (~40 meters of drill path in the material), catastrophic wear (complete destruction of the drill bit) occurred.

Measurement on the roughness verification machine made verifying the shape profile and obtaining results regarding Ra and Rz parameters possible. The diagram (Fig. 16) presents representative real profiles made for the sheet metal package and for the monolith sheet, considering the stages of tool life. It can be said undeniably that the hole made by the tool in the second phase of wear is characterized by a softer profile compared to the new and worn drill bit. While testing the wear of the selected tool, which is a head drill, a dimensional and shape evaluation of the drilled holes was also conducted (Fig. 17).

Holes drilled in a monolithic sheet are characterized by a diameter closer to the nominal dimension than holes drilled in a sheet package. Based on the results obtained, it can be seen that there are deviations in the measured diameter, and depending on the degree of wear of the drill, the obtained measurement result increases or decreases. The most significant point is that the dimensional deviations are a maximum of 0.025 mm (IT8) over the tool's life, which allows us to conclude that the use of the tool in drilling tubesheets is possible regardless of the degree of wear.

a) b)

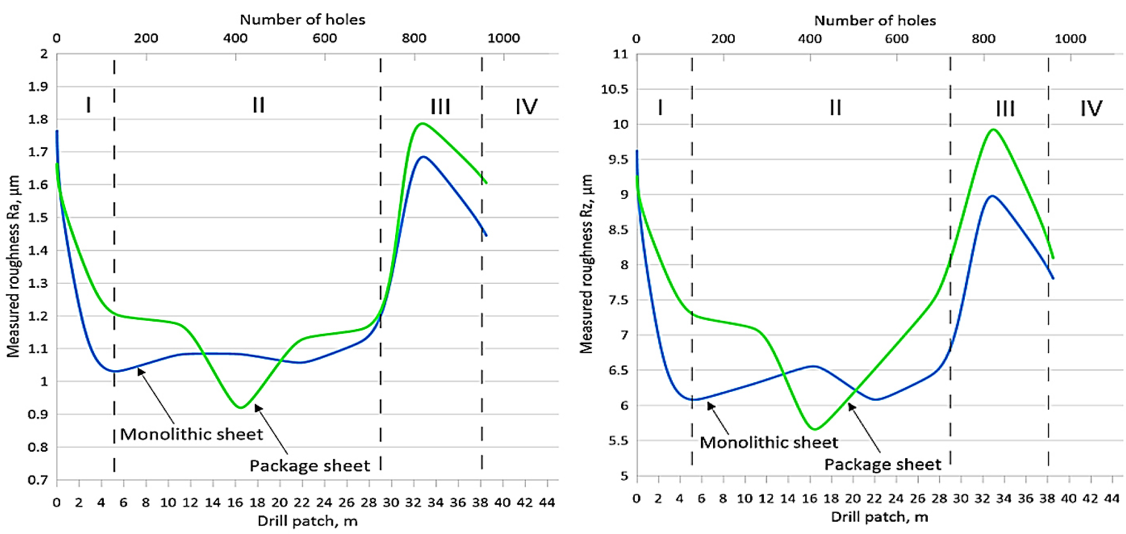


Figure 15. Roughness of the hole: a) roughness of the hole over the tool life cycle, *Ra, b)* roughness of the hole in the tool life cycle, *Rz*, phases: (I) no wear, (II) abrasive wear in the chisel edge and cutting edge area, (III) chipping in the chisel area, (IV) breakage or complete destruction of the drill withdrawal of the drill from research

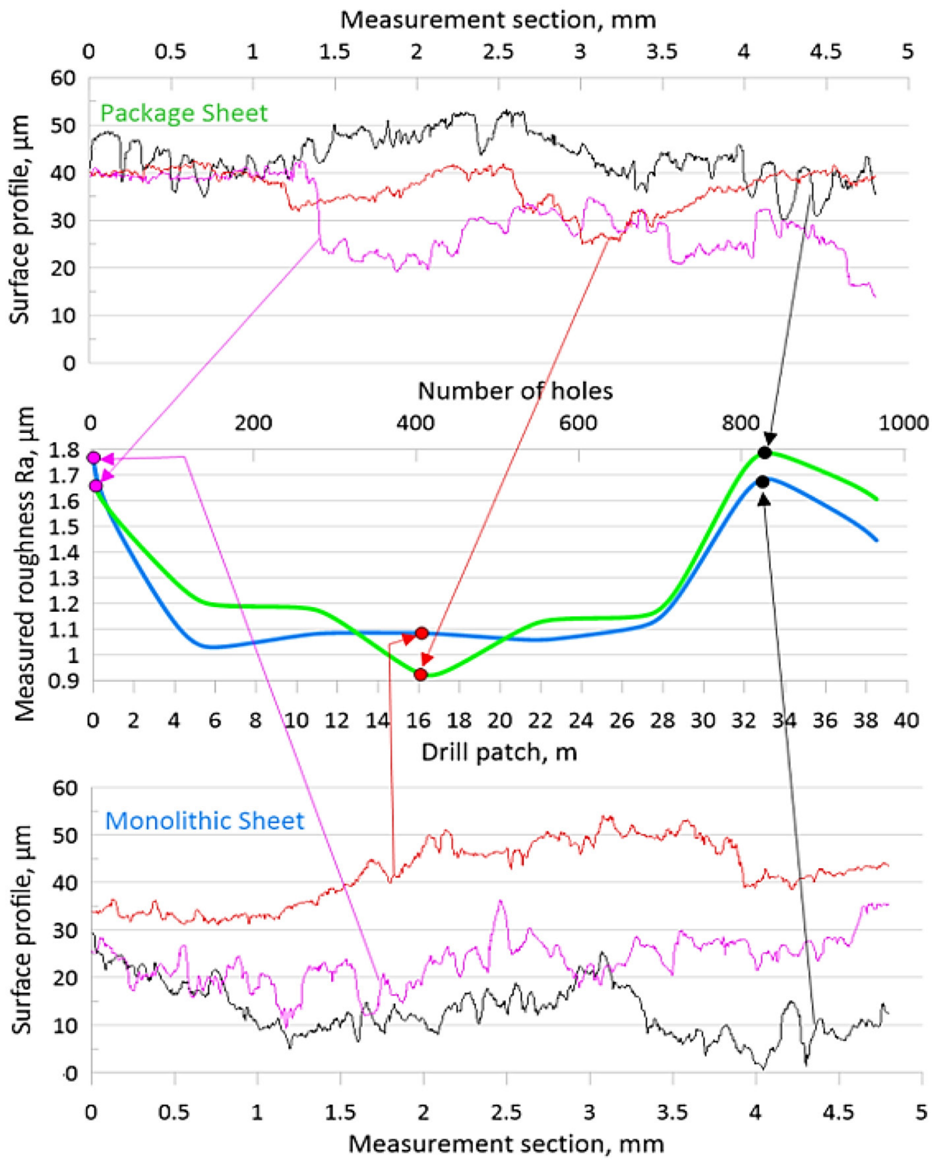


Figure 16. Profile of hole shape in package and monolithic sheet at different stages of tool wear

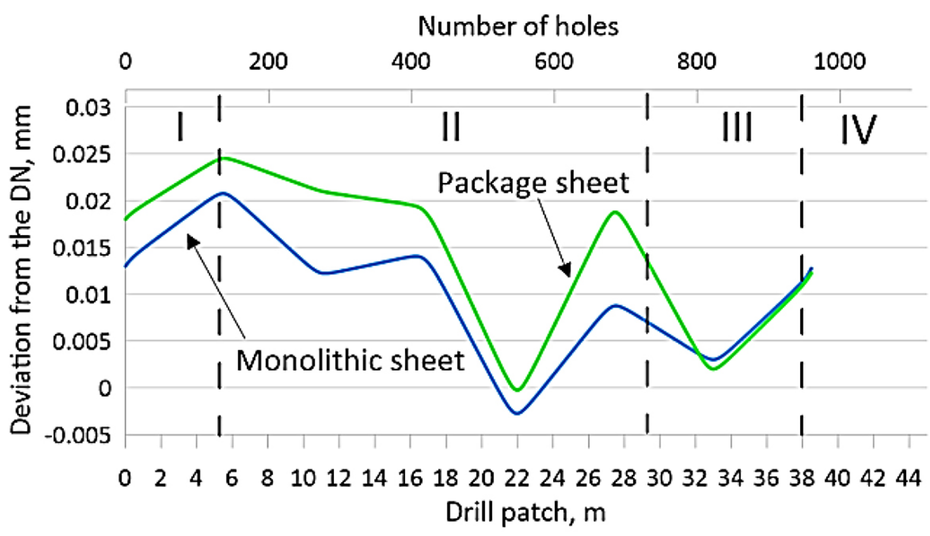


Figure 17. Measured deviation of holes in package and monolithic sheet in relation to tool wear

CONCLUSIONS

As a result of the conducted research, the authors drew the following conclusions. The use of double-insert drills in drilling package sheets is economically unjustified, mainly due to their poor service life and failure to ensure adequate quality of the shaped holes (up to 0.7 mm deviation from the nominal diameter). Such drill bits, after making a few holes in the package sheet, already have signs of wear. It should be assumed that in the case of solid sheet metal, where high hole accuracy is not required, the selection of double-plate drills may be a good solution.

The head drills with the best characteristics in the testing made holes with a spread of up to 0.025 mm in monolithic sheets and up to 0.04 mm in package sheets. Increasing the drilling speed from n = 870 rpm to n = 1200 rpm without change in coolant concentration from cc = 8% to cc = 12 % reduced the drill life from 25 m to 20 m of drill path. Increasing the emulsion concentration (at 1200 rpm) from 8% to 12% increased the tool life by ~100% (from 20 m of drill path to 40 m of drill path in the material), which clearly indicates the significant impact of the use of cooling and lubricating agents. While head drills become chipped in the chisel edge area, this damage progresses in a gradual manner and does not disqualify the drill when it occurs. With the gradual wear of the drill bit, the roughness of the completed hole decreases even from *Ra* 1.7 to *Ra* 0.9. When the chipping occurs, the chisel edge area increases again to a value approximating the initial roughness.

It is noticeable that there is a minimum tendency for the diameter of the hole to change with the progressive wear of the tool while the scale of the deviation is fully acceptable. The deviation of the measured diameter from the nominal diameter is within a range of up to 0.025 mm.

Acknowledgments

This work/research was supported by the Ministry of Science and Higher Education within the framework of the Polish Metrology II Programme, Project entitled:„Multisensor system for measuring thermo-mechanical interactions together with a comprehensive analysis of the state" on the basis of Contract No. PM-II/SP/0040/2024/02.

REFERENCES

1. Feldshtein E, Lisovskaya Y. The effectiveness of nanolayer coatings when drilling through holes in the plates of un-ferrous alloys. Mechanik. 2015 Sep;(8–9):722/159-722/167.
2. Classification of Heat Exchangers. In: Fundamentals of Heat Exchanger Design [Internet]. John Wiley & Sons, Ltd; 2003. p. 1–77. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470172605.ch1
3. Warke V, Kumar S, Bongale A, Kamat P, Kotecha K, Selvachandran G, et al. Improving the useful life of tools using active vibration control through data-driven approaches: A systematic literature review. Eng Appl Artif Intell. 2024 Feb 1; 128: 107367.
4. Jurko J, Panda A. Identification the tool wear mechanisms and forms at drilling of a new stainless steels. AASRI Procedia. 2012 Jan 1; 3: 127–32.
5. Liu CH, Sugihara T, Enomoto T. Interrupted cutting of Inconel 718 with AlTiSiN coated cemented carbide tool under high pressure coolant supply. Precis Eng. 2022 Nov; 78: 124–33.
6. Vilanova AM, Vaz GS, Souza AJ, Passari ÉS. Comparative study of drilling super austenitic stainless steel with external applications of reduced quantity nanofluid and flooded bio-lubricant. Mater Today Proc. 2023 May.
7. Vignesh V, Satish S, Gopi V, Jishnoop J, Menon GA. Comparison of coated and uncoated HSS drill bit on surface roughness, material removal rate and dimensional accuracy of SS410 stainless steel. Mater Today Proc. 2022;58:13–9.
8. Zbigniew Vogel. Temperatura skrawania przy wierceniu i jej rozkład wzdłuż krawędzi skrawających wiertła. Zeszyty Naukowe Politechniki Śląskiej. 1969;
9. Pelikán L, Slaný M, Stránský O, Beránek L, Pitrmuc Z, Čepová L, et al. Novel drill geometries for dry drilling of stainless steel. J Manuf Process. 2023 Apr;92:500–20.
10. Marzouk SA, Aljabr A, Awjah Almehmadi F, Alam T. Dynamic thermal analysis and drill bit temperature in AISI 430 stainless steel. Thermal Science and Engineering Progress. 2024 Aug;53:102706.
11. Sultan AZ, Sharif S, Kurniawan D. Effect of Machining Parameters on Tool Wear and Hole Quality of AISI 316L Stainless Steel in Conventional Drilling. Procedia Manuf. 2015 Jan 1; 2: 202–7.
12. Mushtaq M, Ramesh B. A novel investigation on effect of process parameters on surface roughness while drilling normalized and annealed SAE 304 stainless steel and comparing the outputs with untreated stainless steel. Mater Today Proc. 2022;69:980–5.
13. Tubular Exchanger Manufacturers Association I. 1. Standards of the Tabular Exchanger Manufacturers Association. 2007.
14. American Petroleum Institute. API Standard 661. 2013;Seventh Edition.