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Original Article

Assessment of drilling kinematic configurations and their contribution to surface roughness formation in 40HM+QT steel

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ABSTRACT

The study investigates the influence of three different drilling kinematic systems on the surface roughness (Rt) of holes machined in quenched-and-tempered 40HM (AISI 4140) steel. A full experimental campaign was carried out using a CNC machining center and solid carbide internal-coolant drills. The spindle speed (n), feed per revolution (fn), and drilling kinematics were evaluated using a Taguchi L27 orthogonal array supported by ANOVA and response surface methodology (RSM). The results show that spindle speed is the most influential parameter (46.27% contribution to Rt variability), followed by the kinematic system (34.45%) and feed per revolution (19.28%). The most favorable surface roughness was obtained for the first kinematic system, combining tool rotation with an additional axial oscillation. Higher spindle speeds and a feed of 0.14 mm/rev yielded the lowest Rt values across most configurations. The findings highlight the importance of selecting an appropriate kinematic system, demonstrating that non-standard drilling kinematics can significantly enhance hole quality in heat-treated steels.

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INTRODUCTION

Drilling is one of the basic processes of material removal, commonly used in the manufacture of machine parts made of structural steel, tool steel, and difficult-to-machine alloys [1–3]. A particularly important area of research is the drilling of heat-treated steels, which, due to their high hardness, strength, and fatigue resistance, are difficult to machine [4–6]. During the drilling process, hardened and tempered steels generate significant cutting forces, increased temperatures, and intensive tool wear, which directly affects the surface quality of the holes made. One of the key indicators of this quality is surface roughness, which affects dimensional accuracy, joint durability, load-bearing capacity, and the functionality of machine components [7–9].

An important factor influencing the drilling process is the kinematic arrangement, i.e., the distribution of rotational and feed movements between the tool and the workpiece. In a classic system, the tool performs both rotational and feed movements, while in a reverse system, the workpiece rotates [10–12]. In mixed systems, the rotational movement is shared between the tool and the workpiece in different proportions, which changes the dynamic parameters of the process, chip removal, and temperature distribution. These differences directly affect cutting stability, vibration amplitude, and thermal conditions, which in turn influence sur-

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face roughness parameters such as Ra, Rz, and Rt [11, 12]. Despite the importance of kinematic arrangements, most available studies focus on classical drilling, indicating that the topic remains insufficiently explored in the literature. In the available studies on drilling, mathematical models describing surface roughness are rarely found, as emphasized by numerous authors. Balaji, Rao, and Murthy [13] developed a predictive model for the Ra parameter, taking into account the drill tip angle, feed rate, and spindle speed. Kumar and Singh [14] proposed a similar model structure, but included the type of drill bit as an additional factor. Other models presented in the literature, e.g., Kilickap et al. [15], are based only on cutting speed, feed rate, and drilling environment (dry, MQL, air), while Pakistani researchers [16] used a logarithmic approach, describing the Ra parameter as a function of rotational speed, feed rate, and depth of cuts. Ravindranath et al. [17] presented a more comprehensive model, including four input factors: workpiece material, rotational speed, feed rate, and drill coating, achieving an accuracy of 83%. One of the most extensive models was presented by Indian authors [18], who took into account as many as five input parameters – tool type, rotational speed, feed rate, drill diameter, and workpiece material – achieving a high correlation between the model and experimental results, reaching 98%. However, the vast majority of publications focus not on the development of mathematical models, but on the analysis of the impact of individual or several technological parameters on hole roughness. Aamir et al. [19] studied the impact of feed rate and rotational speed, while Italian authors [20] analyzed 3D height and amplitude parameters (Sa, Sq, Ssk, Sku). Khanna et al. [21] assessed the importance of cooling conditions, and German researchers [22] focused on Rz parameters for different tools. Wegert et al. [23] analyzed the Ra, Rz, and Rt parameters depending on the drilling depth, and researchers from India [24] took into account the presence of cooling, feed rate, rotational speed, and hole depth, basing their analysis on an L18 orthogonal table. Subsequent studies concerned, among other things, the optimization of drilling parameters [25, 26], analysis of the influence of drill geometry [27], the influence of rotational speed [28], the impact of feed and cutting speed [29], evaluation of the design of cooling channels, the use of LN_2 and LCO_2 cryogenic cooling [30], and the influence of tool coatings [31, 32]. In summary, the world literature indicates a large number of studies on the influence of technological parameters on hole roughness, but there are few studies that take into account different kinematic arrangements of the drilling process. There is therefore a need for further exploration of the influence of the kinematic system on surface roughness, especially in the case of heat-treated steels, where machining conditions are particularly demanding. A thorough understanding of these relationships may contribute to the development of more effective machining strategies and improve the quality of holes made in materials with increased hardness.

Recent studies have emphasized that drilling machinability and hole surface quality are strongly influenced not only by cutting parameters, but also by material condition and microstructural modifications resulting from alloying or heat treatment. Güldibi et al. [33] demonstrated that variations in aging conditions significantly affect drilling forces, surface quality, and tool wear in high-strength steels, highlighting the critical role of material state in drilling performance. Similarly, Baysal et al. [34] reported that microstructural refinement induced by rare-earth alloying in aluminum alloys leads to improved surface integrity and reduced thrust force during drilling.

Despite these advances, current literature predominantly focuses on conventional drilling kinematics, while the influence of alternative or non-standard kinematic configurations on surface roughness formation remains insufficiently explored. Therefore, the present study aims to fill this gap by systematically evaluating the effect of different drilling kinematic systems on the Rt surface roughness parameter in heat-treated 40HM (AISI 4140) steel.

MATERIALS AND METHODS

The material selected for testing was medium-carbon alloy steel 40HM (equivalent to AISI 4140), supplied in a heat-treated state (QT – quenching and tempering). This steel is commonly used in machine components subjected to high variable loads due to its favorable combination of high strength, impact resistance, and wear resistance. The process of hardening followed by tempering stabilizes the mechanical properties of the material and ensures a homogeneous structure with controlled hardness, which is crucial for precision machining. 40HM+QT steel is characterized by increased hardenability resulting from the presence of chromium and molybdenum, which promote the formation of a tempered martensitic-bainitic structure. This structure provides both high strength and adequate fracture resistance, which distinguishes this material from non-alloy structural steels. An additional advantage of 40HM steel is its good machinability compared to other high-strength steels, which is important for turning, drilling, and milling operations. These properties make 40HM steel suitable for manufacturing shafts, gears, pins, bushings, and other components exposed to high operational loads [35, 36]. Figures 1 and 2 depict the percentage chemical composition and properties of heat-treated steel 40HM (equivalent to AISI 4140).

The research was conducted using a machining center equipped with a twelve-position tool head in the VDI30 standard according to DIN 5480, enabling automatic replacement of fixed and rotating tools. The machine has a main spindle with a maximum speed of 5000 rpm, a rated power of 20 kW, and a maximum torque of 2200 Nm, which allows drilling processes to be carried out within a wide range of parameters, including in difficult-to-cut materials.

The design of the center is based on a rigid support frame with optimized geometry, ensuring high resistance to dynamic loads and minimizing vibrations and displacements of the tool-workpiece system. Such structural rigidity is essential for achieving high geometric accuracy and low surface roughness in drilled holes. In addition, the device is equipped with a coolant filtration system that maintains the

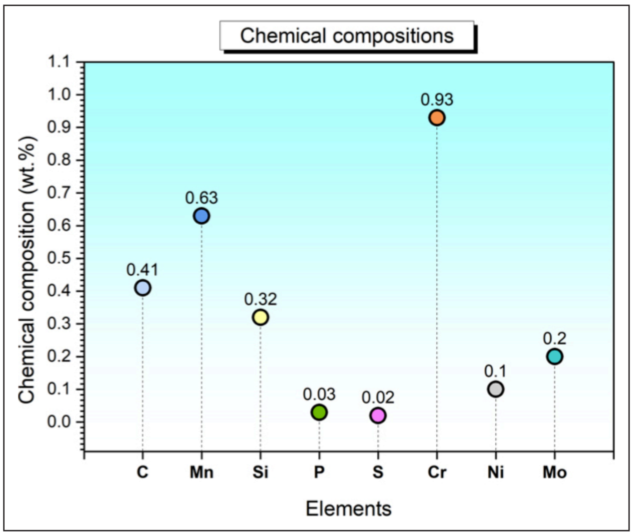

Figure 1. Chemical composition of heat-treated 40HM+QT steel.

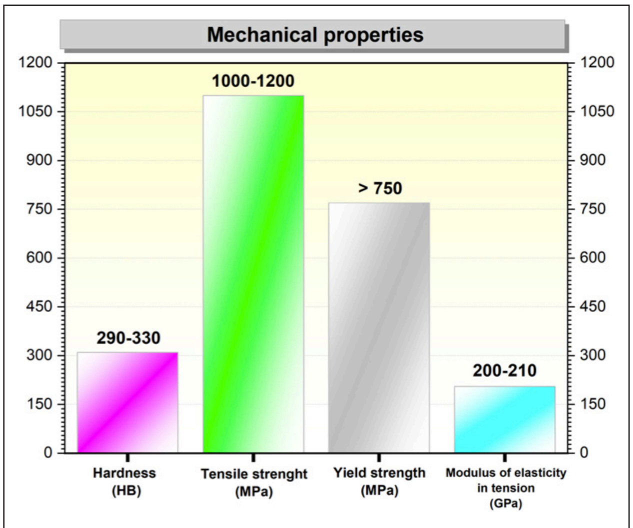

Figure 2. Properties of heat-treated steel 40HM+QT.

cleanliness of the machining fluid by effectively removing metal particles, which translates into increased tool life and improved surface quality of machined parts. The "DMG CTX Alpha 500 CNC machine" used in this experimental research is depicted in Figure 3.

In the experimental part, a monolithic drill with a diameter of 6 mm was used, equipped with internal channels supplying coolant directly to the cutting zone. This design promotes effective heat dissipation and efficient chip removal, which in turn reduces tool wear and has a positive effect on the quality of the machined hole surface.

The research included an analysis of three innovative methods of drilling. The first one involved a configuration in which the tool performs the main rotary motion and an additional reciprocating motion along the drilling axis, while the workpiece remains stationary, clamped in the soft jaws of a lathe chuck. A schematic diagram of this method is depicted in Figure 4. This configuration reduces cutting forces, improves chip evacuation, and minimizes adverse

Figure 3. View of the DMG CTX alpha 500 CNC machine.

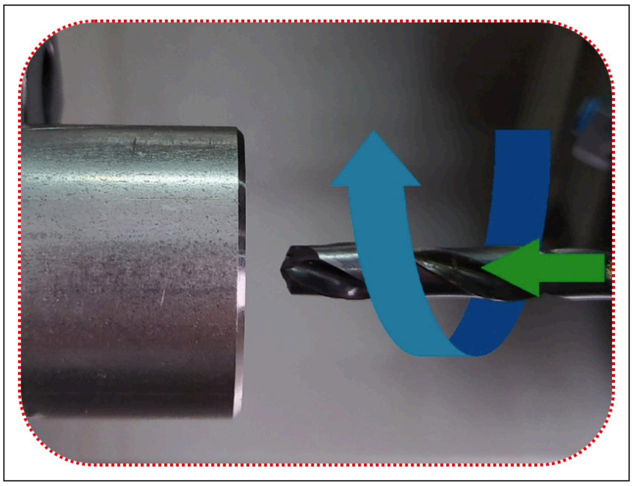

Figure 4. First kinematic system.

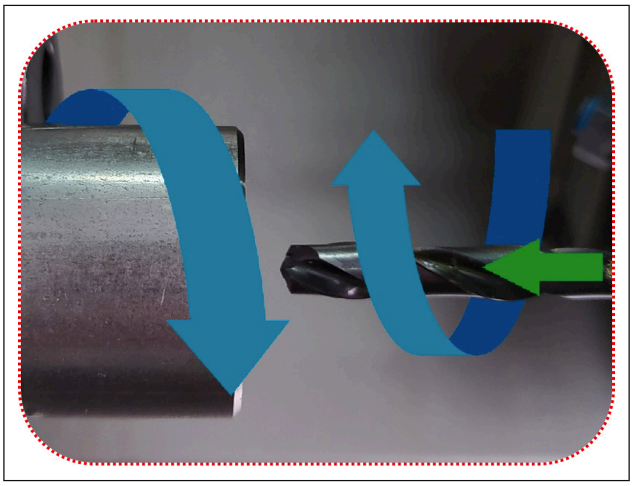

Figure 5. Second kinematic system.

effects associated with material expansion during drilling. In addition, the oscillatory motion helps to reduce internal stresses and improves the straightness of the hole.

The second solution analyzed was based on simultaneously setting both the tool and the workpiece in rotational motion, with both elements rotating in opposite directions (Fig. 5). This kinematic arrangement made it possible to

Table 1. Drilling process parameters used in the experiments

Factor	Symbol	Unit	Values
Spindle speed	n	rpm	3183, 3979, 4775
Feed per revolution	f_n	mm/rev	0.10, 0.12, 0.14
Kinematic system	KIN	-	I, II, III
Drill diameter	D	mm	6
Point angle of tool	-	°	140
Chip flute length	-	mm	44
Drill type	-	-	Solid carbide, internal coolant
Coating	-	-	TiAlNPlus
Cooling method	-	-	Flood cooling
Workpiece material	-	-	40HM (AISI 4140) + QT

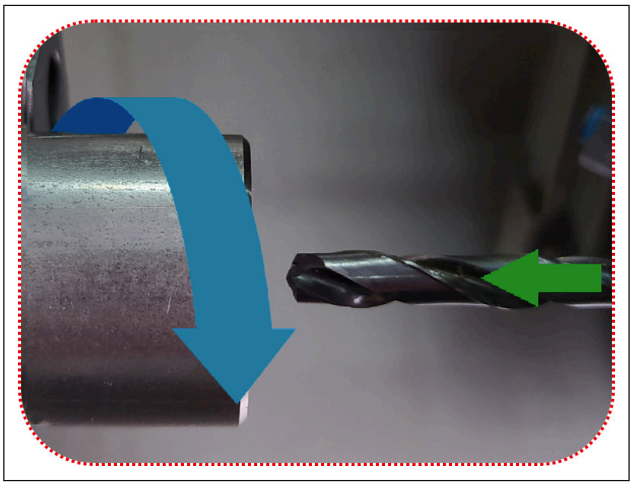

Figure 6. Third kinematic system.

achieve a total rotational speed corresponding to the values used in the first and third test configurations.

The use of counter-rotating movements leads to an increase in cutting speed in the tool-material contact area, which can contribute to the intensification of the stock removal process and reduce the formation of build-up on the cutting edge. Additionally, this motion configuration has been shown to reduce axial forces and improve geometric hole parameters of drilled holes, in particular their straightness and surface roughness.

This variant is an example of a non-standard approach to machining, in which the modification of the process kinematics allows for the optimization of cutting parameters and improvement of the quality of the results obtained.

The third drilling concept analyzed was based on a classic kinematic arrangement, in which the tool remains stationary in terms of rotational movement and only performs axial feed along the drilling direction, while the main rotational movement is performed by the workpiece (Fig. 6). This type of configuration is commonly used in traditional drilling operations, both on conventional and numerically controlled (CNC) lathes. In this system, the drill is mounted in a stationary holder, and the rotation of the workpiece results from the operation of the machine spindle. This configuration ensures high concentricity and repeatability of hole geometry, particularly in rotationally symmetrical components, and with appropriately selected feed and cooling parameters, it ensures efficient chip removal.

A set of combinations of various input parameters was created to carry out the experimental work (n = 3183; 3979; 4775 rpm, f_n = 0.1; 0.12; 0.14 mm/rev, KIN I, KIN II, KIN III). The kinematic system was recorded as equation (1) containing the resultant rotational speed of the cutting process.

$$KIN = n_n - n \tag{1}$$

where: KIN – kinematic system n_n – tool rotational speed, n – spindle rotational speed

To systematically investigate the influence of drilling parameters and kinematic configuration on surface roughness (Rt), the Taguchi design of experiments (DOE) method was employed. The Taguchi approach enables efficient evaluation of multiple control factors with a reduced number of experiments while maintaining statistical robustness.

In this experimental research, three control factors were selected: spindle speed (n), feed per revolution (f_n), and drilling kinematic system (KIN). Each factor was examined at three levels, resulting in a Taguchi L27 (3^3) orthogonal array. This design allows for the assessment of both main effects and interactions between parameters while minimizing experimental effort.

Table 1 summarizes the main drilling parameters and technological conditions applied in the experimental study. These parameters were selected based on tool manufacturer recommendations, preliminary trials, and machine tool limitations.

The selected spindle speed and feed per revolution levels were determined based on tool manufacturer recommendations for drilling heat-treated alloy steels, preliminary trial cuts, and the operational limits of the CNC machining center. The adopted parameter ranges ensured stable cutting conditions without excessive tool wear, chatter, or thermal damage while allowing a clear differentiation of surface roughness responses. The three kinematic systems were chosen to represent fundamentally different drilling motion configurations, including non-standard kinematic solutions, enabling a direct comparison of their influence on surface roughness formation under identical cutting conditions.

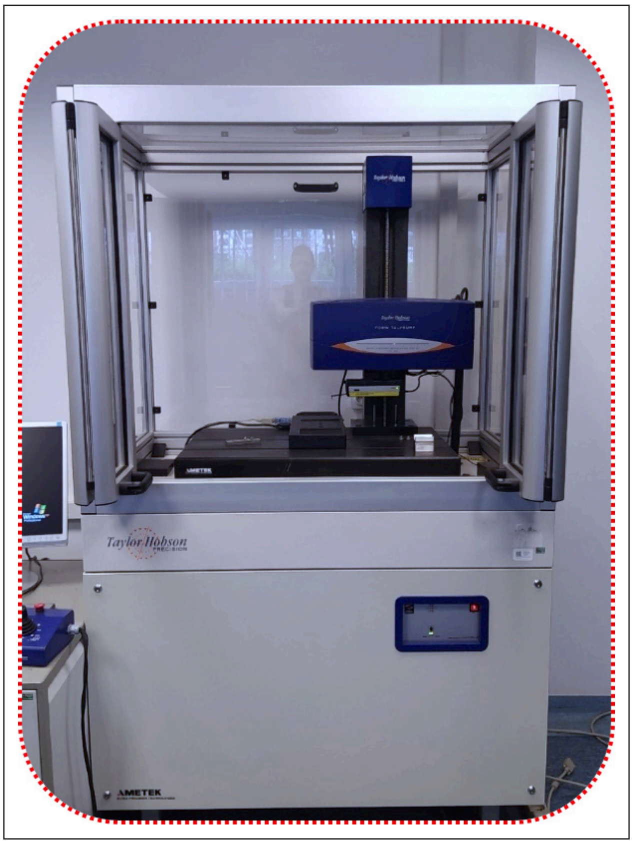

Figure 7. View of the Taylor Hobson Form Talysurf PGI 1230 contact profilometer used to measure hole surface roughness (Rt) in 40HM+QT. Measurements were taken on the internal sidewall at mid-depth.

In this experimental research, surface roughness was determined using a Taylor Hobson Form Talysurf PGI 1230 contact profilometer (Fig. 7). The device used ensures high measurement accuracy and repeatability of the results obtained.

The design of experiments (DOE) approach was then applied, using an orthogonal L27 matrix in accordance with the Taguchi method. This allowed for the simultaneous evaluation of the influence of spindle speed (n), feed per revolution (f_n), and kinematic drilling variant as input factors on surface roughness (Rt) as a response. A multi-factor analysis of variance (ANOVA) was performed to determine the significance of individual parameters and their interactions. The approach used made it possible to reduce the number of necessary trials while maintaining statistical reliability, providing a solid basis for identifying the key factors affecting the quality of the holes made.

RESULTS AND DISCUSSION

Table 2 depicts the experimental results obtained within the scope of this research. The following results are presented in relation to the roughness Rt of the 40HM+QT samples. The study utilized a total of 27 samples.

Table 2. Experimental results

Trial	*n*, rpm	f_n, mm/rev	KIN, rpm	Rt, µm
1	4775	0.14	4775	2.222
2	4775	0.14	-4775	3.698
3	4775	0.14	0	3.806
4	3979	0.14	3979	3.835
5	3979	0.14	-3979	4.138
6	3979	0.14	0	4.336
7	3183	0.14	3183	3.711
8	3183	0.14	-3183	3.822
9	3183	0.14	0	4.254
10	4775	0.12	4775	3.594
11	4775	0.12	-4775	4.38
12	4775	0.12	0	4.003
13	3979	0.12	3979	3.987
14	3979	0.12	-3979	4.254
15	3979	0.12	0	4.574
16	3183	0.12	3183	4.054
17	3183	0.12	-3183	4.107
18	3183	0.12	0	3.945
19	4775	0.1	4775	3.924
20	4775	0.1	-4775	4.215
21	4775	0.1	0	4.209
22	3979	0.1	3979	4.277
23	3979	0.1	-3979	4.116
24	3979	0.1	0	4.235
25	3183	0.1	3183	4.152
26	3183	0.1	-3183	4.371
27	3183	0.1	0	4.006

KIN: Kinematic system.

The experimental results revealed a significant variation in the Rt surface roughness values depending on the drilling parameters and kinematic configuration. The lowest Rt value of 2.222 µm was obtained for the first kinematic system (KIN I) at a spindle speed of 4775 rpm and a feed of 0.14 mm/rev, whereas the highest Rt value reached 4.574 µm for the third kinematic system (KIN III) at 3979 rpm and a feed of 0.12 mm/rev. This corresponds to an increase in surface roughness of approximately 106%, indicating a substantial deterioration in surface quality when unfavorable kinematic and cutting conditions are applied. On average, the use of the first kinematic system resulted in Rt values that were approximately 30–45% lower compared to the second and third kinematic configurations, confirming the beneficial effect of superimposed axial oscillation on surface quality. The Rt values obtained within the scope of this experimental research are depicted in Figure 8.

Analysis of variance (ANOVA) was performed using the response surface method (RSM), which is a structured approach to modeling and optimizing process results depending on input variables (Table 3). This method combines the features of polynomial regression, which describes the vari-

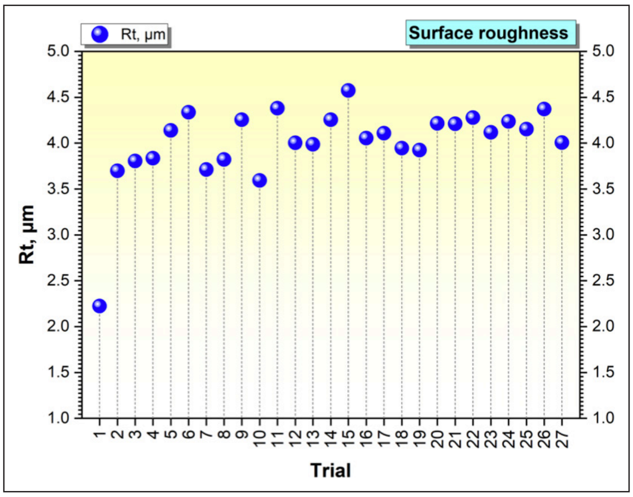

Figure 8. Rt values obtained within the scope of this experimental research.

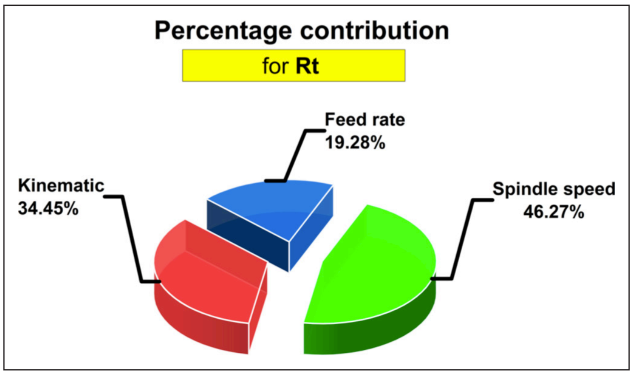

Figure 9. Percentage contribution for Rt.

ability of the response as a function of the numerical values of independent variables, and factorial regression, which is characteristic of classical experimental designs. The response surface regression model allows for both linear and nonlinear (quadratic) effects, as well as interactions between factors. The generalized form of the model for two independent variables is represented by the following equation (2):

$$Y=b_0+b_1 X_1+b_2 X_2+b_3 X_1^2+b_4 X_2^2+b_5 X_1 X_2 \quad (2)$$

where:

– y – the value of the response variable (e.g. Rt),

– b_0 – free expression,

– b_1, b^2 – linear regression coefficients,

– b_3, b_4 – quadratic regression coefficients,

– b_5 – interaction coefficient between variables.

In the context of this experimental research, the contribution rates obtained as a result of the ANOVA analysis are depicted in Figure 9.

Figure 9 depicts that spindle speed accounted for 46.27% of the variation in the Rt parameter. The kinematic system had an impact of 34.45%, while the rest was attributable to the feed per revolution (19.28%).

In analyzing kinematic system (equation 3),

$$Rt_{40HM}=-10.44+4.52\cdot10^{-3}\cdot n-4.31\cdot10^{-7}\cdot n^2+ +111.22\cdot f_n-342.91\cdot f_n^2+3.77\cdot10^{-4}\cdot KIN+ -1.42\cdot10^{-8}\cdot KIN^2-9.84\cdot10^{-3}\cdot n\cdot f_n-4.99\cdot10^{-8}\cdot n\cdot KIN+ -1.83\cdot10^{-3}\cdot f_n\cdot KIN \quad (3)$$

where: n – spindle speed value, f_n – feed rate per revolution, KIN – kinematics, $n\cdot f_n$ – interaction of spindle speed value with feed rate per revolution, n· KIN – interaction of spindle speed value with kinematics, $f_n\cdot$ KIN – interaction of feed rate per revolution with kinematics. As seen in Figure 10, the main effects plot is depicted.

The data presented in Figure 10 depicts that using a rotational speed of 4775 rpm, the lowest Rt parameter value of 3.783 µm was obtained, which corresponds to a reduction in surface roughness of approximately 17–18% compared to the highest Rt values recorded at the lowest rotational speed used in the experiments. The most favorable feed rate per revolution, for which the Rt parameter value of (Rt =

Table 3. ANOVA statistical analysis for the roughness Rt drilled in 40HM+QT

Source	SS	DF	MS	F	p	PC
Model	3.6093	9	0.4010	5.9780	0.0008	
Constant	0.2835	1	0.2835	4.2264	0.0555	
n	0.6583	1	0.6583	9.8135	0.0061	21.84
n^2	0.4486	1	0.4486	6.6866	0.0192	14.89
f_n	0.1893	1	0.1893	2.8221	0.1113	6.28
f_n^2	0.1129	1	0.1129	1.6827	0.2119	3.75
KIN	0.4155	1	0.4155	6.1936	0.0235	13.79
KIN2	0.3510	1	0.3510	5.2316	0.0353	11.65
n·fn	0.2945	1	0.2945	4.3904	0.0514	9.77
n·KIN	0.2806	1	0.2806	4.1834	0.0566	9.31
fn·KIN	0.2629	1	0.2629	3.9186	0.0642	8.72
Error	1.1405	17	0.0671			24.01
Total	4.7498	26				100.00

KIN: Kinematic system.

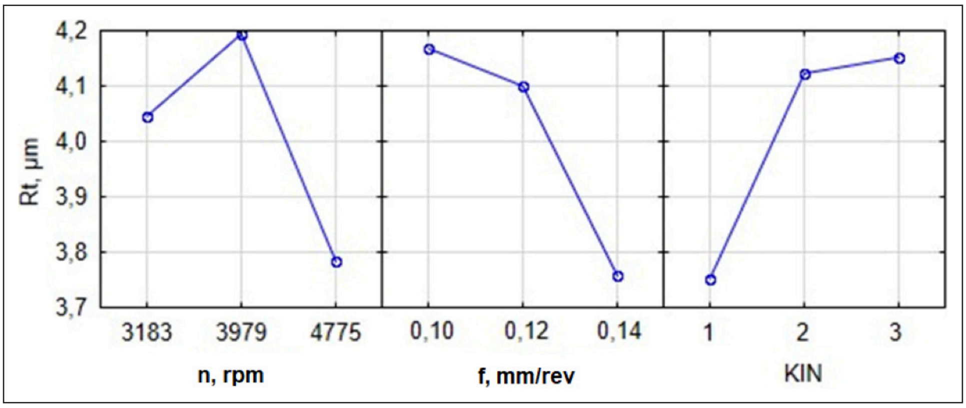

Figure 10. The main effects plot for Rt.

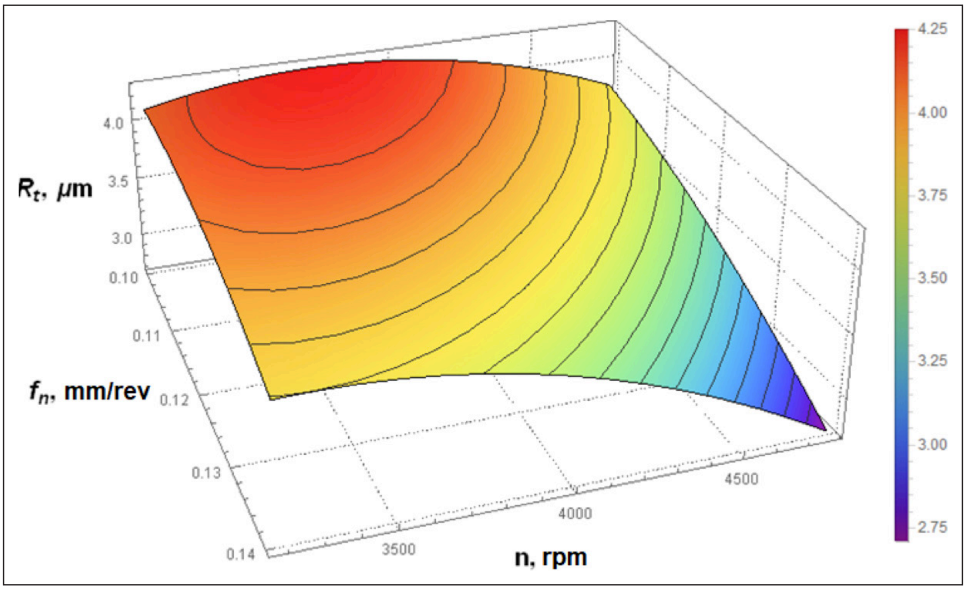

Figure 11. Influence of technological parameters in the first kinematics on the Rt parameter of a hole in heat-treated 40HM+QT steel based on equation (3).

3.758 µm) was obtained, is 0.14 mm/rev, representing an improvement in surface roughness of approximately 10-12% in comparison with the least favorable feed rate applied in this study. Using the first kinematic system in the process of drilling heat-treated 40HM+QT steel, the lowest Rt parameter value of 3.751 µm was obtained, which is approximately 18-19% lower than the Rt values obtained using the third kinematic system. It was observed that reducing feed per revolution generally decreases the Rt value.

Graphical simulations based on response surface regression (RSM) enable visual representation of the relationship between input parameters (spindle speed, feed rate per revolution, and kinematic drilling variant) and output responses (surface roughness Rt). The developed models provide a consistent tool for assessing the impact of technological variables on hole quality and allow for comparison of the effectiveness of different drilling process variants.

Analyzing Figure 11 for the first kinematic system, it was found that using the highest tested feed rate per revolution of 0.14 mm/rev and the highest spindle speed of 4775 rpm, the lowest Rt parameter value was obtained. In this case, changing the spindle speed and feed per revolution significantly worsens the Rt parameter.

When analyzing Figure 12 for the second kinematic system, it was found that using the smallest feed per revolution of 0.1 mm/rev and the lowest spindle speed of 3183 rpm resulted in the lowest Rt parameter value. In this case, using the highest feed value 0.14 mm/rev and the highest tested spindle speed value also resulted in the lowest Rt parameter value.

On the other hand, when analyzing Figure 13 for the third kinematic system, it was noticed that using the highest feed rate per revolution of 0.14 mm/rev and the highest spindle speed of 4775 rpm resulted in the lowest Rt parameter.

CONCLUSION

The experimental results clearly demonstrate that the kinematic system applied during drilling plays a decisive role in shaping the surface roughness of holes machined in heat-treated 40HM+QT steel. Based on the Taguchi L27 design, ANOVA, and RSM modeling, the following conclusions can be drawn:

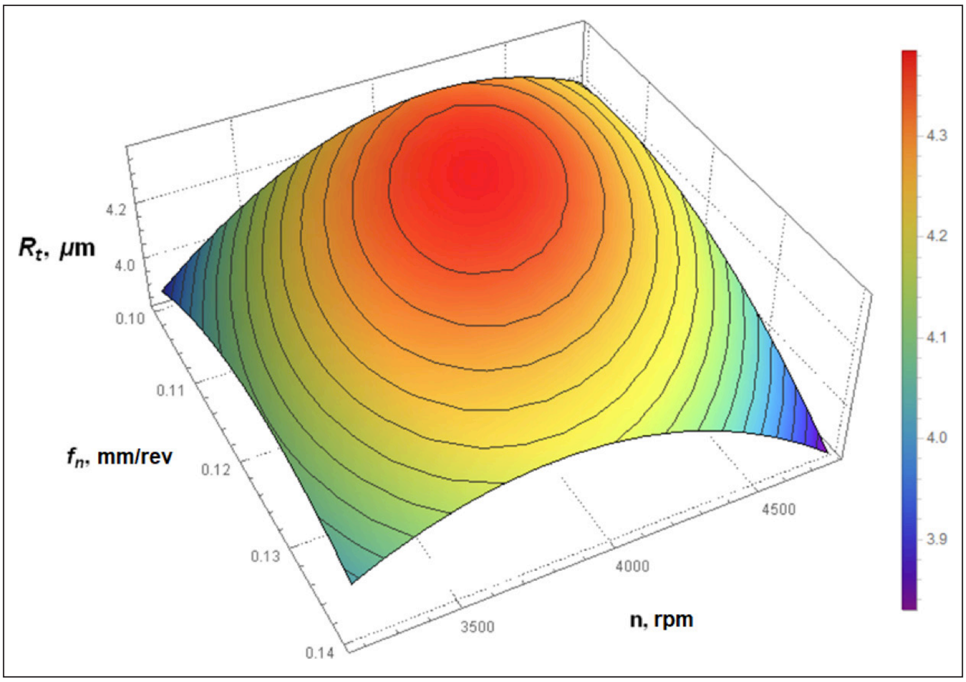

Figure 12. Influence of technological parameters in the second kinematics on the Rt parameter of a hole in heat-treated 40HM+QT steel based on equation (3).

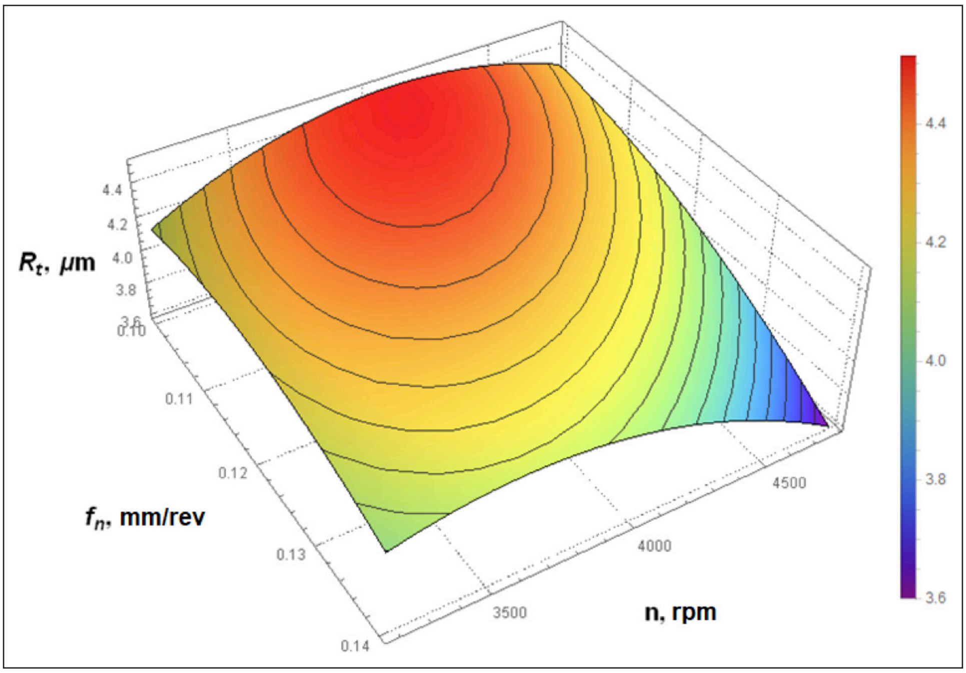

Figure 13. Influence of technological parameters in the third kinematics on the Rt parameter of a hole in heat-treated 40HM+QT steel based on equation (3).

- Spindle speed (n) was the dominant factor, accounting for 46.27% of the total influence on the Rt parameter. Higher spindle speeds generally resulted in lower roughness values due to more stable chip formation and reduced cutting force fluctuations.
- The kinematic system contributed 34.45%, confirming that the way rotational and feed motions are distributed between the tool and the workpiece has a substantial impact on the dynamic behavior of the process.
- The first kinematic system, combining tool rotation with an additional axial oscillation, provided the lowest overall Rt values (3.75 μm).
- The oscillatory component improves chip evacuation and reduces built-up edge formation, resulting in smoother surface profiles.
- Feed per revolution (19.28% contribution) showed a less pronounced but still relevant effect.
- Interestingly, the lowest Rt values were often obtained at

the highest tested feed of f_n = 0.14 mm/rev, which suggests more stable chip segmentation within the tested range.

- RSM visualizations confirmed that the combination of high spindle speed and the first kinematic system forms the most favorable drilling conditions for achieving minimal Rt values.
- The results also show that for the second and third kinematic systems, optimal parameter windows differ significantly, indicating that each kinematic variant should be optimized independently rather than by direct parameter translation.
- Overall, the study demonstrates that non-traditional kinematic systems can significantly improve surface roughness in drilling heat-treated steels, and may be considered a practical alternative for boosting hole quality without additional technological modifications.
- The findings provide a foundation for future optimization of drilling operations in difficult-to-cut materials and indicate that kinematic configuration should be treated as a primary process parameter rather than an auxiliary factor.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Mehmet Şükrü Adin: Conception, Design, Supervision, Analysis and Interpretation, Literature Review, Writer, Critical Review.

Mateusz Bronis: Conception, Materials, Design, Data Processing, Supervision, Analysis and Interpretation, Literature Review, Writer, Critical Review.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Statement on the Use of Artificial Intelligence

Artificial intelligence was not used in the preparation of the article.

Ethics

There are no ethical issues with the publication of this manuscript.

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