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Investigation of thrust force, torque and chip formation in tapping threading by finite element method

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Investigation of Thrust Force, Torque and Chip Formation in Tapping Threading by Finite Element Method

Highlights

- *The presented work focuses on the analysis of tapping operations with Third Wave AdvantEdge.*
- *There was a 75% to 97% similarity between the simulation results and the experimental results.*
- *The best convergence for thrust forces and torque occurred with hole diameters of 8.3 mm and 8.4 mm*
- *In terms of experimental and simulation results, the best convergence occurred in A303 coded tools.*
- *The chip forms in the experiments and those obtained in the simulation are similar to each other.*

Graphical Abstract

In this study, the thrust forces and torque values that occur in tapping processes with coated and uncoated tapping tools with different forms were investigated. The results obtained after the experiments were compared with the simulation results. In addition, chip shapes that occur during cutting are simulated.

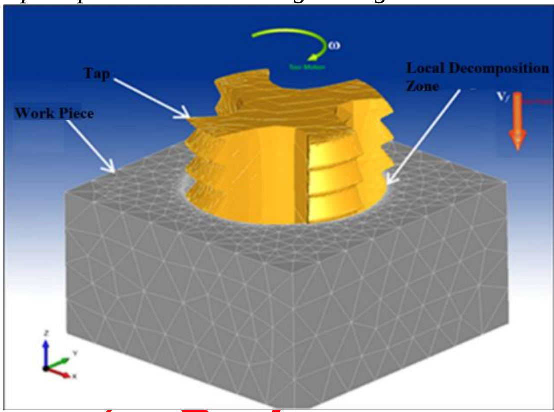

Figure 1. Movements of the tapping tool

Aim

In this study, aims to determine the thrust forces and torque values that occur in tapping processes with coated and uncoated tapping tools in different forms and to simulate these values with the help of the Third Wave AdvantEdge program.

Design & Methodology

Cutting tools in three different geometries were used in the study. Point clouds were created by using the three-dimensional laser scanner of the cutting tools used in the study. These point clouds were converted to STL format with Geomagic Design X. This STL format was transferred to the Catia program and 3D models of the cutting tools were obtained by combining point clouds.

Originality

When the literature review is examined, it is seen that there are a limited number of studies on tapping in general. In this study, the thrust forces that occur in tapping with different forms of tapping tools were investigated and simulated.

Findings

In general, it has been observed that the thrust force decreases as the hole diameter increases. The highest thrust force values occurred in the holes drilled with 8.3 mm.

Conclusion

It has been observed that there are similarities between the simulation results and the experimental results, varying between 75% and 97%.

Declaration of Ethical Standards

The author(s) of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Investigation of Thrust Force, Torque and Chip Formation in Tapping Threading by Finite Element Method

Research Article

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ABSTRACT

Threading with taps is a method frequently used in machining. Since this process takes place in a closed area due to its nature, some difficulties are encountered. In this study, the results of a previous experimental work were compared with the results of a simulation program. In the experimental work, the tapping process was performed using M10 taps with three different geometries for the drilled holes on AISI 1050 material. Tapping operations were carried out with uncoated and TiN coated HSS tools. For the simulation program, the 3D CAD models of the tested taps were created by reverse engineering method and then imported into a simulation program, called Third Wave AdvantEdge program. The CAD models were evaluated by Third Wave AdvantEdge program based the finite element method. The thrust force, torque, chip formation occurring during the threading process were examined. It was concluded that the simulation and the experimental results were quite compatible.

Keywords: Tapping, thrust force, simulation, chip forms, finite element method.

1. INTRODUCTION

With the present technology, the concepts of quality and cost have gained more importance in the manufacturing industry. These concepts are directly related to the selection of suitable cutting tools and cutting conditions [1]. Many parameters need to be considered for the selection of the appropriate tap in thread tapping operations [2]. The ratio of cutting tool costs to total cost in machining operations is quite high. For this reason, the selection of the cutting tool and cutting parameters is important for optimum tool life. Breaking of cutting tools is one of the most important problems, especially in machining operations carried out in closed areas such as tapping and drilling. Therefore, studies on thread tapping, which is one of the machining processes that are frequently used in the aerospace industry, are frequently encountered in the literature. Some of these studies are as follows.

Gökçe and Yavuz investigated the impact of cutting speed on thread tapping in commercial grade molybdenum. They used HSS drills in their work. In the study, they concluded that material losses occur during tapping and these losses are higher at low cutting speeds [3].

Uzun and Korkut investigated the effects of cutting parameters on tool life and torque during tapping on AISI 304 stainless steel. They tried to indentify the depth of cut during thread cutting for each cutting feed rate (Q). As a result, they reached the best tool life at 5 mm Q for M5 tap and 3 mm Q for M6 tap [4]. Uzun and Korkut investigated the effects of the cryogenic treatment applied to the cutting tool on the cutting torque during the tapping process. They have seen that the cutting torque obtained with the cryogenically treated cutting tools is lower [5]. Ma et al. investigated the dynamics of tapping. To reduce the effects of feed rate error and spindle speed error, a well-optimized series of rigid tapping experiments were performed. They stated that the large chamfer of the tap may cause unstable machining [6]. Kayır examinated the influence of the hole diameter on the thrust forces in AA5083 material with tapping tools. In the study, four different diameter holes were drilled. It was concluded that the torque during cutting decreased with the increase of hole diameters [7].

In addition to these experimental studies, using various modeling methods are available in the literature. Yağır and Mete made numerical model analysis of tapping process in process reducer mold design. They observed that there was an increase in temperature after tapping and most of the temperature progression was in the direction of material advancement [8].

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Armarego and Chen performed predictive cutting models for force and torque in machine tapping formed straight flute. They concluded that thrust force and torque can be predicted [9]. Cao and Sutherland investigated the load occurring in tapping processes by mechanical modeling method. They reported the factors causing tap breakage by causing severe chip clogging and excessive torque after the study [10]. Karuppusamy et al. analyzed the square threading process using response surface methodology. Experiments were carried out in dry conditions and using oil. They concluded that chip clogging can be reduced thanks to improved chip containment and chip evacuation and an optimized design in the tap geometry [11]. Lee et al. developed an analytical mechanical thrust forces model for thread milling operations. They concluded that the thrust forces model proposed for threading can be used to fit cutting parameters, for example, feed per tooth and axial depth of cut to increase productivity in practical applications [12]. Araujo et al. developed a mechanical model for the estimation of threading forces. In the study, they examined the thrust forces and stated that the model predicted the test results within 10% error [13].
Besides these works, studies using different finite element methods are available in the literature. The finite element method is a frequently used method for modeling various machining processes [14-18]. However, this method has been used sparingly for tapping [19]. Although the finite element method is rarely used for tapping, it has been widely used for pre-tapping drilling. Biermann and Oezkaya carried out a simulation using the Computational Fluid Dynamic (CFD) method to reduce tool wear. As a result of the CFD simulation, they determined that the cutting edges were not cooled sufficiently [20]. Kheireddine et al. the hardness of the holes in the drilling of Mg AZ31B material was analyzed using finite elements. They stated that the hardness values measured from cryogenically cooled holes were higher than the hardness values in uncooled holes [21]. Yıldız et al. analyzed the drill stresses theoretically with finite element simulation for drilling operations. After the study, they concluded that the stress analysis would significantly contribute to the improvement of the cutting performance and the selection of the optimum cutting parameters. Moreover, they emphasized that the stress analysis can be applied to other machining processes, for example, turning and milling [22].

In this study, thrust force, torque, and chip formation during tapping were investigated. Unlike the literature Third Wave AdvantEdge program, which evaluated with the finite element method, was used for the simulations.

2. MATERIAL AND METHOD

In the experiments, AISI 1050 material, which is easy to machine and can be heat treated, was used. Material dimensions are 65x50x30 mm. Holes have been drilled all the way through. The chemical properties of the test sample are given in Table 1 and the physical features are illustrated in Table 2. Test specimens were drilled in the diameters 8.3, 8.4, 8.5, and 8.6 mm and tapped with M10x1.5 machine tap.

Table 1. Chemical properties of the AISI 1050 material

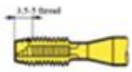
C	Si	Mn	P	S	Cr	Ni	Mo
0.533	0.293	0.883	0.033	0.012	0.255	0.183	0.098

Table 2. Physical properties of the AISI Material

Thermal conductivity	51.9 W/m°C
Specific heat	470 J/kg°C
Melting temperature	1440-1460 °C
Intensity	7800 kg/m³
Coefficient of thermal expansion	1.2E-5 1/°C

The three types of M10 tapping tools, which were TiN-coated and uncoated HSS (Blau brand), were tested in the experiments. Coated and uncoated tools are of the same type. Cutting tool types and geometric specs are shown in Table 3.

Table 3. Tap types and forms

Screw Size	Tap Shape (DIN 371)		Head Shape	Channel Type	Material
M10x1.5	Form B		15°	Flat	HSS/TiN Coated HSS
	Form C		Flat	15° Helical	HSS/TiN Coated HSS
	Form C		Flat	30° Helical	HSS/TiN Coated HSS

The experiments were done on the Johnford VMC-550 CNC vertical machine tools in Gazi University, Faculty of Technology, Department of Manufacturing Engineering. In order to measure thrust forces and torque, Kistler 9272 type dynamometer operating on the basis of quartz crystal were used. The force-measuring device is given in Figure 1. As a result of the cutting tool manufacturer's recommendation and literature research, the cutting speed was determined as 10 m/min and the feed rate as 1.5 mm/rev. [2,3,7]. Experiments were carried out in two repetitions. Boron oil was used as the cooling liquid during the tapping process.

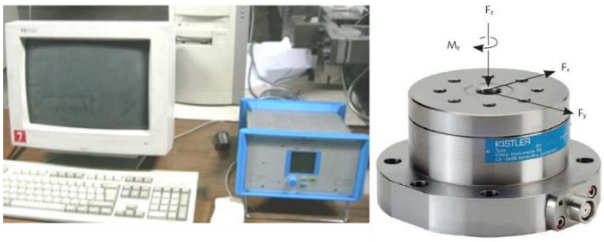


Figure 1. Force measuring device

In the modeling of the cutting tools, a point cloud of the taps was created by using a three-dimensional laser scanner. The point data was evaluated by the Geomagic Design X software for converting the STL format. Further, the STL file was opened with a CAD program, and 3D models of the taps were generated. These models are shown in Figure 2.

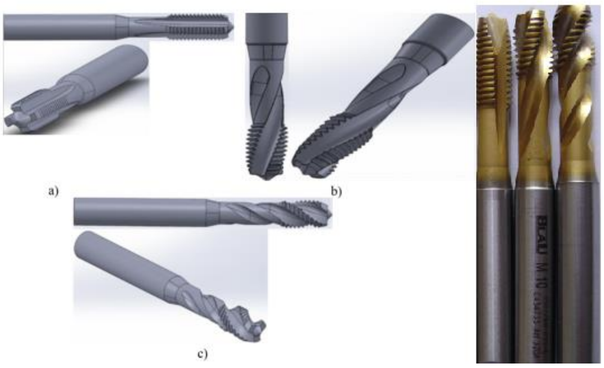


Figure 2. 3D images of taps [23] a) A303 b) A320 c) A330

Third Wave AdvantEdge (or AdvantEdge for short); is a simulation program used by aerospace, automotive, medical, and cutting tool companies to improve their machining processes. In the finite element method, it is important to determine the meshing assignment process correctly, to prevent the solution time from taking too long and to obtain correct results. In similar studies [24, 25], the largest element size of 0.2 mm and the smallest element size of 0.012 mm were preferred for mesh generation. After the meshing process, 3 simulations were run to identify how many turns the tap would be rotated. In these simulations, the 1080º was used for the rotation of the tap so that the screw with a length of 3 steps was obtained. In this way, the process might take 36 days which means roughly 12 days for each step. Korkmaz et al. [24], in their study involving drilling simulation, ran the simulation by giving a 60º rotation to the drill for a drilling simulation in the AdvantEdge program. Similarly, in this study, 3 trial simulations were run by making the tap rotate 60º. The thrust forces and torque values were compared for the simulation results obtained by rotating the tap by 60º and by rotating the tap by 1080º corresponding to 3 full turns. An acceptable amount of variation (1.5-3.5%) was observed in the data obtained due to the rotated tap by 60º and 1080º. Thus, the rotation movement of the tap was preferred as 60º in this work. In this study, the dimensions for the test material model were decided as 15x8x15 mm so that all the teeth of the taps are in full contact with the workpiece. The AdvantEdge program library contains many standard materials. Material assignments can be made from the program library as well as special material assignments. As a result of the trial simulations using the material model data in the program; It was observed that the differences between the experimental and simulation results were over. For this reason, several iterative trials were made to detect the appropriate Johnson-Cook parameters. In these trials, similar studies in the literature [25] were taken as reference, and Johnson-Cook material models [26, 27] used in the literature were used for AISI 1050. The new material model created for AISI 1050 material is given in Table 4. As a result of the comparison of the experiment and simulation results, the most appropriate model parameters were obtained with the A, B, C, and n values in Soldani's [27] study and the revised m value. During the iterative trials, the thermal softening value (m) lead to a decrease the thrust force, but the C value affected the torque values conversely.

Table 4. New material model created for AISI 1050

A (Mpa)	B (Mpa)	n	C	m
553,1	600,8	0,234	0,2	0,003

A single layer TiN coating with a thickness of 0.002 mm was formed for the coated tools. In the simulations, the default values of the AdvantEdge program were used for the coefficient of friction, the heat transfer coefficient of the coolant, and the cooling temperature, which were 0.5, 10000 W/m2K, and 20°C, respectively. In Figure 3, the motion conditions of the tap including the rotation and translation movements are given.

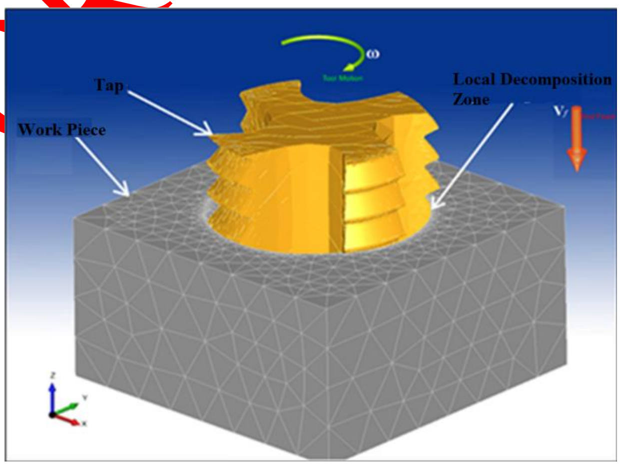


Figure 3. Movements of the tapping tool [23]

After the simulation run was completed, the thrust force, torque, and chip formations in the tapping process were obtained by the Tecplot interface, which is integrated with the AdvantEdge software, which is used to play the simulation and display the evaluated results. While running the simulation with simulation/analysis software using the finite element method, distortions may occur in the network structure as shown in Figure 4a [20]. Due to the resizing of the elements during the chip formation process, degeneration of the elements is very common [20]. This degeneration in the network structure causes sudden/instantaneous increases or decreases in the force and torque values that occur during the simulation (Figure 4b) [23].

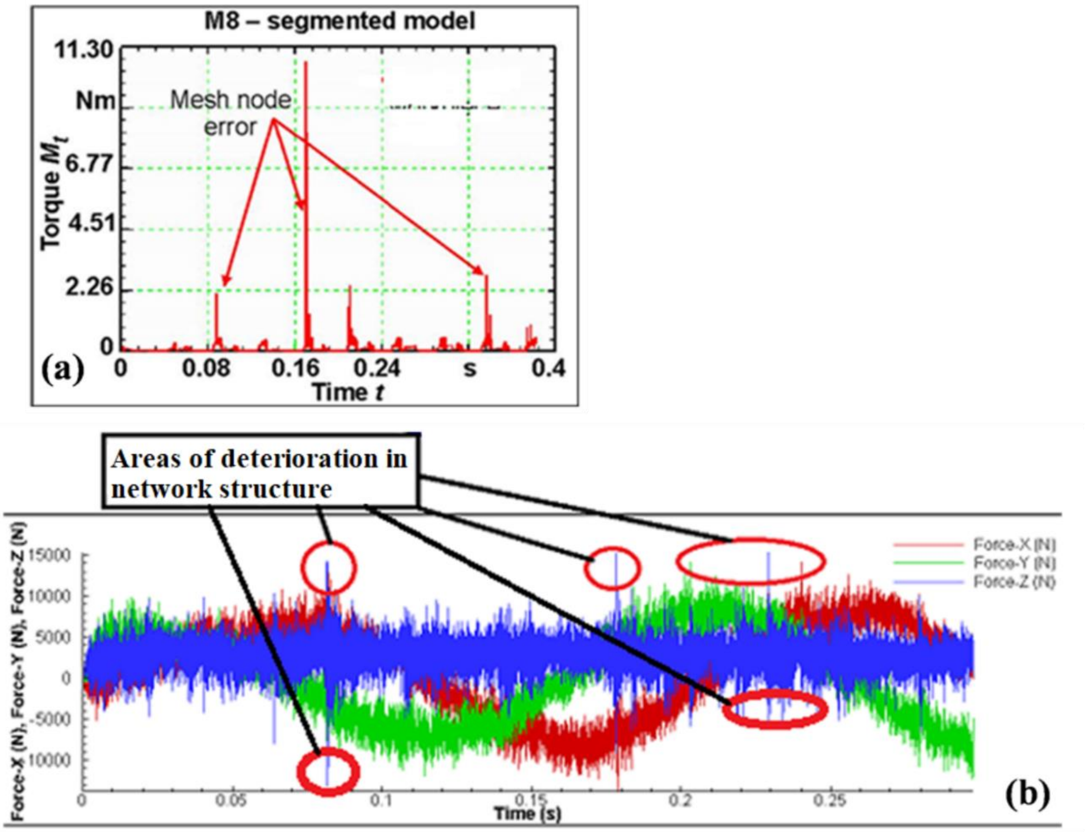


Figure 4. Degeneration of elements in the simulation process [23]

In this study, a total of 24 simulations were run, 12 for each of the uncoated HSS and TiN-coated HSS taps, using each tap form shown in Table 3. Each simulation took an average of 24 hours.

3. RESULTS AND DISCUSSION

3.1. Thrust Forces and Torque

The test results and simulation results for thrust force and torque were compared. Chip formation was investigated during the simulations. The convergence rates of the test result and simulation result data are given in Table 5.

Simulations were carried out at a cutting speed as 10 m/min and a feed rate as 1.5 mm/rev. The values of the thrust force and torque obtained as a result of experiments and simulations were compared (Figure 5-8). In order to facilitate the comparison of the test and simulation results, the ±10% limits of the test results are also shown in Figure 5-8. The test and simulation results for uncoated HSS tools are given in Figure 5. In general, it is seen that as the hole diameter increases, the thrust force decreases except for 8.6 mm.

Normally, it is expected that the chip volume, which decreases with the increasing of the hole diameter, lead to reduce the thrust forces [28]. The minor diameter of the M10 tap is 8.376 mm. As the diameter gets smaller, the tap's attempt to enlarge the hole wall will increase the thrust forces and torque [6]. The thrust forces generated in the threads opened with the channel type straight taps (A303) were higher than the thrust forces obtained in the 15º helical (A320) and 30º helical (A330) channel type taps. This is attributed to the relatively more difficult evacuation of swarf formed during the tapping process due to the smooth flute type. The lowest thrust force was obtained in the operations opened with 15º helical channel type taps. In terms of simulation results, it was determined that over 95% convergence values occurred in the 8.3 mm and 8.6 mm diameters in the tool coded A303, while the convergence values were around 78% and 77%, respectively, in the 8.4 mm and 8.5 mm diameters (Figure 5). These convergence rates were 83%, 79%, 75%, 73% for 8.3, 8.4, 8.5 and 8.6 diameters in the tool coded A320 and 85%, 80%, 78% and 81% in the tool coded A330, respectively.

Table 5. Convergence rates of test results and simulation result data

Tap Code	Hole Diameter (mm)	Thrust Force			Torque		
		Experiment Result Fz (N)	Analysis Result Fz (N)	Percent Convergence	Experiment Result Mz Ncm)	Analysis Result Mz (Ncm)	Percent Convergence
A303	8.3	154	158	97%	658	684	96%
	8.4	113	144	78%	633	633	98%
	8.5	108	141	77%	601	537	89%
	8.6	121	126	96%	551	519	94%
A320	8.3	70	84	83%	1141	989	87%
	8.4	33	42	79%	820	886	93%
	8.5	12	16	75%	714	804	89%
	8.6	26	19	73%	638	749	85%
A330	8.3	144	123	85%	1394	1172	84%
	8.4	69	86	80%	665	817	81%
	8.5	57	73	78%	563	458	81%
	8.6	74	91	81%	580	467	80%
A303 (TiN coated)	8.3	135	164	82%	696	628	90%
	8.4	105	147	71%	573	604	94%
	8.5	107	136	78%	595	563	94%
	8.6	110	131	84%	504	531	95%
A320 (TiN coated)	8.3	93	81	87%	784	869	90%
	8.4	87	74	85%	687	742	93%
	8.5	60	68	88%	959	815	85%
	8.6	59	62	95%	651	693	94%
A330 (TiN coated)	8.3	56	72	78%	663	581	88%
	8.4	67	83	80%	659	565	86%
	8.5	89	91	97%	615	493	80%
	8.6	61	79	77%	764	608	79%

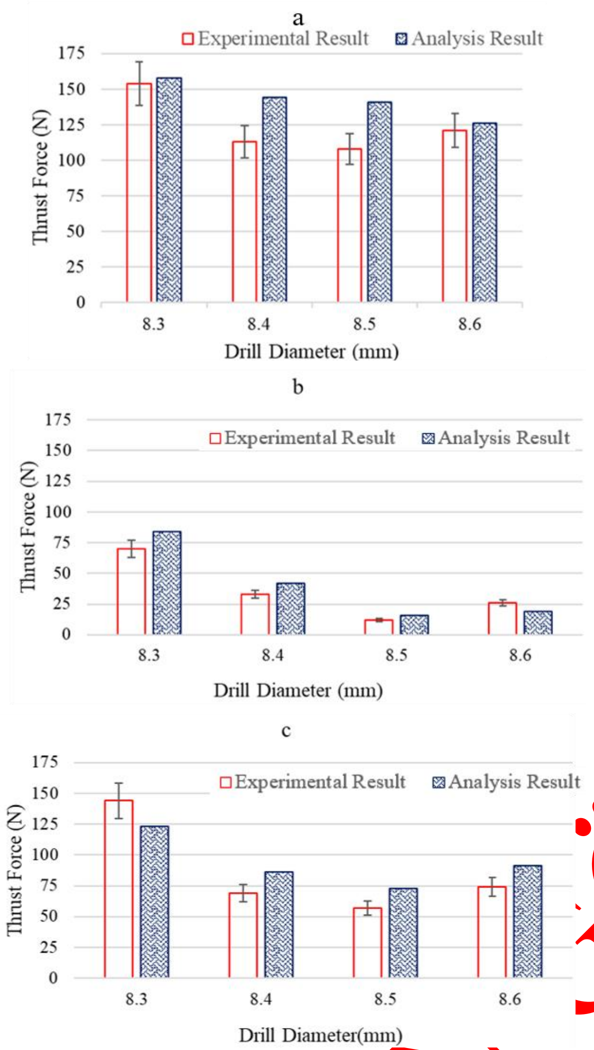


Figure 5. Thrust force that occurs in the uncoated HSS tools
a) A303 b) A320 c) A330

It is seen that the thrust force values obtained in the experiments performed on TiN coated HSS taps show similar trends to the values obtained in the experiments performed on uncoated HSS taps (Figure 6).

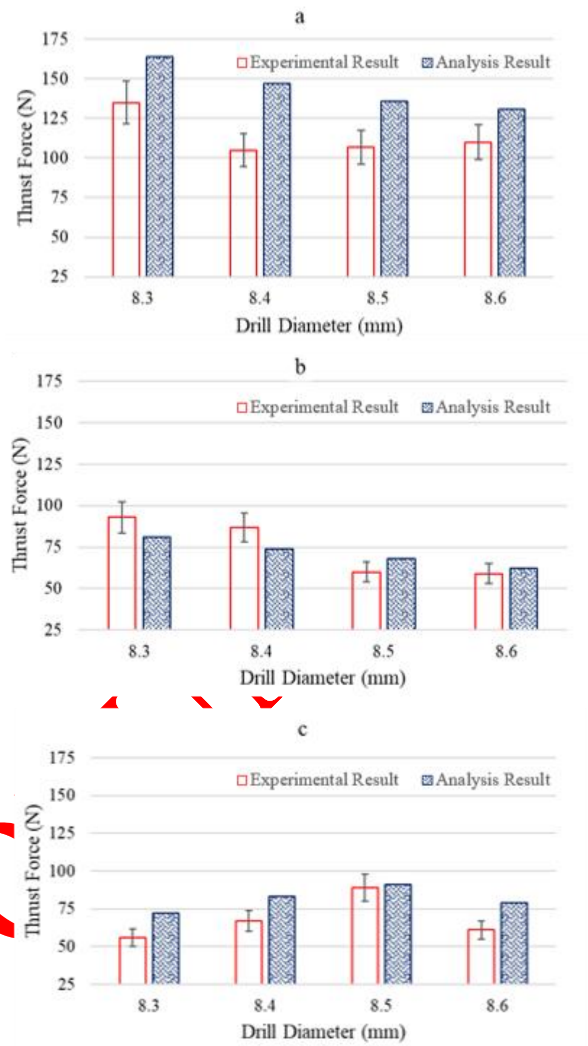


Figure 6. Thrust force that occurs in TiN coated HSS tools
a) A303 b) A320 c) A330

When the graphs given in Figures 5 and 6 are examined, the highest thrust force values occurred in holes drilled with 8.3 mm. This is true for all three cutting tools with different flute types. As with the uncoated tools, the increased chip volume caused an increase in the thrust force. Again, as in the uncoated tools, the lowest thrust force occurred in the screws opened with a 30º helical channel type tapping. In terms of thrust force, this tap is followed by 15º helical channel type tap and straight channel type, respectively. The increased helix angle in the taps with the coating application facilitated the chip evacuation and thus caused the thrust forces to decrease [2,7].

When the experimental and simulation results were compared, the convergence rates were determined as 82%, 71%, 78% and 84%, respectively, in the 8.3, 8.4, 8.5 and 8.66 mm hole diameters in the coated A303 tap. While this ratio is 87%, 85%, 88%, and 95%, respectively, for 8.3, 8.4, 8.5 and 8.6 mm hole diameters in the A320 coded tap, 78%, 80%, and 95%, respectively, for 8.3, 8.4, 8.5 and 8.6 mm hole diameters in the A330 code tap. 97 was 77%.

The variation of torque values occurring in tapping operations with coated and uncoated tools are given in Figure 7 and Figure 8.

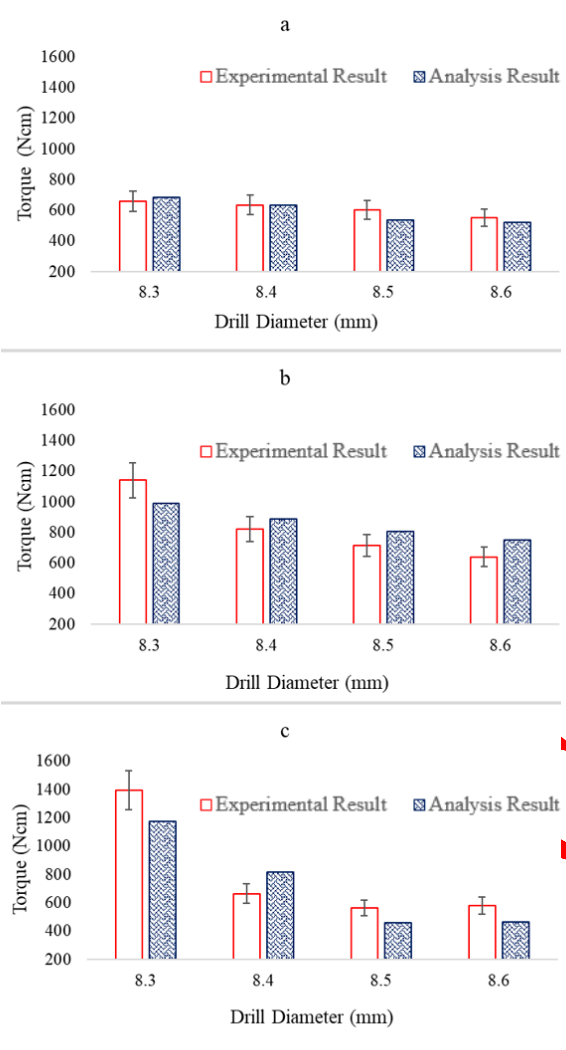


Figure 7. Torque that occurs in uncoated HSS tools
a) A303 b) A320 c) A330

When a general evaluation is made; It is seen that there is a difference of around 5-25% between the experimental results and the simulation results. This difference can be attributed to the absence of tool wear due to the rigid modeling of the tool, and the parameters in the Johnson-Cook material model created for the workpiece. On the other hand, it is thought that the coefficient for heat transfer between the material and the cutter varies according to the experimental platform conditions, which causes these differences [29-30]. In terms of providing an approximate solution rather than a definitive solution, and thus facilitating inferences about the problem under investigation; When making simulations with the help of programs such as AdvantEdge, it is expected that such differences will occur.

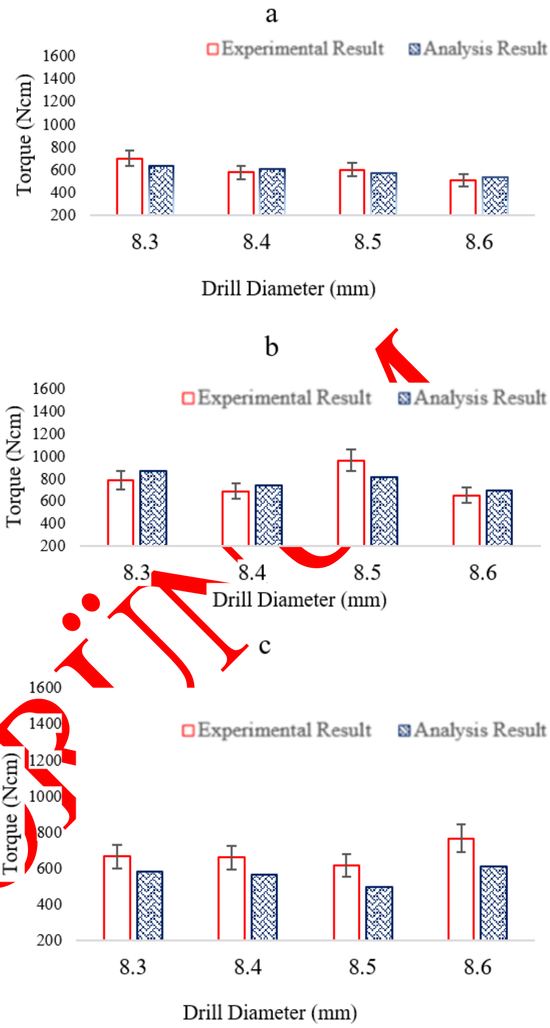


Figure 8. Torque that occurs in TiN coated HSS tools
a) A303 b) A320 c) A330

3.2. Chip Formation

Figure 9 shows the chip types resulting from the simulation of tapping with straight flute (A303), 15º helix flute (A320), and 30º helix flute (A330) taps. In Figure 10, the chip forms that occur during the experiments are given. During the experiments, it was observed that the chip cutters in both coated and uncoated tools were the same. For this reason, uncoated tools are based on the modeling of chip formation.

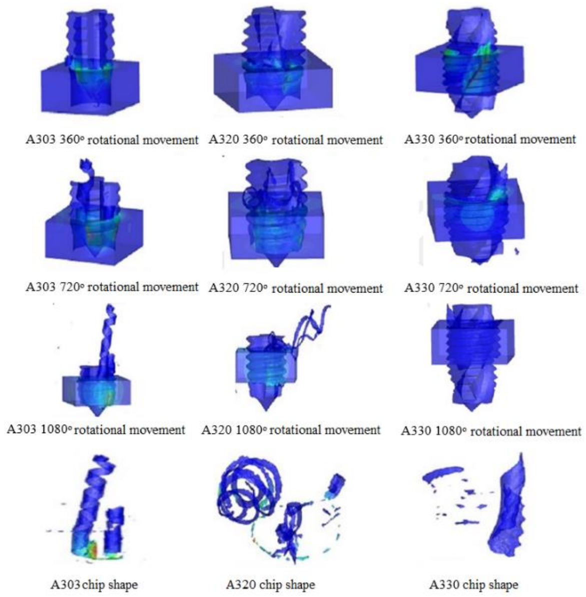


Figure 9. 1, 2, 3 full turns and chip formations of uncoated HSS taps coded

While continuous chips are formed in the straight channel type tap (A303), these chips are jammed in the channels. As a result of this, strains occur and it is thought that it starts to force the set from the first tooth. Chip formation in taps with 15º helix flute type; between continuous chip and broken chip tendency. It has been observed that the chips formed in the taps with this channel type started to break. Especially in the case of a helix angle of 30º with an 8.6 mm hole diameter, since the chip tends to be completely broken, it can easily break off and be evacuated without causing jamming in the channels.

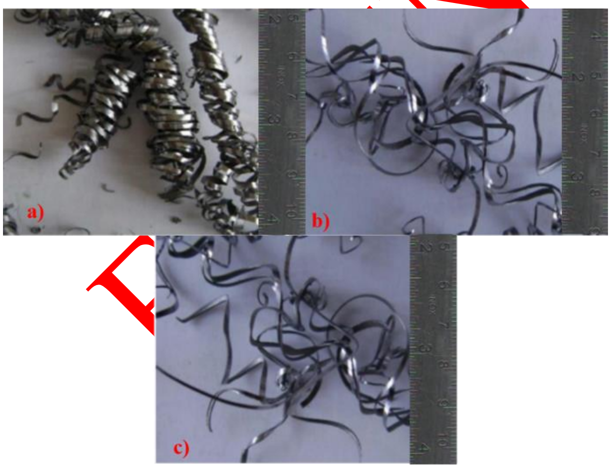


Figure 10. Chip forms of uncoated HSS taps
a) A303 b) A320 c)A330

One of the important parameters that affects the thrust forces and torque values, is the chip type. Prediction of the chip type of the material to be machined is important in terms of the machining economy [23].

Test pieces screwed with taps were cut and sliced. Thus, it is ensured that the screws can be viewed more easily through each hole drilled (Figure 11).

Figure 11. Cross-section view of the tapped material

4. CONCLUSIONS

Within the scope of the study, the thrust force and torque values that occur in the tapping process were measured with HSS taps with coating and TiN coating. The simulation was carried out with the chip types formed during cutting.

The results obtained in the study can be summarized as follows:

- It has been observed that there are similarities between the simulation and the experimental results, varying between 75% and 97%.
- When the experimental and simulation results are compared, the best convergence was obtained in A303, A320, and A330 coded TiN coated and uncoated HSS taps, respectively.
- The best convergence in terms of thrust forces and torque values was seen in the A303 uncoated HSS tool with hole diameters of 8.3 mm and 8.4 mm.
- It is seen that the chip forms obtained after the experiments and the chip forms formed as a result of the simulations are quite compatible.

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DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Tuncer DEMİREL: He conducted simulation studies and analyzed the results. Wrote the manuscript.

Selçuk YAĞMUR: He Analyzed the results and wrote the manuscript.

Yunus KAYIR: He conducted the experiments and analyzed the results

Abdullah KURT: He conducted simulation studies and analyzed the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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