SSRG International Journal of Mechanical Engineering
ISSN: 2348 – 8360 / https://doi.org/10.14445/23488360/IJME-V9I7P102

Volume 9 Issue 7, 10-18, July 2022

Original Article

Comparison of Machinability of Cast Irons with Different Mechanical Properties

Yahya Isik[1], Ahmet Tuzer[2]

[1,2] *Mechanical Engineering Department, Bursa Uludag University, Bursa, Turkey.*

Received: 15 May 2022 Revised: 05 July 2022 Accepted: 11 July 2022 Published: 28 July 2022

Abstract *- The machinability of different ductile cast irons having different mechanical properties has been studied in terms of surface quality and tool life with the help of the Taguchi method. Solid solution-reinforced ferritic spheroidal cast iron (SSF) and spheroidal cast iron (GJS) was selected for machining comparison, as SSF is a new material according to GJS. The tests were performed at a CNC turning machine with five control factors. They have used three levels of cutting velocity (200 m/min, 250 m/min, 300 m/min), three levels of feed (0,1 mm/rev, 0,2 mm/rev, 0,3 mm/rev) and three levels of cutting depth (0,5 mm, 1 mm, 1,5 mm). Two types of tool holders with 60º and 93º clearance angles and two types of cutting conditions, wet and dry, were used. Also, the maximum temperature was measured by the infrared thermal scanner during the dry-cutting processes. A taguchi L36 orthogonal array was used to determine the experiment design. Finally, the effects of these factors on the machinability of these materials have been compared, and the optimal cutting combination was determined in terms of surface quality and tool wear. The effect of temperature was also associated with the control factors.*

Keywords *- Ductile graphite cast iron, Machinability, Surface quality, Tool life.*

1. Introduction

Ductile cast iron production accounts for around % 24 of the total casting production all over the World [1]. Because of its wide range of properties, usage of ductile cast iron has increased up to now. However, this material has strong properties. A different type of ductile cast iron, named Solid Solution Ferritic Ductile Iron (SSF), has better mechanical properties and was invented in 2012. SSF materials provide higher elongation and yield strength value than ductile cast iron. These advantages come from SSF materials' high silicon content. SSF materials have a full ferritic microstructure and a narrow range of hardness because of their high silicon content [2]. A homogenous hardness distribution and full ferritic microstructure provide good machinability for SSF material [3, 4].

There are a lot of studies that have been done related to the mechanical properties of SSF materials. Stets [5] studied the SSF material's mechanical properties, which are affected according to Silicon content. Nová [6] studied the SSF material part's hardness distribution. Scruton [7] examined the effect of the difference in the amount of Copper and Manganese elements, which are in the content of the ferritic SSF material, which can make pearlitic on the strength of the part and the pearlitic ratio in part. Bahkali [8] investigated the effect of different cutting conditions and inserted radii on the surface roughness of a cylinder block with a diameter of 80 mm and a length of 150 mm, produced from EN-GJS 500/7 spheroidal graphite cast iron material. Grzesik [9] EN GJS 500/7 investigated the surface roughness values, cutting forces, and temperatures resulting from machining spheroidal graphite cast iron with different cutting parameters using a CBN insert. But these studies show hardly any studies on the machinability of the SSF. Making a profit and providing quality in machining production is very important for companies. Increasing the production of SSF material shows that it needs more studies on machining to determine the optimal surface quality and provide long tool life.

Therefore, this study has been carried out to learn the effect of high silicon on the machinability of the SSF material. SSF material has been compared to ductile cast iron regarding surface quality and tool wear. According to the different cutting parameters and conditions, the advantages and disadvantages of SSF materials in machinability have been compared to ductile cast iron.

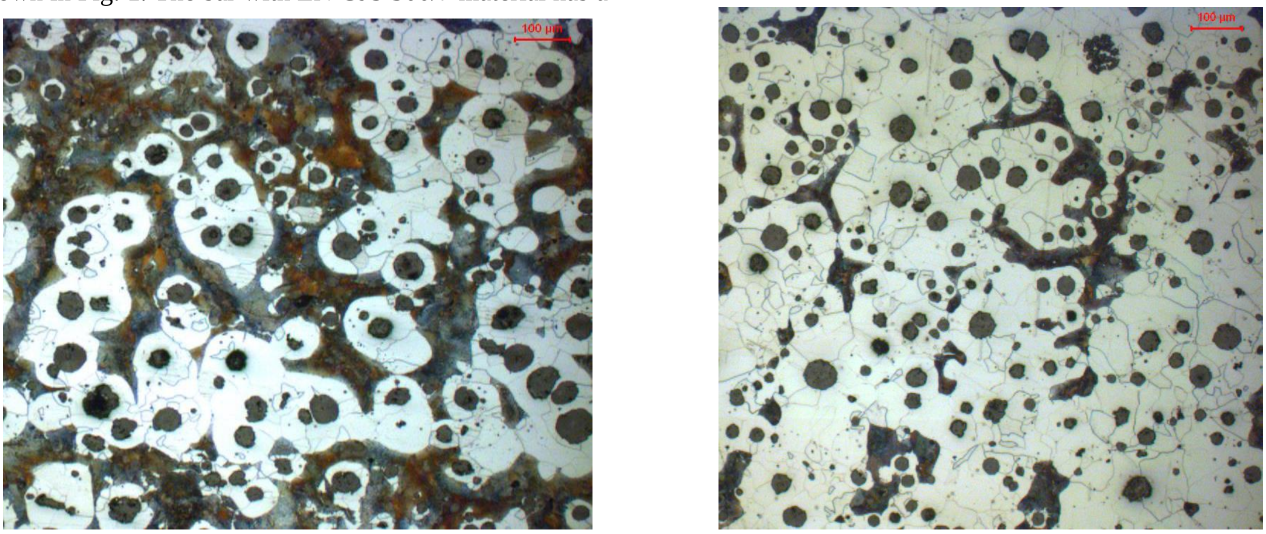
2. Experimental Procedures

Cylindrical bars, which have 160 mm in length and 75 mm in diameter, were produced. These bars were produced with EN GJS 500/7 ductile cast iron and EN GJS 500/14 solid solution ferritic ductile iron material. The chemical composition of these materials is given in Table 1.

Table 1. Chemical composition of ductile irons (%)

Material	C	Si	Mn	P	S	Cr	Ni	Cu	Mg
EN GJS 500/7	3,71	2,2	0,32	0,024	0,012	0,034	0,012	0,055	0,03
EN GJS 500/14	3,3	3,838	0,232	0,04	0,011	0,034	0,011	0,037	0,053

EN GJS 500/7 material has pearlitic/ferritic microstructure, whereas EN GJS 500/14 material has a ferritic structure, as shown in Fig. 1. The bar with EN GJS 500/7 material has a 185 HB hardness value, whereas the bar with EN GJS 500/14 material has 197 HB.



EN GJS 500/7 **EN GJS 500/14**

Fig. 1 Microstructure of the EN GJS 500/7 and EN GJS 500/14 material

2.1. Machinability Testing

The tests were performed using the Taguchi method to determine optimal surface quality and tool wear-cutting parameters. The cutting parameters are cutting velocity, feed rate, depth of cut, dry and wet cutting conditions, and clearance angle of the tool holder. Cutting parameters and their levels are shown in Table 2 according to the mix level design type; the L36 orthogonal array was selected.

Before tests, the casting skin of the bars was removed up to 70 mm in diameter and 150 mm in length.

In all experiments, the machining length was equal and 350 mm. After every experiment, surface roughness was measured. When all experiments were over, all cutting tools were investigated in terms of wear, shown in Fig. 2(a), with the help of a binocular microscope.

In dry condition experiments, the maximum temperature at the cutting tool tip shown in Fig. 2(b) was measured to determine the effect of temperature on the surface quality and tool wear.

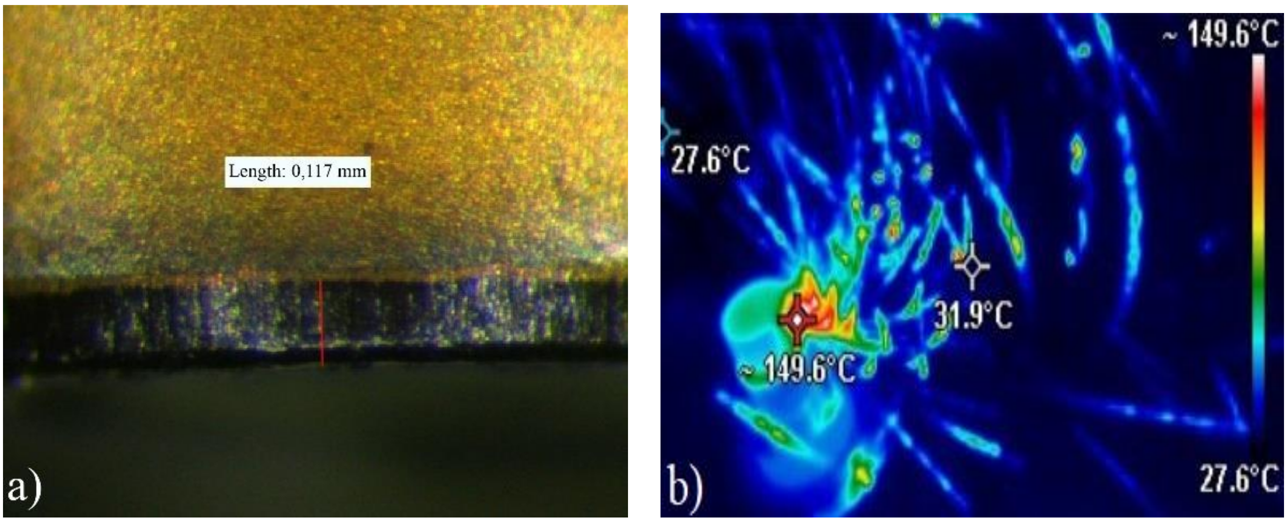


Fig. 2 Cutting tool wear and the temperature at the tool's tip

In all experiments, only one type of cutting tool was used, and every experiment started with a new cutting tool. The cutting tool was carbide with CVD TICN+AL2O3+TIN coating. Two tool holders were used in the experiments with 60o and 93o clearance angles.

Table 2. Cutting parameters and their levels

Parameters	Levels		
	Level 1	Level 2	Level 3
Material	EN-GJS 500/7	EN-GJS 500/14	
Tool holder angle	93^o	60^o	
Wet / Dry machining	Wet	Dry	
Velocity (m/min)	200	250	300
Feed rate (mm/rev)	0.1	0.2	0.3
Dept of cut (mm)	0.5	1	1.5

Table 3. Cutting parameters and their levels

Level	Material	Clearange angle	Wet/dry cutting	Velocity(m/min)	Feed (mm/rev)	Dept (mm)
1	-3.238	-2.909	-1.575	-3.972	3.930	-2.570
2	-2.366	-2.522	-3.855	-2.308	-0.747	-3.720
3				-1.865	-11.329	-1.856
Difference	0.872	0.387	2.280	2.106	15.259	1.864
Order	5	6	2	3	1	4

The experiments were carried out according to the determined plan and experiment order. A new insert was used in each experiment. In each trial, determining parameter values were applied, and the duration of each trial was measured. The results of the experiments were determined according to the "Smallest is the best" feature in the Taguchi method [10]. The results were evaluated by converting the measured surface roughness values into an S/N ratio, and variance analysis was performed. The effect of cutting velocity, feed, depth, clearange angle, and wet/dry cutting conditions on the surface roughness and wear of the tools were examined separately.

3. Results and Discussion

3.1. Results of Surface Roughness Tests

The results of 36 trials were analyzed using the Taguchi method. The value with the highest S/N ratio shows the best result in terms of surface roughness. According to the analysis results in Table 3, the parameter with the most effect on surface roughness was feed rate, followed by wet/dry cutting, cutting velocity, depth, type of material, and tool clearange angle, respectively.

According to the results of variance analysis, the effective rates of the parameters that affect the surface roughness are shown in Table 5. It is seen that the feed rate has a very high effect on the surface roughness of 97,28%. Wet/dry machining with 0,97% and cutting velocity with 0,18% affect the surface roughness. As seen in Fig. 3, it has been observed that the surface roughness values in EN GJS 500/14 material are lower than in EN GJS 500/7 material.

The surface roughness values in the experiments performed with the tool holder with an angle of clearange of 60^o were lower than the surface roughness in the experiments with the tool holder with a clearange angle of 93^o. Again, lower surface roughness was obtained in both materials under wet cutting conditions. It was observed that the surface roughness values increased as the amount of feed increased in both materials. While the results obtained with a 0.2 mm feed were approximately 2 times the results of a 0.1 mm feed, it was observed that the results obtained with a 0.3 mm feed were approximately 3.5 times the results obtained with a 0.2 mm feed.

It was observed that the surface roughness values decreased as the velocity increased. It is seen that the effect of the depth on the surface roughness is not linear; the surface roughness increases from 0.5 mm depth to 1 mm depth, and the surface roughness decreases at a higher depth.

In the experiments carried out under wet and dry cutting conditions, the surface roughness of both materials under wet cutting conditions was lower than in dry cutting conditions. Although the surface roughness values of both materials under wet cutting conditions were better than in dry cutting conditions, EN GJS 500/14 material showed better surface roughness under wet cutting conditions. The effect of cutting conditions on surface quality according to material type is shown in Fig. 4. The average roughness value in EN GJS 500/14 material was 1.61µm, while this value was 1.75µm in EN GJS 500/7 material. Although the values are close to each other in dry cutting conditions, the average surface roughness values in EN GJS 500/7 material were lower than EN GJS 500/14 material.

The average roughness value for EN GJS 500/14 material was 1.96µm, while this value was 1.9 µm for EN GJS 500/7 material. The effect of cutting conditions on surface roughness based on workpiece material was found to be more effective in EN GJS 500/14 material.

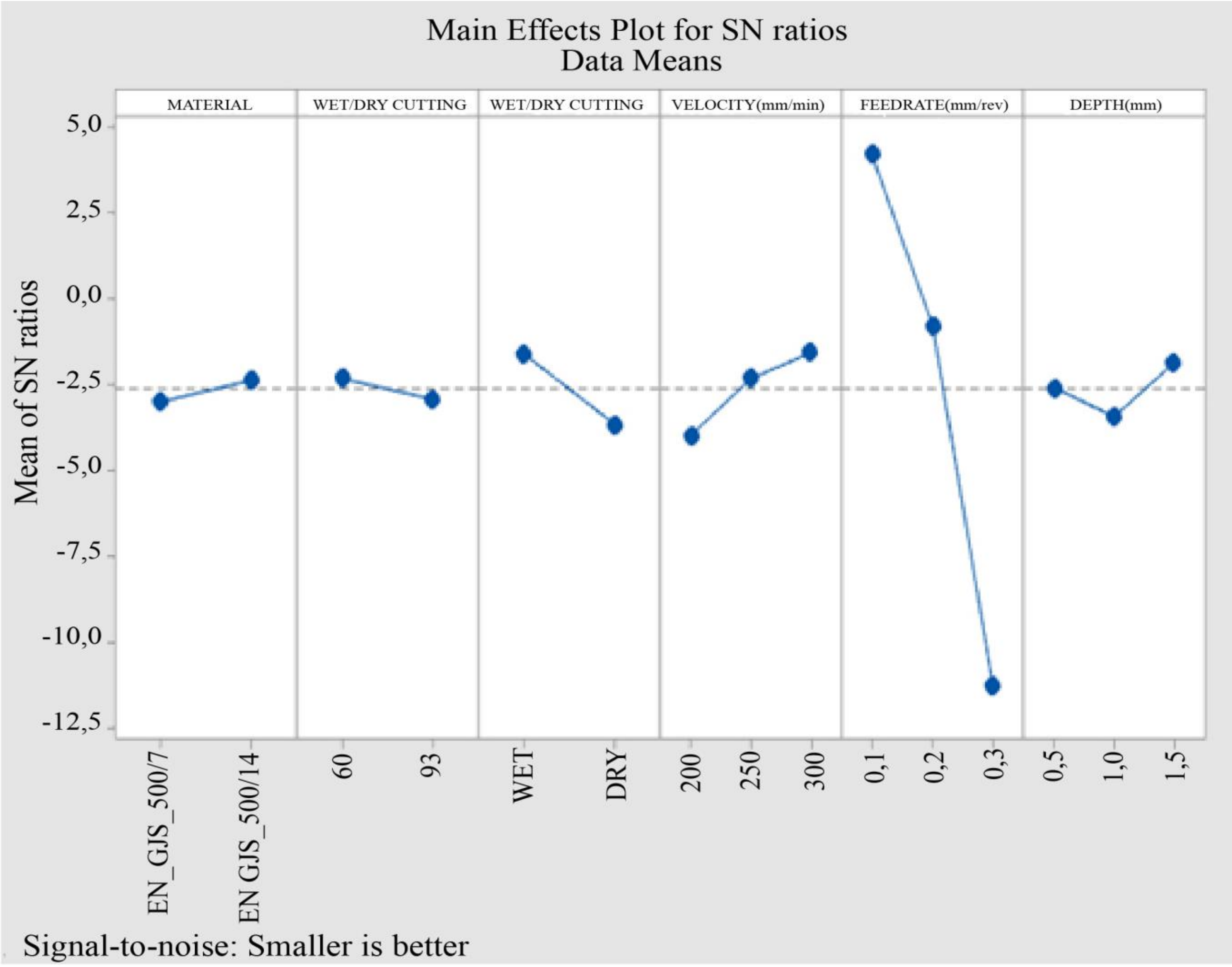


Fig. 3 Main effect plot for S/N ratios of surface roughness

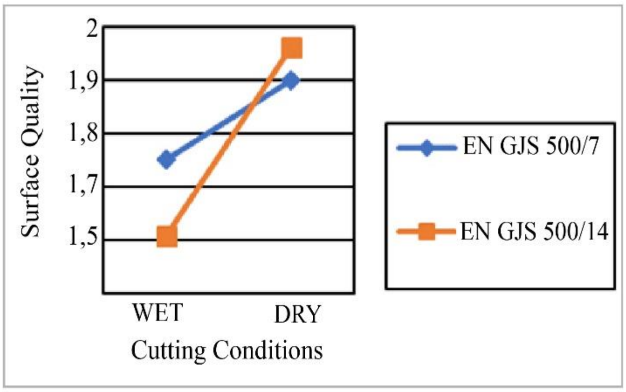


Fig. 4 Effect of cutting conditions on surface quality according to material type

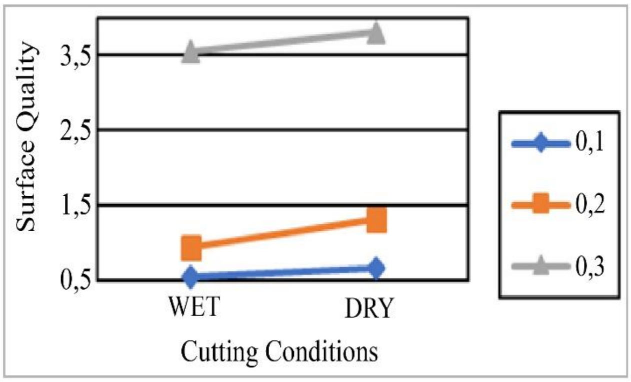


Fig. 5 Effect of cutting conditions on surface quality according to feed rate

As seen in Fig. 5, surface roughness in dry cutting conditions was higher than the surface roughness in wet cutting conditions at each feed level. It was observed that the surface roughness values under coolant and dry cutting conditions at a feed rate of 0.1 were close to each other, but at a feed rate of 0.2 and 0.3, the surface roughness in dry cutting conditions increased.

The experiments observed that the surface roughness values increased as the clearange angle increased in both materials.

It is a more stable cutting process since the cutting force occurring in the tool with a smaller clearange angle is smaller than the cutting force occurring in the tool with a larger clearange angle [11]. In the tests performed with tool holders with 60^{o} and 93^{o} clearange angles, it is seen in Fig. 6 that the effect of the clearange angles on the surface roughness on the material basis is very low. It is known that as the feed rate increases, the surface roughness increases. The experiments show that the surface roughness value formed at 0.2 mm feed is approximate twice the surface roughness value formed at 0.1 mm feed.

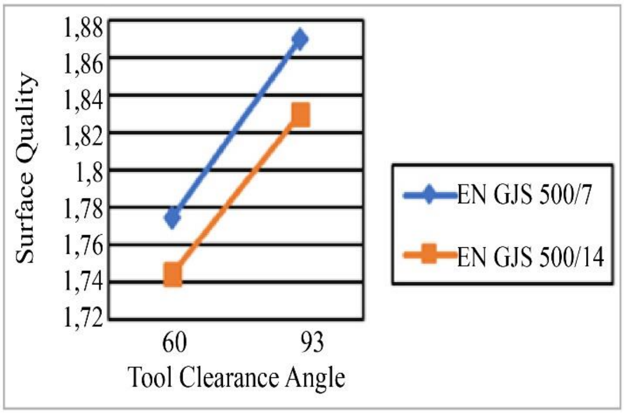


Fig. 6 Effect of tool clearange angle on surface quality according to material type

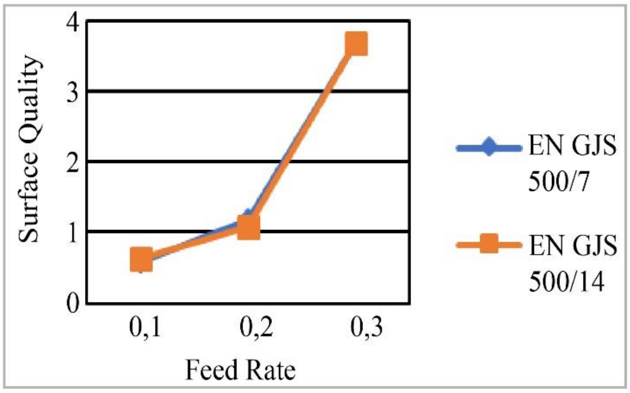


Fig. 7 Effect of feed rate on surface quality according to material type

In comparison, the surface roughness formed at 0.3 mm feed is approximately 3.5 times the surface roughness formed at 0.2 mm feed. The effect of feed rate on surface roughness produced similar results in both materials. The effect of feed on the surface roughness was lower in EN GJS 500/7 material, although it gave close results in both materials at the feed level of 0.1 mm/rev. At 0.2 and 0.3 mm/rev feed rates, it was lower in EN GJS 500/14 material. It is seen in Fig. 7 that the effect of feed and feed amount on surface roughness on a material basis is not different.

The graph of its interaction with the clearange angle is shown in Fig. 8 since the parameter that has the greatest effect on the surface roughness is the feed.

It was observed that the average surface roughness of the experiments performed with the tool holder with a 60° clearange angle at each feed level was lower than the average surface roughness in the experiments performed with the 93° clearange angle tool holder. It is seen that the surface roughness value increases with the increase of the clearange angle. It was observed that the effect of the clearange angle on the surface roughness was similar at different feed rates. The surface roughness values in the tests performed with tool holders with different clearange angles at different feed levels were close. Trials with low feed (0,1 mm/rev) and 60° provided the best surface roughness values.

As the cutting velocity increases, the surface roughness generally decreases. Although the effect of the cutting velocity on the surface roughness is not much in the experiments, it is seen that it decreases from 0.65 µm to 0.57 µm when the velocity is increased from 200m/min to 300m/min at 0.1 mm/rev feed. It is seen that it decreases from 1.2 µm to 0.9 µm at 0.2 mm/rev feed, and it increases from 3.6 µm to 3.66 µm at a feed rate of 0.3 mm/rev. It can be seen in Fig. 8 that the cutting velocity does not have much effect on the surface roughness.

The depth of cut also does not seem to have much effect on the surface roughness. While there was no significant change in the surface roughness values as the depth increased at 0.1 mm/rev feed. It was observed that the surface roughness value increased from 0.58 µm to 0.63 µm, and with a 0.2 mm/rev feed rate, as the depth increased, it decreased from 1.2 µm to 1 µm. It has been observed that at a feed rate of 0.3 mm/rev. It has increased from 3.76 µm to 3.69 µm. Fig. 10 shows the effect of the depth of cut on surface roughness.

3.2. Results of Tool Wear

In the experiments, equal and 350 mm length machining was performed in each trial. A new insert was used in each trial. After the trials, the tools were measured with a Nikon SMZ800 brand binocular microscope device and ZOLLER GENIUS 3S universal measuring bench, and the wear amounts were recorded. The amount of wear was evaluated, and the appropriate measurement was chosen. A comparison of the amount of wear was made based on material and according to cutting parameters. Comparisons were made by checking the side surface wear on the tool. As seen in Table 4, it is seen that the most important parameter affecting tool wear is feed rate. Increasing the feed rate causes a decrease in tool wear in these trials.

The feed greatly affects tool wear due to the equal-length machining process. Since the total machining length is equal in all trials, the machining time at 0.1 mm/rev takes longer than the machining time at 0.2 and 0.3 mm/rev feed, respectively. Increasing the machining time increases the tool's wear and reduces the tool's life. It is seen that the increase in the clearange angle has a positive effect on tool wear; it is seen that tool wear is more in dry cutting conditions, and tool wears increases. As the cutting velocity and depth increase, in the experiments, it is seen that the effect of EN GJS 500/7 material on tool wear is less than EN GJS 500/14 material.

It is seen in Fig. 8 that the tool wear of EN GJS 500/14 material is higher than EN GJS 500/7 material. While the average tool wears EN GJS, 500/14 material with a tool holder with a 93° clearange angle is 0.178 mm, this value increases by 9% to 0.195 mm when a tool holder with a 60° clearange angle is used. In EN GJS 500/7 material, when a tool holder with a 93° clearange angle was used, average tool wear of 0.151 mm occurred.

Table 4. Cutting parameters and their levels

Level	Material	Clearange angle	Wet/dry cutting	Velocity(m/min)	Feed (mm/rev)	Dept (mm)
1	15,94	15,01	15,92	16,90	12,81	16,37
2	15,12	15,88	14,97	14,86	16,41	15,61
3				14,58	17,12	14,36
Difference	0,83	0,87	0,95	2,32	4,31	2,00
Order	6	5	4	2	1	3

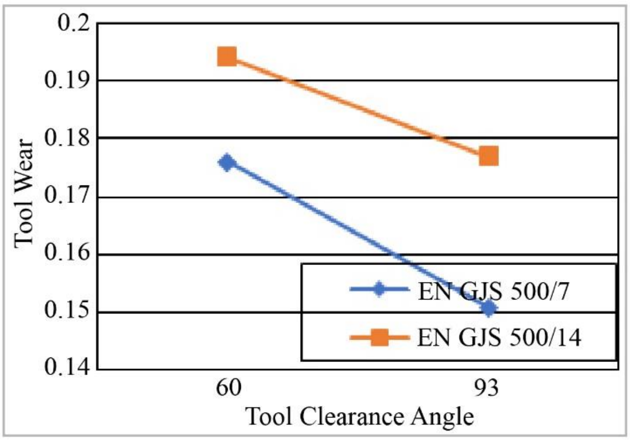


Fig. 8 Effect of tool clearange angle on tool wear according to material type

When the tool holder with a 60° clearange angle is used, it is seen that the wear increased by 17% and reached 0.177 mm. The lowest tool wear is achieved when a tool holder with a 93° clearange angle is used in EN GJS 500/7 material. The most tool wear is seen in EN GJS 500/14 material when a tool holder with a 60° clearange angle is used.

Fig. 9 compares the wear caused by different feed rates on the tool according to the clearange angle. It was observed that the tool wear was higher at 0.1 mm/rev feed rate in both clearange angles compared to other feed rates. It has been observed that the tool wear in the experiments with the tool holder with a 60° clearange angle is higher than the tool holder with a 93° clearange angle. While the average wear in the experiments with the tool holder with a 60° clearange angle was 0.244 mm, it was observed that this value improved by 9% and became 0.22 mm in the tool holder with a 93° clearange angle. While the wear at 0,2 mm/rev feed is parallel to the amount of wear at 0.1 mm/rev feed, it is seen that there is lower wear at both clearange angles than at 0.1 mm/rev feed. At a 0,3 mm feed rate, it is seen that the clearange angle has little effect on the tool wear amount. The amount of wear in the trials with the tool holder with a 93° clearange angle decreased by 3% compared to the trials with a 60° clearange angle. It is seen that the lowest wear amount is at 93° clearange angle and 0,2 mm/rev feed rate.

Fig. 10 shows the tool wear at different velocities of tool holders with different clearange angles. The experiment's lowest wear value was seen using a tool holder with a 93° clearange angle at 200 m/min cutting velocity. While the average tool wear value was 0.153 mm at the 60° clearange angle at 200 m/min cutting velocity, this value decreased by 7% to 0.142 mm at the 93° clearange angle. While the average tool wear value was 0.199 mm at the 60° clearange angle at 250 m/min cutting velocity, this value decreased by 18% to 0.163 mm at the 93° clearange angle. While the average tool wear value is 0,2 mm at the 60° clearange angle at 300 m/min cutting velocity, it is seen that this value decreases by 6% and becomes 0.188 mm at the 93° clearange angle. It is seen that the tool holder with a 93° clearange angle causes less wear on the tool in operations at low velocities, while the tool holder with a 60° clearange angle causes high wear at high velocities. The clearange angle's effect on tool wear is less at low velocities, such as 200 m/min, compared to high velocities.

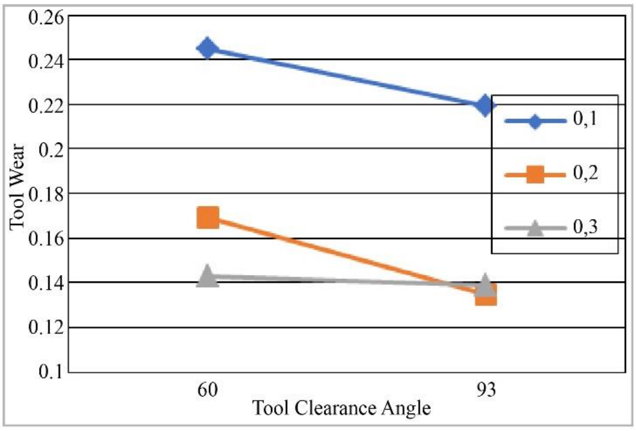


Fig. 9 Effect of tool clearange angle on tool wear according to feed rate

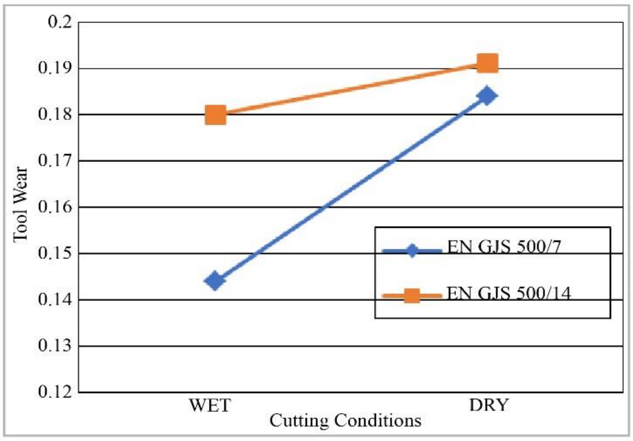


Fig. 10 Effect of cutting conditions on tool wear according to material type

It has been observed that the wear in both materials under dry cutting conditions is higher than that in wet cutting conditions, and tool wear during the machining of

EN GJS 500/14 material is higher than EN GJS 500/7 material in both clearange angles. The lowest wear is seen in Fig. 15, 0.144 mm, which occurred in EN GJS 500/7 material machining under wet cutting conditions. It is seen that this value increased by 28% in dry-cutting conditions to 0.184 mm. In EN GJS 500/14 material, the average tool wear was 0.18 mm under wet cutting conditions, and this value increased by 6% and reached 0.192 mm in dry cutting conditions.

It is interpreted that the effect of cutting wet/dry cutting conditions in EN GJS 500/14 material wear is more than in EN GJS 500/7 material. In EN GJS 500/14 material, it is seen that the tool wear is close in dry and wet cutting conditions, and the tool wear that occurs during the machining of both materials in dry cutting conditions has close values.

The comparison was made using tool holders with fixed 60° and 93° clearange angles. The wear on the tools as a result of wet and dry machining on both materials is shown in Fig. 11. In the experiments using tool holders with 60° and 93° clearange angles, the wear that occurred was high in dry cutting conditions. It is seen that the difference in the clearange angles has a similar effect in wet and dry cutting conditions.

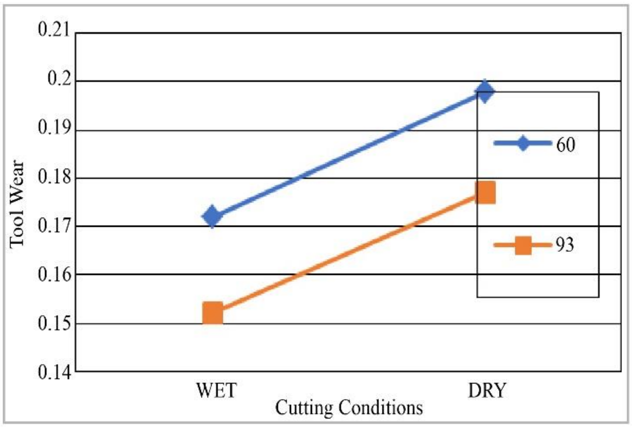


Fig. 11 Effect of cutting conditions on tool wear according to clearange angle

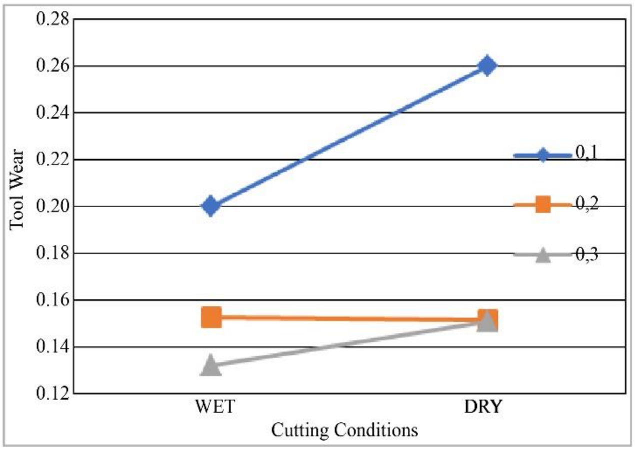


Fig. 12 Effect of cutting conditions on tool wear according to feed rate

Fig. 12 shows the effect of wet/dry cutting conditions on wear at different feed levels. At all feed levels, it is seen that the tool wear in dry-cutting conditions is higher than the wear in wet-cutting conditions. At a feed of 0,1 mm/rev, the tool wear in dry cutting conditions is 30% higher than in wet. It is seen that the effect of wet/dry cutting on tool wear is less at 0,2 and 0,3 mm/rev feed. Increasing the feed rate reduces the contact time between the insert and the workpiece while reducing the wear.

Cutting conditions with coolant has an important role in reducing wear. Since the cutting length is fixed in the experiments, contact the tool with the workpiece at a low feed rate is more than higher feed rates. The temperature at the cutting tip reaches high degrees, which increases the tool wear. The contact time is short at a high feed rate, and the temperature does not reach high values. For this reason, it can be interpreted that the effect of cutting conditions with coolant is more effective at a low feed level.

The effect of the long contact time of the tool with the workpiece at a low feed rate and the temperature increase at high cutting velocities are seen. It is seen that the effect of cutting velocity on tool wear decreases with increasing feed rate. It is seen that the average tool wear remains close to the values when the cutting velocity increases, especially at the feed rate of 0,3 mm/rev. It is seen that the highest tool wear value occurs at low feed and high cutting velocities, and the lowest wear occurs at high feed and low cutting velocities.

The interaction between feed rate and depth. It is seen that the tool wear is also higher at the low feed level since the increase in the depth brings about an increase in the temperature, similar to the effect of the cutting velocity. It can be interpreted that tool wear increases more as the depth increases at low feed levels, and the effect of depth on tool wear decreases with increasing feed rate.

The depth and cutting velocity are parameters that generally affect tool wear. In the experiments, it is observed that the tool wear increases linearly with the increase of depth at 200 m/min cutting velocity. When the cutting velocity increases to 250 m/min, the tool wear increases more with the feed increase. If the cutting velocity reaches 300 m/min, it is seen that the wear of the tool does not increase as the depth increases. As the depth increases, it causes the contact surface and cutting forces between the cutting tip and the workpiece to increase [12]. It causes the cutting edge to be forced against the workpiece in the direction of chip removal and increases the plastic deformations. For this reason, the amount of heat generated is directly proportional to the increase in depth carried out in different experiments.

The relationship between the feed rate in different trials and the temperature at the cutting workpiece interface. With the effect of cutting time, it is seen that the highest temperature occurs at the lowest feed rate, while the lowest temperature occurs at the highest feed rate. When the effect of material type on temperature is examined, it is observed that the average tool/workpiece interface temperature in EN GJS 500/14 material is higher than in EN GJS 500/7 material. Although the structure of EN GJS 500/14 material is ferritic, it can be interpreted that the higher hardness of the material causes the temperature to increase and, accordingly, the tool wear to be higher. It is observed that the temperature difference caused by the clearange angle is lower than the other cutting parameters.

4. Conclusion

This study compared the machinability of EN GJS 500/7 and SSF EN GJS 500/14 materials with different mechanical properties. Two tool holders with clearange angles (60° and 93°) were used in the trials, and the trials were carried out under two different cutting conditions (wet and dry). Trials were carried out at three different cutting velocities (200 m/min, 250 m/min, 300 m/min), three different feed rates (0,1 mm/rev, 0,2 mm/rev, 0,3 mm/rev) and three different cutting depth (0,5 mm, 1 mm, 1,5 mm). The experimental plan was prepared and carried out with the Taguchi method. The following results were obtained from turning hardened cast iron at various cutting conditions.

- It has been observed that the most important parameter affecting the surface roughness is feed rate, followed by wet/dry cutting conditions, cutting velocity, depth of cutting, material type, and clearange angle. It was observed that the average surface roughness of EN GJS 500/14 material was lower than that of EN GJS 500/7 material.
- The mean surface roughness value increased as the clearange angle increased. The reason is more stable machining process occurs since the cutting force at 60° is smaller than the cutting force at 93°.
- The surface roughness values decrease as the cutting velocity increases at 0,1 and 0,2 mm/rev feeds, and the surface roughness does not change at 0.3 mm feed. It is seen that the amount of depth has little effect on the surface roughness.
- The clearange angle's effect on tool wear is less at low velocities, such as 200 m/min, compared to high velocities. It has been observed that tool wear in dry cutting conditions is higher than in wet conditions. At a low feed rate, more parts of the tool come into contact, and the temperature at the insert reaches high degrees, increasing tool wear. For this reason, it has been observed that dry-cutting conditions have more effect at low feed levels.
- The temperature at the cutting edge increased with the depth amount. Tool wear increases as the depth increase at low feed levels, and the effect of depth on tool wear decreases with increasing feed rate. It is seen that the temperature increases as the depth and cutting velocity increase.
- It is observed that the tool wear increases linearly with the increase of depth at 200 m/min cutting velocity, and when the cutting velocity increases to 250 m/min, the tool wear increases more with the increase in depth. If the cutting velocity reaches 300 m/min, it is seen that the wear of the tool does not increase as the depth increases.

Acknowledgment

The authors thank DOKTAS A.Ş. for providing the cylinder blocks with GGG 500/7 and SSF 500/14 materials and OYAK RENAULT A.Ş. for machining the blocks.

References

[1] “Census of World Casting Production, Modern Casting,” *Pub AFS Inc*., pp. 24, 2017. [Google Scholar]

[2] *EN 1563 2012 Datasheet,* Founding – Spheroidal Graphite Cast Irons English Translation of DIN EN 1563, 2012.

[3] A.Çetin, *Solid Solution Reinforced Ferritic Ductile Irons*, Foundryman's Handbook, vol. 1, no. 3, pp. 6-9, 2016.

[4] M. Dhanenthiran, "An Investigation of the Effect of Process Parameters in Turning Operation on Cast Iron," *SSRG International Journal of Mechanical Engineering*, vol. 3, no 2, pp. 6-9, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[5] Wolfram Stets et al., "Solution Strengthened Ferritic Ductile Cast Iron Properties, Production and Application," *International Journal of Metalcasting,* vol. 8, no. 2, pp. 35-40, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[6] I. Nova, I. Nováková, and J.Machuta, “A New Type of Ductile Iron for the Automotive Industry,” *ACC Journal,* vol. 15, no. 1, pp. 24-29, 2009. [Google Scholar] [Publisher Link]

[7] Julia M. Scruton, "*Effects and Limitations of Residual Alloying Elements in Silicon Solid Solution Strengthened Ferritic Ductile Iron*," Michigan Technological University, Materials Science and Engineering, M.Sc. Thesis, Houghton, 2018. [Google Scholar] [Publisher Link]

[8] Essam Ali Al Bahkali et al., "An Investigation of Optimum Cutting Conditions in Machining Nodular Cast Iron Using Carbide Inserts with Different Nose Radius," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 230, no. 9, pp. 1584-1591, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hoang Xuan Tu et al., "Determining Optimum Parameters of Cutting Fluid in External Grinding of 9CrSi Steel using Taguchi Technique," *SSRG International Journal of Mechanical Engineering,* vol. 5, no. 6, pp. 1-5, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[10] W. Grzesik et al., “Investigation of the Machining Process of Spheroidal Cast Iron Using Cubic Boron Nitride (CBN) Tools,” *Metalurgija,* vol. 53, no. 1, pp. 33-36, 2014. [Google Scholar] [Publisher Link]

[11] S. Neşeli, and S. Yaldız, "The Effects of Approach Angle and Rake Angle Due to Chatter Vibrations on Surface Roughness in Turning," *Journal of Polytechnic*, vol. 10, no. 4, pp. 383-389, 2007. [Google Scholar]

[12] Xu Chuangwen et al., "The Relationships between Cutting Parameters, Tool Wear, Cutting Force and Vibration," *Advances in Mechanical Engineering*, vol. 10, no. 1, 2018. [Google Scholar] [Publisher Link]