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# The Effect of Mechanical Properties and the Cutting Parameters on Machinability of AISI 5140 Steel Cooled at High Cooling Rates After Hot Forging

***Research Article/Araştırma Makalesi***

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**ABSTRACT**

In this study, the effect of mechanical properties and cutting parameters (Cp) on the machinability of AISI 5140 steel cooled at high cooling rates after hot forging was investigated. The microstructural examinations and hardness measurements of the as-received AISI 5140 steel and the workpieces cooled in the oil and polymerized water after hot forging were performed. Turning process was conducted by using a coated ceramic tool at five different cutting speeds (Vc) (120, 150, 180, 210, and 240 m/min), four different feed rates (fn) (0.04, 0.08, 0.12, and 0.16 mm/rev), and four different depths of cut (ap) (0.4, 0.6, 0.8, and 1 mm) under dry machining conditions. SEM examinations of the cutting tools were also performed. It was seen from the results that the changing microstructure and hardness values had a significant effect on cutting forces (Fc) and surface roughness (Ra) from the Cp depending on cooling rate. While the highest Fc were reached in the workpiece with the highest hardness cooled in the polymerized water after hot forging, the lowest surface roughness (Ra) was obtained in the same workpiece.

**Keywords: Hot forging, tempered steel AISI 5140, machinability.**

# Sıcak Dövme Sonrası Yüksek Soğuma Hızlarında Soğutulan AISI 5140 Çeliğinin Mekanik Özelliklerinin ve Kesme Parametrelerinin İşlenebilirliğe Etkisi

**ÖZ**

Bu çalışmada, sıcak dövme sonrası yüksek soğuma hızlarında soğutulan AISI 5140 çeliğinin mekanik özelliklerinin ve kesme parametrelerinin (Cp) işlenebilirliğe etkisi incelenmiştir. Alınan AISI 5140 çeliği ile sıcak dövme sonrası yağda ve polimerli suda soğutulan iş parçalarının mikroyapı incelemeleri ve sertlik ölçümleri yapıldı. Tornalama işlemi kaplamalı seramik takım kullanılarak kuru işleme şartlarında beş farklı kesme hızında (120, 150, 180, 210 ve 240 m/dak), dört farklı ilerleme miktarında (0.04, 0.08, 0.12 ve 0.16 mm/dev) ve dört farklı talaş derinliğinde (0.4, 0.6, 0.8 ve 1 mm) yapılmıştır. Ayrıca kesici takımların SEM incelemeleri yapıldı. Sonuçlarda, soğutma hızına bağlı olarak değişen mikroyapı, sertlik değerleri ve kesme parametrelerinin (Cp) kesme kuvvetleri (Fc) ve yüzey pürüzlülüğü (Ra) üzerinde önemli bir etkiye sahip olduğu görülmüştür. Sıcak dövme işleminden sonra polimerli suda soğutularak en yüksek sertliğe sahip iş parçasında en yüksek Fc'ye ulaşılırken, aynı iş parçasında en düşük yüzey pürüzlülüğü (Ra) elde edildi.

**Anahtar Kelimeler: Sıcak dövme, ıslah çeliği AISI 5140, İşlenebilirlik.**

## 1. INTRODUCTION

Medium carbon alloyed steels are widely used for the automobile parts such as crankshaft, front axle, axle sleeve, steering shaft and etc. that are produced by applying hot forging method and require high tensile and fatigue strength. Obtaining adequate hardness and strength combination in the products with the formation of martensitic structure obtained by applying high cooling rates after different heat treatment processes is generally ensured with medium carbon steels [1-2]. Fc and Ra are historically known as key performance indicators in machining operations and are mainly affected by material properties, Cp, and selection of cutting tools [3-4]. The traditional method of machining such as rough machining, heat treatment and grinding has been replaced today by hard turning process.

A single-point machining operation of workpieces having hardness levels of 45< HRC is called as hard turning [5]. It is known that a good finishing surface will generally be obtained at low fn in the grinding process. However, when the hard turning process is compared with the grinding process, better Ra at higher machining rates is seen to be obtained in hard turning operation. Hard turning process has drawn more attraction due to its significant advantages such as shortening the finish machining time and reducing the production cost [6-7].

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Hard turning operations require the use of cutting tools that offer high wear resistance and chemical stability at high temperature. These properties are among the properties of the cubic boronı nitride (CBN) and ceramic cutting tools. Since the ceramic cutting tools are generally low cost and more economical, they have become an alternative to CBN cutting tools [8]. In order to understand the events in the hard turning process, numerous studies have been conducted on many hard materials. However, they are insufficient to generalize the knowledge and experiences obtained in the field of hard turning and to estimate the behaviors of other materials used in the manufacturing industry. Therefore, the studies conducted on machining the hard turned materials are ongoing. In this context, many studies have been conducted on the effect of the machining conditions on Fc and Ra during hard turning of hardened materials [9].

Grzesik and Wanat analyzed the part Ra of the hardened (60 HRC) AISI 5140 steel using different machining parameters under dry processing conditions with coated ceramic cutting tool. When the results were compared, it was seen that specific surface profiles were formed in the hard turning process made with coated ceramic tool but the Ra roughness value of 0.25 µm was comparable to the Ra obtained with finish grinding operation [10]. In the study by Oliveira et al., the turning tests were performed on the cylindrical workpieces and also the workpieces having channels with 4 and 8 equal segments opened across the surface of the cylindrical samples. CBN and ceramic cutting tools were used in the hard turning of the hardened workpieces (AISI 4340). They investigated the conditions that can provide the best results for the Ra and the tool wear as a result of the turning operation. The results gave the best tool life in machining the cylindrical part by using the CBN cutting tool. However, a similar tool life was obtained in the hard turning of the workpieces having 4 and 8 channels on their surfaces by using the CBN and ceramic cutting tools. In terms of the Ra, better results were obtained on the Ra of the cylindrical workpieces having 4 and 8 channels on their surfaces machined using the CBN cutting tools [11]. Aouici et al., performed the hard-turning operation on AISI H11 steel hardened up to 40, 45, and 50 HRC. The effects of Vc, fn workpiece hardness, and ap on Ra and Fc components during the hard turning were studied experimentally. They used CBN cutting tools in the hard turning operation. As a result of these processes, they showed that the fn and the workpiece hardness had significant statistical effects on the Ra. They obtained the lowest Ra at high Vc and low fn. It was also seen that the fn and Fc affected by the ap by 56.77% and 31.50%, respectively [12]. Mandal et al., turned AISI 4340 steel using the ceramic cutting tool at different Vc, ap, and fn. Based on the average response and signal to noise ratio (SNR), they determined that the optimum Cp were the Vc of 280 m/min, the of 0.5 mm, and the fn of 0.12 mm/rev. They observed that the ap made the maximum contribution to the tool wear. They formed the regression modeling of the tool wear and performed the reliability estimation as 95% [13]. As understood from the foregoing literature review, many studies have been conducted on the effect of the hardness of workpiece, the cutting tool material and the Cp on the Fc and Ra and these studies will continue for many years.

In this study, hot forged AISI 5140 steel used especially in automotive industry was used as the workpiece material. The aim of the present study was to investigate the effect of mechanical properties and machining parameters on the Fc and Ra as a result of the hard turning of the workpieces cooled at high cooling rates after hot forging.

## 2. EXPERIMENTAL STUDIES

### 2.1. Hot Forging, Microstructure, and Hardness
(Sıcak Dövme, Mikroyapı ve Sertlik)

AISI 5140 tempered steel was selected since it has a wide area of usage in the automotive sector and the carbon rate in its chemical composition is suitable for hardening. Table 1 shows the chemical composition of the AISI 5140 tempered steel used in the experiments.

For the forging process to be performed in a closed mold, the workpieces were turned in the diameter of 46.7 mm and the length of 250 mm. The prepared workpieces were heated at 1200 ºC for 30 minutes in the induction heating system in order to obtain a homogeneous structure before the forging process. The heated workpieces were subjected to the forging process in a closed mold connected to an eccentric press. The diameter of the workpieces was reduced to 35 mm after the forging process and the final temperature of the workpieces before cooling was measured as 1150±20 ºC. The workpieces, the temperatures of which were measured, were cooled in the oil and polymerized water. In order to obtain healthy results from the hardness, microstructural examinations and machining tests after the forging process, 1-2 mm surface layer were removed from the surfaces of the workpieces. The hardness values of the prepared workpieces were determined by using the Vickers hardness measurement method. The hardness was determined by applying a load of 1 kg (Hv1) via Buehler Micromet 5103 model device. For the microstructural examinations, the workpieces were etched with 2% nital solution and their surfaces were then cleaned with alcohol. Microstructural examinations were performed using Nikon ECLIPSE L150 optical microscope. Images in different sizes were taken from different regions of the workpieces in order for the microstructural images to represent the whole microstructure.

**Table 1.** The chemical composition of AISI 5140 tempered steel used in the experimental study (wt. %).

| | Elements | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | Mo | Ni | Al | Cu | Sn | V |
| Wt% | 0.418 | 0.52 | 1.37 | 0.008 | 0.058 | 0.144 | 0.025 | 0.068 | 0.016 | 0.175 | 0.017 | 0.099 |

### 2.2. Machining Tests

The turning tests of the as-received AISI 5140 steel and the workpieces cooled in different media (oil and polymerized water) after the forging process were performed on a CNC turning centre at five different Vc, four different fn and four different ap under dry machining conditions. The machining parameters were chosen from the values specified in the catalogues of the cutting tool manufacturers. Table 2 shows the Cp used in the turning tests.

**Table 2.** The Cp used in the turning tests.

| Workpiece | Cp | | |
|---|---|---|---|
| | Vc, mm/min | fn, mm/rev | ap, mm |
| As-Received<br>Oil Cooled<br>Polymerized<br>Water<br>Cooled | 120<br>150<br>180<br>210<br>240 | 0.04<br>0.08<br>0.12<br>0.16 | 0.4<br>0.6<br>0.8<br>1 |

In the turning operation, the $Al_2O_3$/TiCN-TiN coated ceramic cutting tool by using PVD method in KY4400 quality group in the form of the WNGA 080404T01020 was selected. A DWLNR 2525 M08 KC04 tool holder appropriate to the indexable inserts used in the turning operations was used. During the turning tests, the Fc were measured using Kistler 9257 B force dynamometer which can measure three force components mounted on the turret of the CNC turning centre. Figure 1 schematically shows three force components during the cutting process. During the turning operation, they were determined by taking the averages of the force values obtained from the data transferred to Dynoware software. The roughness measurements on the surfaces obtained as a result of turning the test workpieces were performed with Mitutoyo Surftest 211 device. In the measurements, Ra values were calculated by taking the arithmetic mean of three values taken in parallel to the axis of the test workpieces.

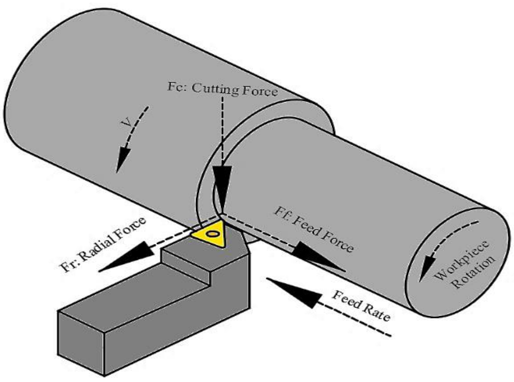


**Figure 1.** Three force components during the turning operation.

## 3. EXPERIMENTAL RESULTS AND DİSCUSSIONS

### 3.1. Microstructureı and Hardness

Figure 2 shows the optical microscope images of the as-received AISI 5140 with the workpieces cooled in different media after hot forging.

When the image obtained from the as-received AISI 5140 steel was examined, it is seen that it is composed of ferrite and perlite phases in different sizes, Figure 2a. When examining the images obtained after the cooling of AISI 5140 steel, whose as-received microstructure was ferrite and perlite, in the oil and polymerized water after hot forging, the formation of a martensite structure was observed (Figure 2.b,c). This points out that the critical cooling rate of AISI 5140 steel lower than the cooling rate in oil and polymerized water. The alloy elements in the steel affects the critical cooling rate of the steel. Alloying elements shift the CCT and TTT diagrams to longer times, permitting to obtain all martensitic [14].

Figure 3 shows the hardness test results. The hardness value of the as-received AISI 5140 steel was measured as 208 Hv1 while the hardness values of the workpieces cooled in the oil and polymerized water were measured as 587 Hv1 and 646 Hv1, respectively. It shows that the workpiece cooled in the polymerized water had the highest hardness value. This was associated with the fact that the cooling rate in the polymerized water was higher than the cooling rate in the oil. Oil or water quenching leads to a formation of martensite phase which is very hard phase and increase the hardness [15].

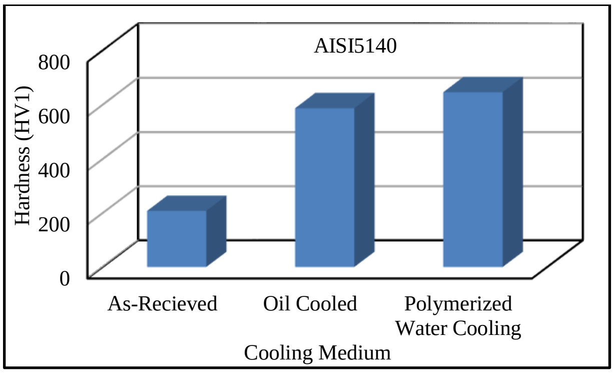


**Figure 3.** Vickers hardness value (VHV) of the workpieces of AISI 5140 steel cooled in different media (as-received, in the oil, and in the polymerized water) after forging.

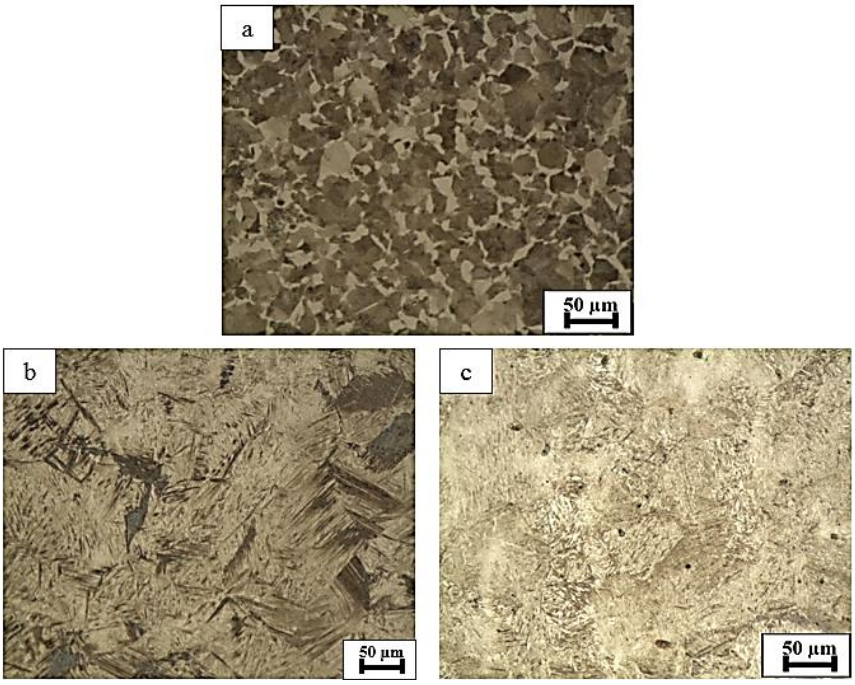


**Figure 2.** Optical microscope images taken from AISI 5140 steel; (a) as-received, (b) oil, (c) polymerized water.

### 3.2. Cutting Forces

Figures 4 a, b, and c show the change of the main Fc depending on different Cp during theı turning operation of the as-received AISI 5140 steel and the workpieces, cooled in different media (in the oil and polymerized water), using the coated ceramic tool.

Figure 4.a shows the main Fc obtained during turning of all the workpieces. While the main Fc for the as received AISI 52140 steel was 136.86 N at 120 m/min Vc, it decreased at the rate of 14,38% (117.18N) when the Vc is increased up to 180 m/min. When the Vc increased from 180 m/min to 240 m/min, the main Fc showed an increase of 15.78% (135.67 N). The main Fc of the workpieces cooled in the oil and polymerized water after the forging operation were measured as 239.40 N and 254.66 N at 120 m/min Vc. A slight decrease was observed at the rates of 25,18% (179.11 N) and 23,95% (193.65 N), respectively in the Fc of the workpieces cooled in oil and polymerized water when the Vc increased from 120 m/min to 210 m/min. When the Vc increased from 210 m/min to 240 m/min, the main Fc of the workpieces cooled in the oil and polymerized water increase at the rates of 8.8% (194.88 N) and 18.44% (229.35 N), respectively. Due to the high friction coefficient between the cutting tool and the workpiece, higher Fc is obtained at low Vc. The increase temperature caus a decrease in the workpiece hardness in the region of the are removed chips as a result of the increased Vc allowed to remove chips from the material at lower Fc. As the Vc increases, the chip thickness and the Fc reduced. In addition, the decreasing of the Fc depended on the decrease in the contact area of the chip cutting tool and partially on the decrease in the shear strength in the yield region on the rake surface of the tool partially along with the temperature increasing with the increased Vc [16]. It was an expected result that the Fc decreased with the increased Vc. However, especially the Fc of the workpieces cooled in the oil and polymerized water increased with the increase of Vc from 210 m/min to 240 m/min. Figure 5 shows this was observed to be caused by the plastic deformation, side edge, crater and notch wears occurring on the cutting tool as a result of high temperatures in the cutting region during the use of ceramic cutting tools.

Figure 4.b shows the main Fc obtained during the turning of the as-received AISI 5140 steel and the workpieces cooled in the oil and polymerized water at four fn (0.04, 0.08, 0.12, and 0.16 mm/rev), constant Vc (180 m/min), and constant ap (0.6 mm). The Fc of the as-received AISI 5140 and the workpieces cooled in the oil and polymerized water after hot forging at the fn of 0.04 mm/rev were measured as 117.18 N, 181.43 N, and 198.86 N, respectively. The Fc increased gradually as the fn increased gradually from 0.04 mm/rev to 0.16 mm/rev. The Fc of the as-received AISI 5140 steel and the workpieces cooled in the oil and polymerized water at 0.16 mm/rev fn increased at the rate of 149.94% (292.88 N), 82.63% (331.35 N), and 76% (350 N).

Figure 4.c shows the main Fc. The Fc in the turning of the as-received AISI 5140 material and the workpieces cooled in the oil and polymerized water at ap of 0.4 mm were measured as 106.58 N, 131.28 N, and 154.53 N. The Fc increased at the rate of 80.06% (191.91 N), 149.18% (327.12 N), and 126.51% (350.03 N) in the tests in which the ap was increased to 1 mm.

The increase in the fn not only creates a dynamic effect on the Fc, and also results in larger sized chips. In addition, it results in an increase in the normal contact stress in the chip contact tool rake surface. Therefore, the Fc increase with the increase in the fn [17,18]. Similarly, the increase in the ap caused an increase in the Fc. The increase in the ap increased the contact length of the cutting tool and workpiece. The increase in the chip amount caused the deformed metal volume to grow and the need for larger Fc to remove the stone becomes important [19,20]. Thus, the lowest Fc were obtained at 0.04 mm/rev fn and 0.04 mm ap.

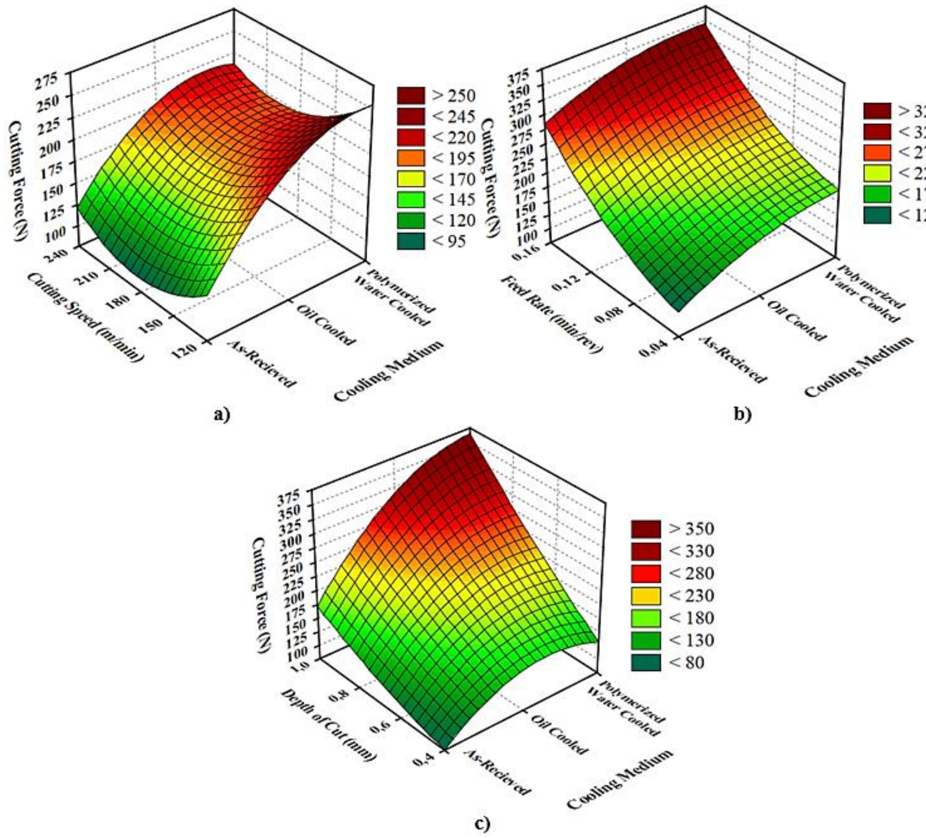


**Figure 4.** Changes in the main Fc of the as-received AISI 5140 steel and the workpieces cooled in oil and polymerized water after hot forging during the process with coated ceramic tool.

a) f=0.04 ımm/rev, a=0.6 mm,

b) V=180 ım/min, a=0.6 mm,

c) V=180 m/min, f=0.04 mm/rev

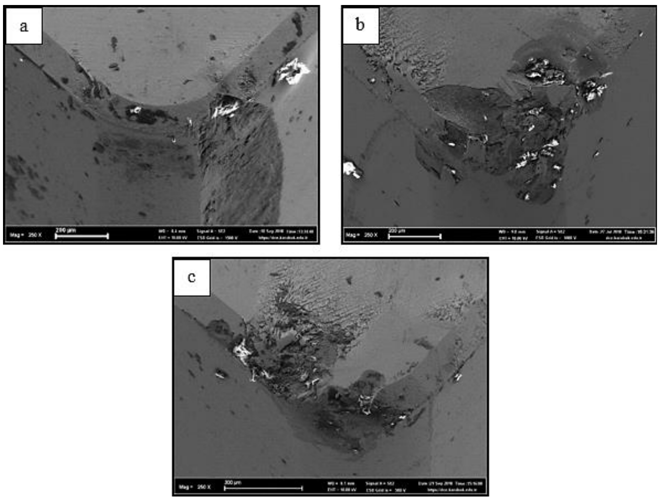


**Figure 5.** SEM images of the cutting tools worn at maximum Fc and Ra during the machining of the workpieces cooled in the polymerized water.

a) Figure 4-7.a. The image of the cutting tool worn at Vc=240 m/min,

b) Figure 4-7.b. The image of the cutting tool worn at fn=0.16 mm/rev,

c) Figure 4-7.c. The image of the cutting tool worn at ap=1 mm.

### 3.3. Cutting Force and Hardness

Figure 6 shows the correlation between the averages of the Fc and the hardness of the workpieces obtained as a result of the hard turning process at different Cp of AISI 5140 as-received material and the workpieces cooled in the oil and polymerized water after hot forging.

The lowest Fc was obtained at the average Fc of 127.6 N depending on the Vc of the as-received AISI 5140 material having a hardness value of 208 Hv1 and the microstructure composed of perlite/ferrite structures. The average Fc depending on the ap and fn increased at the rate of 12.54% and 57.42%, respectively based on Fc. With the presence of martensite in the workpiece cooled in the oil after hot forging, its hardness increased at rate of 182.2% compared to the as-received workpiece. With the increase of the hardness, the average Fc increased at the rate of 55.62% based on Vc in the workpiece cooled in the oil compared to the as-received workpiece and its average Fc increased at the rate of 18.2% in terms of the ap and fn. The cooling rate of the workpiece cooled in the polymerized water was higher than the workpiece cooled in the oil. Since the cooling rate of the workpiece cooled in the polymerized water was higher, its hardness increased at the rate of 210.58% compared to the as-received workpiece during the formation of martensite microstructure. The Fc depending on the Vc of the workpiece cooled in the polymerized water increased at the rate of 71.40% compared to the as-received workpiece and its Fc increased at the rate of approximately 15,64% in terms of the ap and fn. The fact that the microstructure of the workpieces cooled at high cooling rates (in the oil and polymerized water) after hot forging compared to the as-received workpiece led them to have a martensitic structure and their hardness levels to increase. For this reason, the average Fc depending on the Vc, ap, and fn were affected in a directly proportional way to hardness.

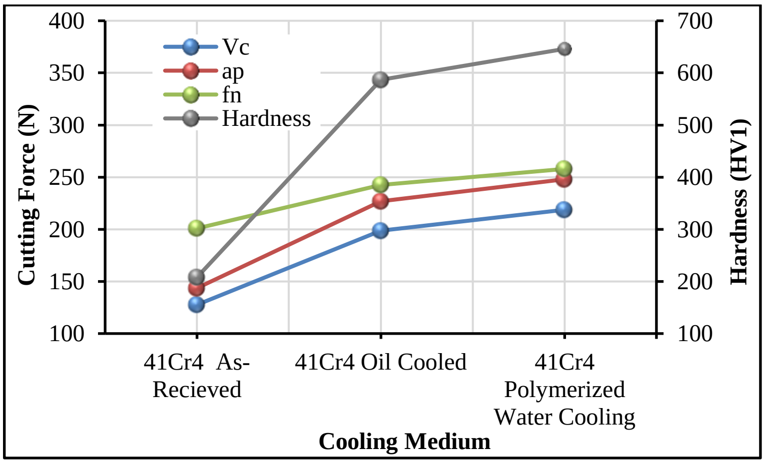


**Figure 6.** The correlation between the average main Fc and hardness.

### 3.3. Surface Roughness

Figures 7 a, b, and c show the Ra values obtained as a result of the hard turning operation of the as-received AISI 5140 material and the workpieces cooled in the oil and polymerized water after hot forging conducted using the coated ceramic tool in different Cp.

In this study, it was clearly observed that the Ra was higher at low Vc (120 m/min) and decreased when the Vc increased to 180 m/min for all machined workpieces. At 120 m/min Vc, the lowest Ra values were measured as 0.48 and 0.56 µm for the workpieces cooled in the oil and polymerized water; whereas, the highest roughness value was obtained as 0.78 µm for the as-received AISI 5140 (Figure 7.a). The Ra values of the as-received AISI 5140 material and the workpieces cooled in the oil and polymerized water at 180 m/min Vc were 0.53 µm, 0.39 µm, and 0.32 µm, respectively. The decreasing Ra values of the turned workpieces were lower at the rate of approximately 40% at 180 m/min Vc compared to the values measured at 120 m/min Vc. The decreasing Ra as a result of the increasing Vc from 120 m/min to 180 m/min can be explained with less built-up edge (BUE) formation due to thermal softening at high temperature caused by the increasing Vc [21,22]. When the Vc reached to 210-240 m/min, an increasig tendency is seen in the Ra values. When the Vc increased from 180 m/min to 240 m/min, the Ra values of the as-received AISI 5140 steel and the workpieces machined after cooling in the oil and polymerized water after hot forging increased at the rates of 3.58%, 48.18%, and 87.64%. Figure 5 shows The fact that the Ra values increased again when the Vc reached to maximum values (210-240 m/min) can be explained by the decreased wear resistance of the cutting tool due to the rapid temperature increase in the cutting edge and thus it increase the wear.

Figure 7.b shows Ra values of the workpieces machined at four fn (0.04, 0.08, 0.12, and 0.16 mm/rev), constant Vc (180 m/min), and constant ap (0.6 mm). The Ra value was measured as 0.53 µm in as-received AISI 5140 material in the turning tests performed at 0.04 mm/rev fn. The roughness values of the machined surfaces of the workpieces cooled in the oil and polymerized water under the same machining conditions decreased at the rates of 33.58% (0.39 µm) and 62% (0.33 µm). The Ra

values of the as-received AISI 5140 steel and the workpieces cooled in the oil and polymerized water increased at the rates of 256.4%, 478.68%, and 657.8% by increasing the fn up to 0.16 mm/rev.

Figure 7.c shows the Ra values of the surfaces machined at constant Vc (180 m/min), constant fn (0.04 mm/rev) and four ap (0.4, 0.6, 0.8, and 1 mm). The roughness values of the surfaces of the as-received AISI 5140 and the workpieces cooled in oil and polymerized water machined at the ap of 0.4 mm were measured as 0.65 μm, 0.51 μm, and 0.43 μm. As the ap increased up to 0.6 mm, the average Ra values decreased at the rates of 22-29% in average. The Ra values of the as-received AISI 5140 and the workpieces cooled in the oil and polymerized water increased at the rates of 35.44%, 161.16%, and 257.70%. According to the test results, Ra value is increased with increasing in the fn. This situation is in parallel with the literature studies [23]. The Ra values of the as-received AISI 5140 steel at 120-210 m/min Vc, 0.04-0.14 mm/rev fn and 0.4-0.7 mm ap were found to be higher than the Ra values of the workpieces cooled in the oil and polymerized water after forging process. This is because the as-received AISI 5140 steel having ferrite and perlite microstructure was more ductile than the workpieces having martensitic microstructure cooled in the oil and polymerized water after hot forging. Furthermore, the increase in the hardness in the ranges of the Cp stated above affected positively the roughness values of the machined surfaces. In addition, when the microstructural images (Figure 2.a,b,c) are examined, the large ferrite/perlite grain sizes of the as-received AISI 5140 steel caused the formation of craters which are larger than the machined surfaces of the workpieces having martensitic microstructure cooled in the oil and polymerized water [22, 24, 26]. In the tests performed at the values higher than 210 m/min Vc, approximately 0.14 mm/rev fn and 0.7 mm ap, the roughness values of the machined surfaces showed an opposite situation. The reason for this is evaluated as the negative effects of the abrasion, forming in the cutting tool due to the high resistance forming by the workpieces with increasing hardness increased against cutting, on the Ra. In addition, the Ra values increased along with the increasing Fc [25].

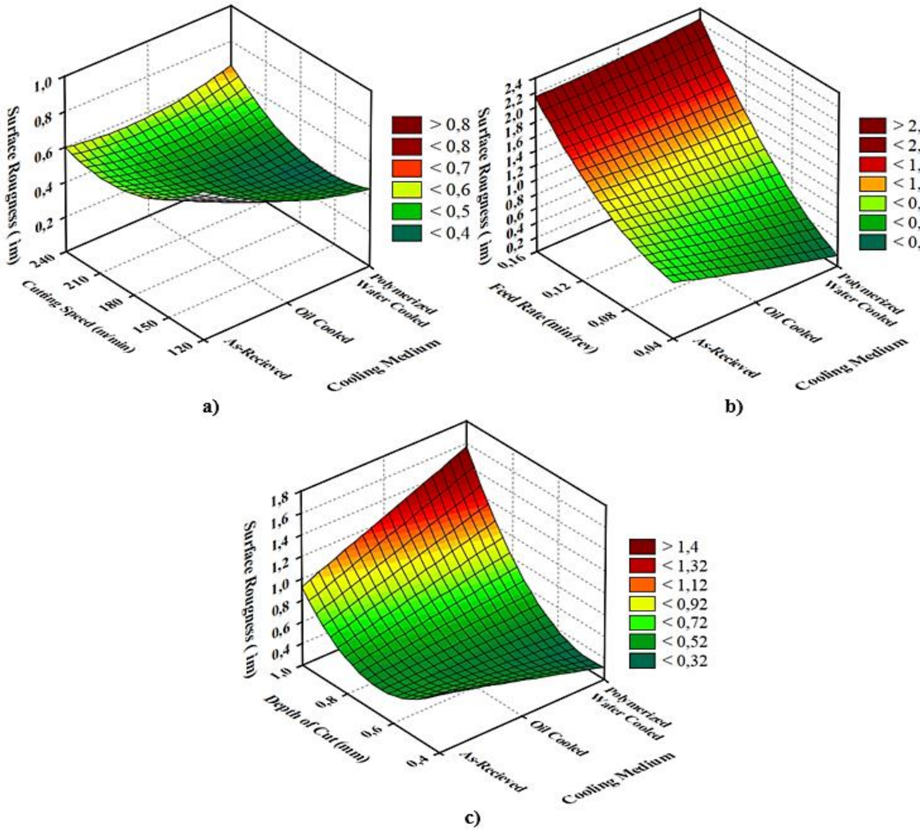


**Figure 7.** Ra values of the as-received AISI 5140 steel and the workpieces cooled in the oil and polymerized water after hot forging by using the coated ceramic tool.

a) f=0.04 mm/rev, a=0.6 mm,

b) V=180 m/min, a=0.6 mm,

c) V=180 m/min, f=0.04 mm/rev.

## 4. CONCLUSIONS

In this study, the impress of the microstructure, hardness, and different Cp on Fc and Ra when turning as-received AISI 5140 steel and the workpieces cooled in different media (oil and polymerized water) after hot forging was investigated. In the tests conducted with turning method, the coated ceramic cutting tools were used. The results obtained in this study are summarized below:

1) It was observed that the microstructure of the as-received AISI 5140 steel had ferrite/perlite structures and its hardness was measured as 208 Hv1. Cooling in the oil and polymerized water having high cooling rates after hot forging operation caused the workpieces to have a martensitic microstructure. However, the fact that the cooling rate in the polymerized water was higher than the cooling rate in the oil led them to have the highest hardness (646 Hv1) value.
2) In all the turning tests, the increases in the hardness and the increase in the Fc were parallel in the workpieces with increasing hardness. In addition, while the most effective Cp in the increase of Fc was determined as fn, it was followed by the ap and Vc.
3) While the lowest Ra until the wear of the cutting tools in the turning tests was obtained in the workpieces cooled in the oil and polymerized water in direct proportion to the hardness, the Ra of these two workpieces increased after the Cp when the wear of the cutting tool started.
4) It was observed during the turning operation of the workpieces with increasing hardness that the wear started in the cutting tool and the cutting tool lost its cutting capability as the Vc, fn and ap increased.

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