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THE EFFECTS OF AUSFERRITE STRUCTURE ON SURFACE TOPOGRAPHY OF AUSTEMPERED GRAY IRON

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Abstract

In this study, effects of ausferrite structure morphology (high carbon austenite+bainitic ferrite) on basic surface topography properties of gray iron were investigated in terms of surface roughness, cylindrical and cyclicity (roundness). The austempered gray iron microstructure was also examined for comprehensive evaluation. Gray iron specimens were austenized at 900°C then quenched to salt bath at austempering temperatures 315°C and 375°C for various austempering times. Some samples were also subjected to specific heat treatment to show martensite phase on basic surface topography properties. All specimens were machined at constant feed rate and after heat treatments. The evaluations of machined surface showed that the ausferrite structure improves the surface texture (surface roughness and surface waviness) properties significantly. The cylindricity of machined surface increased with increasing austempering temperatures. It was also seen that martensite affected adversely surface properties in all heat treated parts. The experimental results showed that the surface topology properties can be improved significantly with austempering heat treatments without any extra surface treatments.

Key Words: Cyclicity (Roundness), Austempering, Surface, Cylindricity, Ausferrite.

1. Introduction

Because of good castability, wear resistance and machinability the gray iron has produced more widely than the other kind of cast irons [1-2]. Especially, the gray iron was preferred to be used for rotating mechanical parts (camshaft) in automotive industry. The importance of surface texture of these parts becomes so crucial day by day. Some surface treatment processes are used to improve the surface quality, but most of these processes require extra operation or they increase the manufacturing cost. Some heat treatments were also developed in order to improve mechanical and surface characteristic properties of gray iron. The austempering heat treatment improves mechanical properties in all heat treatment processes.

Conventional austempering heat treatment consists of following steps;

- Gray iron samples are heated up to 850–920°C for a period of time enough for carbon saturation of austenite.
- After austenizing, samples are rapidly cooled to the austempering temperature in the range of 230–400°C and held at these temperatures. These temperatures must be over martensite start temperature.
- Austenized samples are held at austempering temperatures for a time to obtain desired ausferritic structure.
- Finally, austempered samples are cooled to room temperatures.

The matrix of ferritic or perlitic gray iron changes to an acicular microstructure, consisting of 60–80%

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bainitic ferrite without carbide and 20–40% high carbon austenite. This structure has been called ausferrite structure [3-4].

Aravind et al. studied the austempering behaviour of a series of hypereutectic alloyed gray iron compositions with carbon equivalent from 4.37 to 5.14 to understand the influence of microstructure on its mechanical and wear properties. The experimental result showed that the wear rate increase with volume of austenite, austenite carbon content and austenite lattice parameter which is attributed to increased stability of austenite against strain induced martensite formation and the increased formation of bainitic carbides in the second stage tempering [5]. Ferry and Xu investigated the microstructural and crystallographic features of ausferrite in as-cast gray iron. They found that the ausferrite consists of an acicular ferrite constituent, termed bainitic ferrite, which develops during continuous cooling as a coarse, feathery-type structure within the prior austenite grains [6]. Xu et al. also studied the effect of ausferrite formation on the mechanical properties of gray iron. The test result exhibited that an increase in volume fraction of ausferrite resulted in a concomitant linear increase in key mechanical properties with the fully ausferritic gray iron producing the optimum combination of mechanical properties [7].

Aravind et al. evaluated the structure and property of austempered and as-cast ausferritic gray cast irons. Their analysis showed that the Ni-Mo alloyed austempered gray iron and the directly as-cast austempered gray iron had similar phase constitutions. The strength of the direct as-cast alloy with ausferritic microstructure was higher than the others due to its higher austenite content and carbide distribution [8]. Austempering heat treatment has been studied ductile iron. There are many comprehensive studies about effect of austempering on the mechanical properties ductile iron [9-15]. There are some studies about investigation of austempering heat treatments on mechanical properties gray cast iron [16-21]. Most of the studies proved that the austempering has positive effects on gray iron.

There are some studies about mechanical properties of austempered gray iron, but there is no study about the effect of austempering heat treatments on surface characteristic properties (topology properties) such as surface roughness, cylindricity and circularity in the literature. Effects of austempering, temperature and time were investigated which change the ausferrite structures significantly on the surface characteristic properties. The first aim of this research was to find an association between ausferrite structure and basic surface topography properties. The other important aim of this research was also to develop correlation between the microstructure and surface characteristic properties of austempered gray iron. Some samples were subjected to specific heat treatments to achieve this aim.

2. Experimental Procedure

The gray cast iron material was used in this study. The chemical composition of the material was given in Table 1. The cast material had ferrite+perlite and flake graphite structure, Figure 1.

Table 1. Chemical composition of experimental gray cast iron (wt%)

C	Si	Mn	P	S	Cu
3,65	2,48	0,440	0,223	0,078	0.110

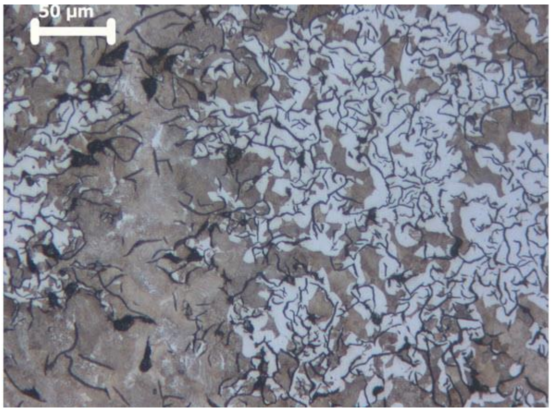


Figure 1. The microstructure of gray cast iron

The work piece bars have 240 mm long and 30 mm in diameter. Specimens were austenitized at the 900°C for 90 minutes. Then specimens were rapidly quenched to a salt bath containing 50% KNO_3 + 50% $NaNO_3$. Finally, specimens were held at the 315°C and 375°C for austempering about 60 minutes and 120 minutes to produce different ausferrite structure morphology. Some samples were also heat-treated at the austenitizing temperature of 900°C and then rapidly quenched to water in order to formed martensite structure for comparison. Some samples were also subjected to specific heat treatment. Figure 2 provides a summary of heat treatments and and Figure 3 shows heat treatments experimental set up respectively. Throughout these heat treatments, the temperature of each specimen was monitored by a thermocouple which spot-welded to the centre of one of its faces.

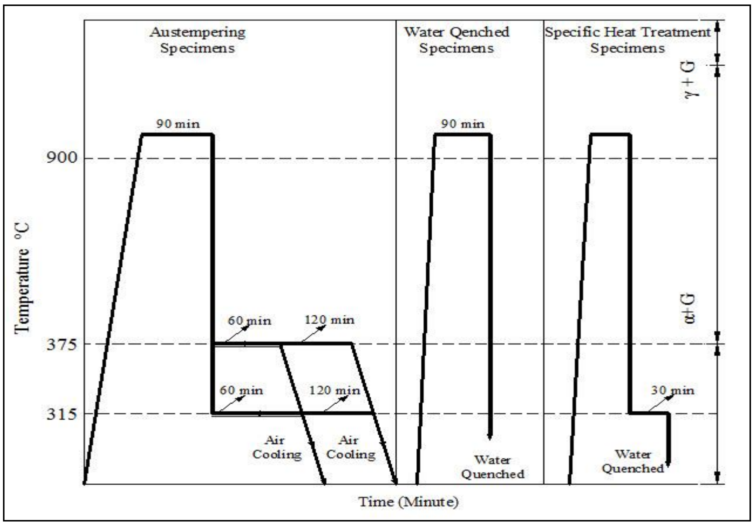


Figure 2. Summary of heat treatments

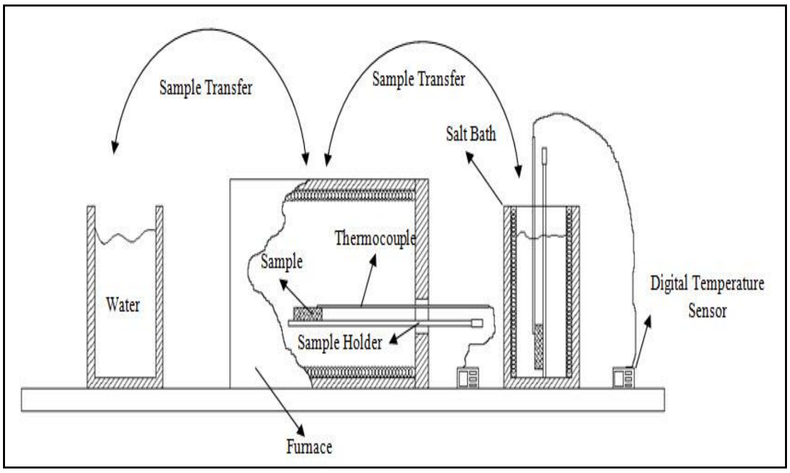


Figure 3. Heat treatments set up

After heat treatments, specimens which have dimensions of ∅ 30 x 5 mm were cut from each test specimen. Afterwards these specimens were prepared for microstructure analysis with standard metallographic processes. Nital was used as an etchant and Leica DM4000M optic microscope was also used in order to analyse microstructures.

All samples were machined (turned) at constant feed rate of 0.3 mm/rev and cutting speed of 210 m/min in CNC lathe machine. The surface of machined parts was analysed in terms of surface roughness cylindricity and roundness after turning. MMQ400 Mahr surface form measurement device was used for cylindricity and circularity measurement. It is known that filter selection is so important in surface forms measurement. For this reason, 15 (UPR) filter, wavelength or lobing limit for form filtering is called the cut off and was specified as the number of undulations per revolution which was used to eliminate measurement error. Five measurements were performed to determine cylindricity value.

Surface roughness measurements were carried out with Marform MMQ 200 surface roughness tester. Three measurements were carried out and the average value of these three measurements was used as surface roughness value (Ra). In addition, some surface roughness parameters such as Rt, Rz and Rq were evaluated for comprehensive surface topography characterizations.

3. Results and Discussion

3.1. Heat Treatments and Microstructures

The cast microstructure has ferrite+perlite and flake graphite, Figure 1. The new totally different microstructure was formed after austempering heat treatments. There are two reaction stages throughout austempering heat treatments of gray cast iron. Firstly, the austenite (γ) decomposes into bainitic ferrite (α_b) and high carbon austenite. Secondly, supersaturated austenite decomposes into bainitic ferrite and carbides. The desired microstructure of the austempered ductile iron is ferrite and high carbon austenite, commonly called ausferrite. It can be seen from Figure 4, Figure 5 and Figure 6 that the matrix of all austempered parts has completely transformed to ausferrite structure.

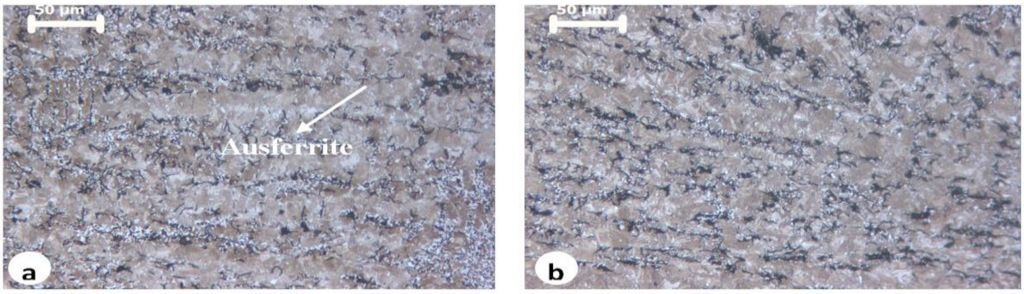


Figure 4. Microstructure of samples austenitized at 900°C for 90 min than austempered at 315°C for various austempering times (a) 60 min, (b) 120 min.

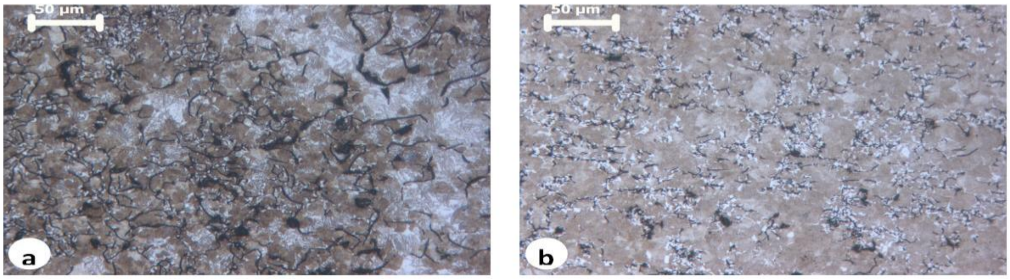


Figure 5. Microstructure of samples austenitized at 900°C for 90 min than austempered at 375°C for various austempering times (a) 60 min, (b) 120 min.

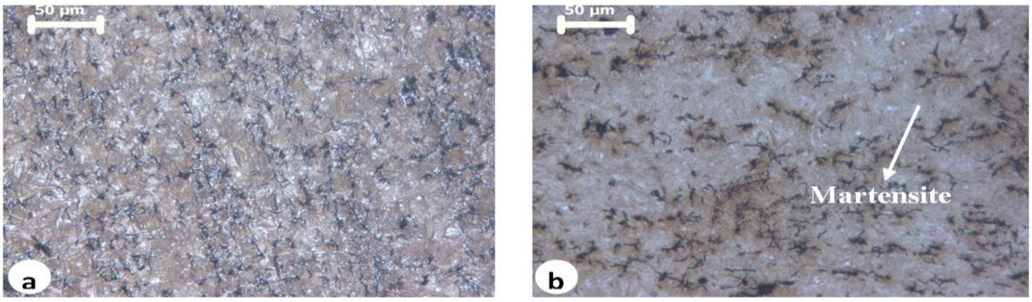


Figure 6. Microstructure of specific heat treatments and water quenched parts (a) Specific, (b) Water quenched.

Furthermore, it can be seen from Figure 4, Figure 5 and Figure 6 that the austempering time and temperature significantly influence the ausferrite morphology. Coarse ausferrite structure was obtained with increasing austempering temperatures. The homogen dispersion of ausferrite structures was formed in the higher austempering time. It was observed that the graphite morphology changed with austempering time and temperatures. Therefore, it can be said that surface topography characteristics are substantially influenced by these parameters. Some samples were subjected to the specified heat treatment to evaluate martensite phase on surface properties of austempered parts. The Figure 6a shows the martensite formation in ausferritic structure. It has been determined that microstructure of specified heat treated parts consisted of ausferrite and martensite. After water quenching process, martensite transformation from austenite has shown in Figure 6b. In addition, flake graphite forms changed from flakes to nodules.

3.2. The effect of ausferrite structure on cylindricity and circularity

The cylindricity and circularity (roundness) are indispensable surface topography characteristic parameters used in the evaluation of rotating mechanical parts' surface forms, Figure 7. Cylindricity can be explained as the condition of a surface of revolution in which all points (elements) of the surface are equidistant from a common axis (20). In circularity, all points on the surface must lie within the limits of size and the circularity limit.

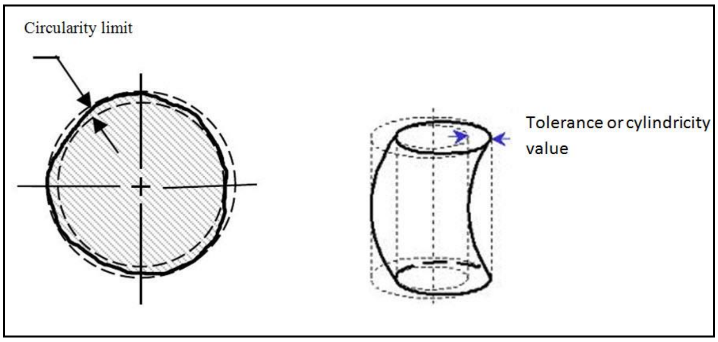
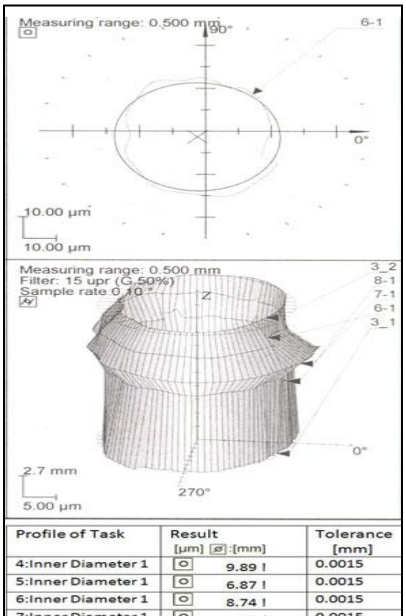


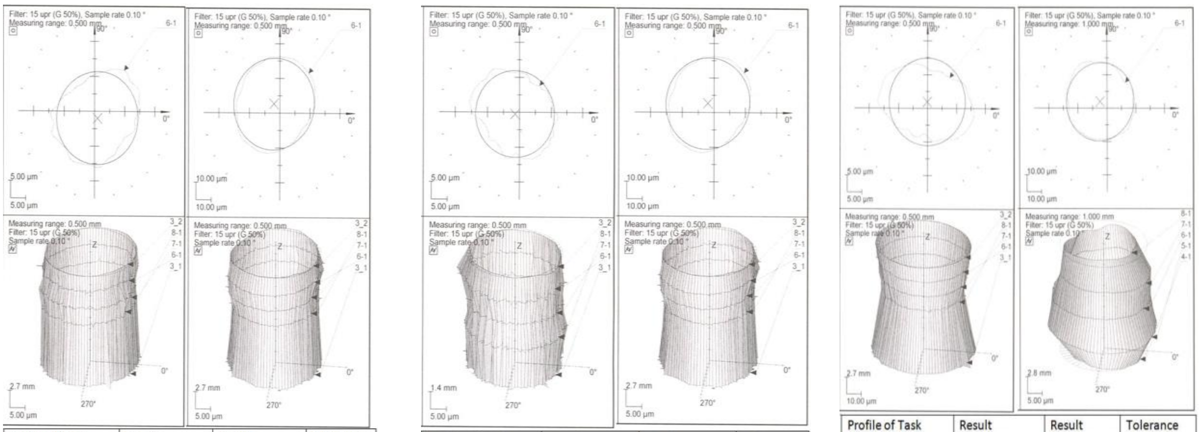
Figure 7. Schematic illustration of circularity and cylindricity

It can be seen from Figure 8 and Figure 9 that ausferrite structure morphology influence cylindricity and circularity of austempered gray iron. The best cylindricity value was obtained at 11.5 μm for 315°C austempering temperature and 60 minute austempering time. This result can be attributed to fine ausferrite structure obtained at lower austempering temperatures. The carbon content of high carbon austenite in ausferrite structure increases with increasing austempering time. Moreover, the hardness of austempered parts increases with higher austempering temperatures. Increase in hardness affects cylindricity and circularity negatively.



Profile of Task	Result [μm] ⌀:[mm]	Tolerance [mm]
4:Inner Diameter 1	9.89 !	0.0015
5:Inner Diameter 1	6.87 !	0.0015
6:Inner Diameter 1	8.74 !	0.0015
7:Inner Diameter 1	12.06 !	0.0015
8:Inner Diameter 1	5.28 !	0.0015
9: Cylindricity	18.96	0.0500
	As Cast	

Figure 8. Cylindricity and circularity of as cast specimen



Profile of Task	Result [µm] [ø]:[mm]	Result [µm] [ø]:[mm]	Tolerance [mm]
4:Inner Diameter 1	5.83 !	6.24 !	0.0015
5:Inner Diameter 1	5.08!	6.16 !	0.0015
6:Inner Diameter 1	5.83 !	7.19 !	0.0015
7:Inner Diameter 1	7.14 !	6.33 !	0.0015
8:Inner Diameter 1	6.84 !	6.84 !	0.0015
9: Cylindricity	14.66	11.05	0.0500
	5.900-90-315/120	6. 900-90-315/60	

Profile of Task	Result [µm] [ø]:[mm]	Result [µm] [ø]:[mm]	Tolerance [mm]
4:Inner Diameter 1	7.01 !	4.86 !	0.0015
5:Inner Diameter 1	6.06 !	6.44 !	0.0015
6:Inner Diameter 1	4.88 !	5.85 !	0.0015
7:Inner Diameter 1	6.21 !	6.56 !	0.0015
8:Inner Diameter 1	5.09 !	5.08 !	0.0015
9: Cylindricity	17.74	15.84	0.0500
	3.900-90-375/120	4. 900-90-375/60	

Profile of Task	Result [µm] [ø]:[mm]	Result [µm] [ø]:[mm]	Tolerance [mm]
4:Inner Diameter 1	9.06 !	7.26 !	0.0015
5:Inner Diameter 1	8.79 !	5.54 !	0.0015
6:Inner Diameter 1	7.66 !	6.55 !	0.0015
7:Inner Diameter 1	8.03 !	5.06 !	0.0015
8:Inner Diameter 1	12.33 !	10.51 !	0.0015
9: Cylindricity	43.32	32.91	0.0500
	1.Specified Heat Treatment	2.Water Quenched	

Figure 9. Variation in the cylindricity and circularity with heat treatment process

The ausferrite showed similar effects on circularity properties of gray iron. The samples which were austempered at 315°C for 60 minutes had the lowest cylindricity value. On the other hand, specific heat treatment samples showed the highest cylindricity value at about 43.32 µm. In addition, the cast structure did not have better circularity (8.568 µm) than austempered parts (4,86 µm).

Because of the transformation of perlite to ausferrite, more homogen microstructure was obtained in austempered structures. Therefore, less irregular cutting forces are formed during machining process which affects surface form significantly. It has been determined that cylindricity and circularity can be obtained at desired values by controlling austempering temperature and time.

It can be understood how cylindricity is affected with ausferrite structure morphology and microstructure. The linear correlation between austempering temperature and cylindricity can be seen from Figure 9.
Comparison about circularity of austempered gray irons has shown in Figure 10. It can be clearly seen that circularity values decrease with decreasing austempering temperatures. Graphite flakes in perlite in the as cast structure give rise to decrease circularity properties because they create irregular cutting force during machining. Higher austempering temperatures formed coarse ausferrite structures. Therefore, it can be said that matrix structures influence the surface basic properties significantly.

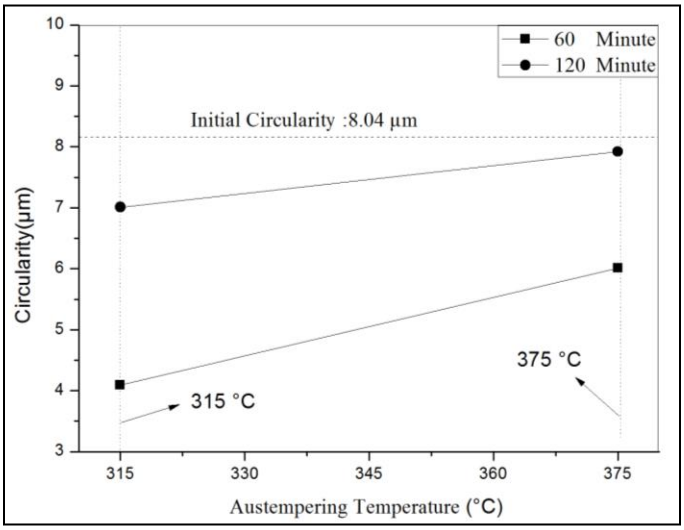


Figure 10. Variation of circularity with austempering temperatures

3.3. The effect of ausferrite structure on surface roughness.

Surface roughness is an important property that used in material selection. Surface roughness affects many kinds of material properties such as tensile, wear resistance and fatigue properties. Understanding of basic surface topography elements is so important to clearly evaluate surface roughness. For this reason, some basic surface topography elements such as roughness, profile and waviness were given in Figure 11.

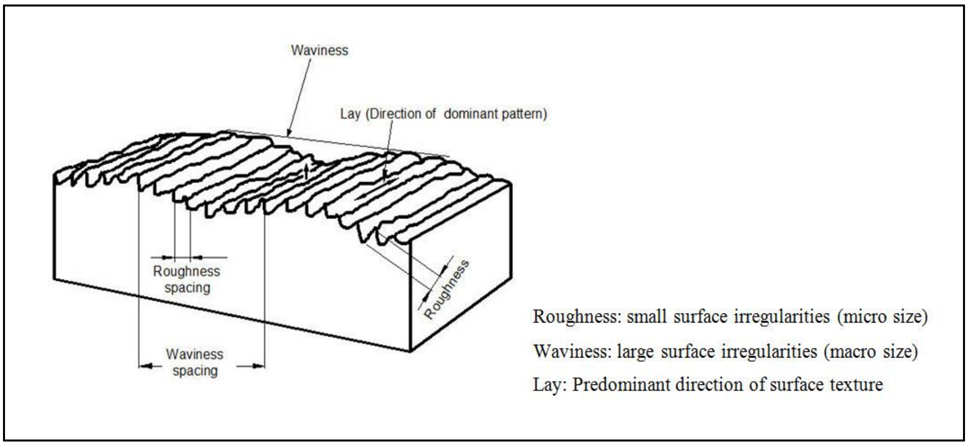


Figure 11. Basic surface topography elements

Figure 12 and Figure 13 illustrate how ausferrite morphology and microstructure affect the surface roughness of gray iron. It should be taken into consideration that the scales are different in graphics given in this figure to accurate assessment. The optimum surface roughness values were obtained at 315°C austempering temperature for 90 minutes. The worst surface roughness value was obtained at specific heat treatment samples (4.9 µm). It was followed by water quenched samples (4.7 µm). The significant decrease in surface roughness on samples which were austempered higher austempering temperatures can be explained with coarse ausferrite structure. The coarse structure increase irregular cutting force between toll and part surface during machining. Therefore, surface roughness is affected negatively by coarse ausferrite structure. It also can be seen from Figure 12 and Figure 13 that ausferrite structure improved other basic surface topography properties such as waviness and surface profile.

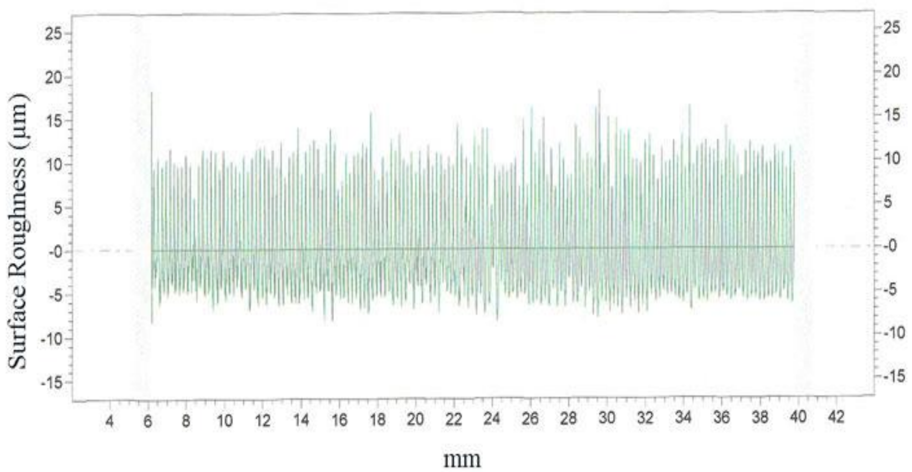


Figure 12. Surface roughness profile of as cast specimens

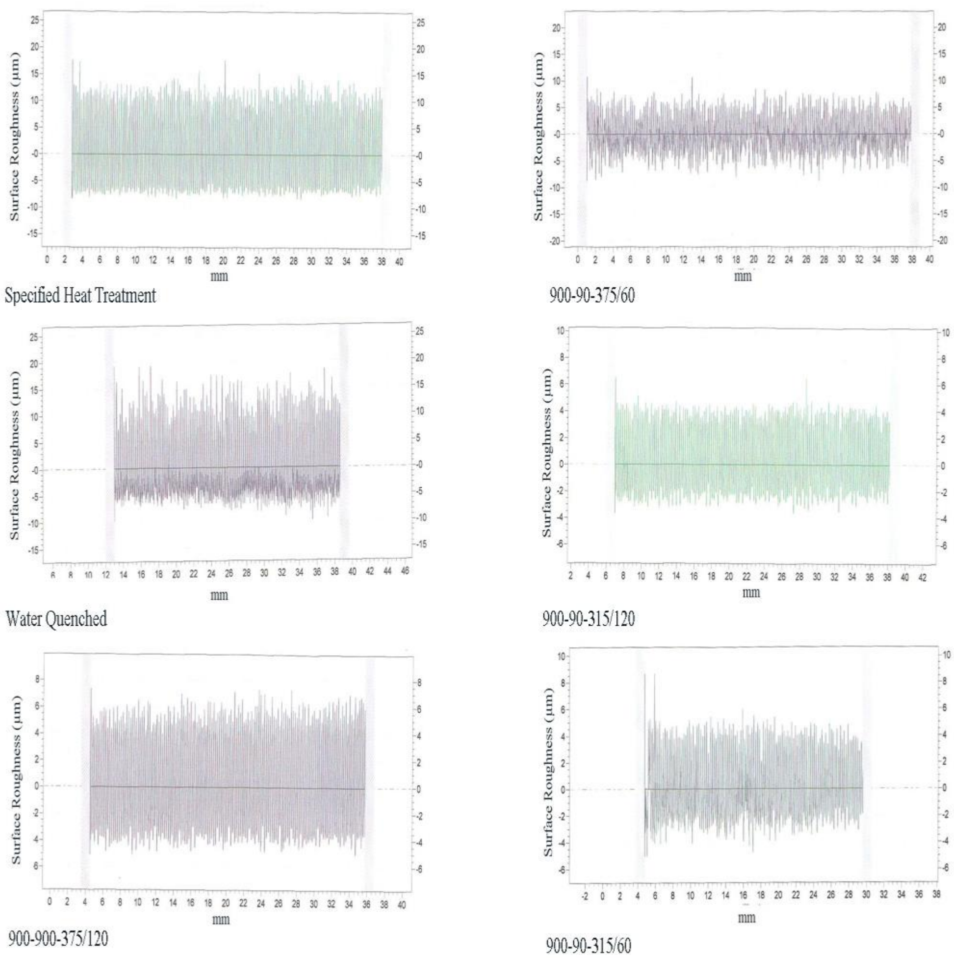


Figure 13. Variation in the surface roughness with heat treatments

Surface roughness values are comprehensively given in Table 2. Some important surface roughness value parameters such as Rp, Rz and Rt were also given in this table to evaluate surface roughness effectively. It can be seen from Table 2 that the finer ausferrite structure (lower austempering temperatures) gives rise to increase all surface roughness parameters.

Table 2. Surface roughness parameter values of all experiment samples

Samples Code	**Surface Roughness Parameters (µm)**						
	Ra	**Rp**	**Rs**	**Rv**	**Rt**	**Rc**	**Rz**
As Cast	4.2028	12.6556	104.93	6.6235	26.4931	16.6526	19.2791
Water Quenched	4.7138	15.6392	72.15	7.3843	29.010	19.2113	23.0235
Specified Heat Treated	4.9252	13.1351	203.09	7.5926	29.055	20.7278	18.5640
315°C- 60 min	1.7860	4.4568	175.42	2.9666	10.3341	6.2154	7.4233
315°C- 120 min	1.8090	5.0215	70.54	3.5321	13.6893	6.9338	8.5536
375°C- 60 min	2.4961	6.9727	49.10	6.4011	19.4410	9.7300	13.3739
375°C- 120 min	2.6780	6.3341	163.59	4.4133	12.4298	9.5959	10.7473

3.4. The relationship between hardness and surface characteristic properties.

Five measurements were made on each specimen to obtain the average value. The as-cast material showed a lower hardness of 220 HV. It can be understood easily from Figure 14 that ausferrite structure microstructure affected hardness of gray cast iron. The ausferrite structure morphology also has important effects on hardness. The higher austempering temperatures reduce the hardness and increase the surface roughness. On the other hand austempering time does not have the same influence on surface roughness. In addition, martensite in the microstructure affected the hardness significantly. Therefore surface topographic properties are directly influenced by martensite phase. Martensite was also formed in the specified heat treatment parts so that the structure consisted of ausferrite and martensite. This structure change topologic properties and hardness outstandingly.

It can be concluded from the result of hardness that the hardness of austempered parts can be controlled with martensite volume fraction which is formed after austempering heat treatments.

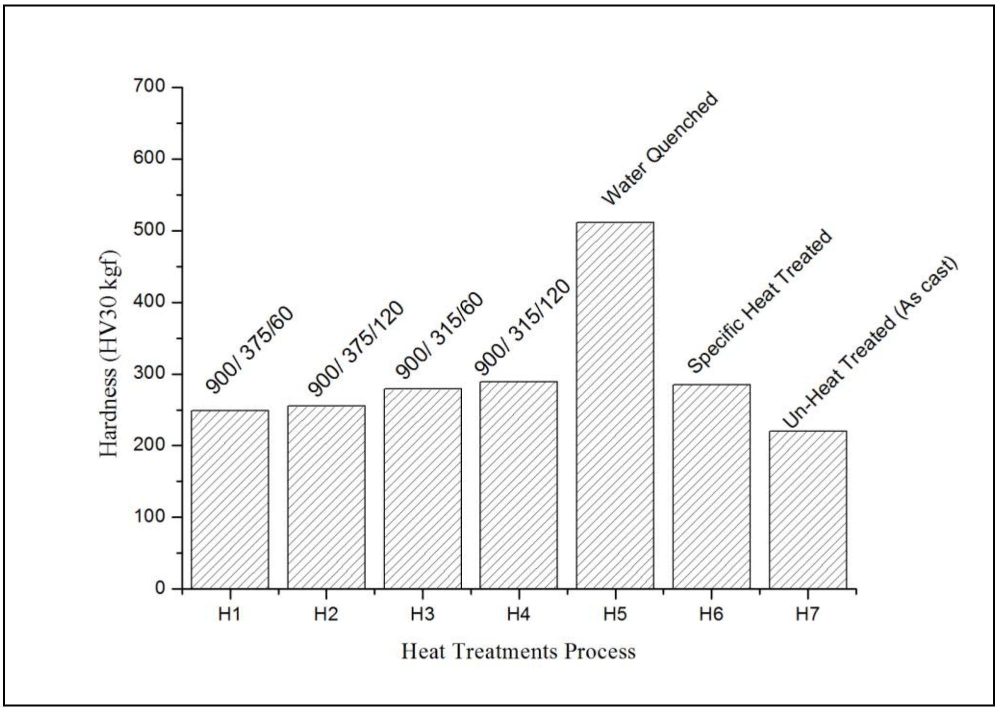


Figure 14. Variation of hardness with heat treatment process

4. Conclusion

It was concluded that austempering heat treatments improved the surface characteristic properties of gray iron significantly. The matrix structures affect surface characteristic properties of gray iron directly. The surface characteristic properties can be adjusted as desired values by controlling the austempering heat treatment parameters. Higher austempering temperatures cause also coarse ausferrite structures. These coarse structures lead to increase surface roughness and cylindricity. In addition, water quenching of samples during austempering process (specific heat treatments) cause martensite formation. This martensite in ausferrite structure affects surface topography properties of gray cast iron adversely. As a result, there is a linear correlation between austempering temperature and circularity.

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