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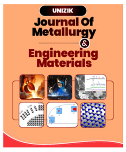

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Investigation of Surface Finish on Orthogonally Machined Heat-Treated Nodular Cast Iron

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Abstract

This study investigated the influence of annealing heat treatment temperature on the surface roughness characteristics of orthogonally machined nodular cast iron (NCI). NCI, known for its excellent mechanical properties, is widely used in various industries. The surface finish of machined components impacts their performance and longevity. Annealing, a critical heat treatment process, was employed to modify the microstructure of NCI, enhancing its machinability. This research aimed to establish the relationship between annealing temperature and the resulting surface roughness after orthogonal machining. The methodology involved annealing NCI samples at different temperatures (750°C - 950°C), followed by orthogonal machining at different cutting speeds (340 rpm - 1400 rpm). Surface finish was quantified using average surface roughness. The hardness and microstructural changes were characterized using a Vickers hardness tester and metallographic techniques. The results showed that increasing annealing temperature improved the surface finish with an optimal surface roughness of 2.62 µm at 900°C. Cutting speed also significantly affected the surface roughness, with higher speeds resulting in smoother surfaces up to a certain threshold. However, excessive cutting speeds increased roughness due to thermal effects, tool wear, and machine vibration. The optimal combination of annealing temperature and cutting speed was identified as 900°C and 1150 rpm, respectively, yielding an average surface roughness value of 2.62 µm. The annealing heat treatment reduced the hardness and improved machinability. Optimizing the annealing process led to a significant improvement in the surface finish of orthogonally machined NCI components. This research provides valuable insights into the machinability of annealed NCI and offers practical guidelines for enhancing manufacturing processes, ultimately improving product quality and performance.

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1. Introduction

Nodular cast iron, also known as ductile iron, has gained significant attention in various industrial applications due to its exceptional mechanical properties, including high tensile strength, ductility, and wear resistance [1]. These properties make nodular cast iron an ideal material for components subjected to dynamic loads, such as automotive parts, gears and machine frames. The manufacturing processes employed in producing these components, particularly machining, play a crucial role in determining the final surface quality, which significantly influences the performance and lifespan of the parts [2]. Surface roughness is a critical parameter in machining, as it directly affects friction, wear and fatigue resistance of the machined components [2]. A smoother surface finish not only enhances the aesthetic appeal but also improves the performance characteristics of the component by minimizing contact area and reducing stress concentration points [3]. As such, understanding the factors that influence surface roughness during machining is essential for optimizing manufacturing processes and ensuring product reliability. The machining of nodular cast iron, particularly under various heat treatment conditions, presents unique challenges and opportunities. Annealing is a common heat treatment process used to improve the machinability of nodular cast iron by altering its microstructure. Annealing at elevated temperatures can lead to a reduction in hardness and an increase in ductility, which can facilitate better chip removal and contribute to a smoother surface finish [4]. However, the relationship between annealing temperature and surface roughness during machining has not been extensively studied, particularly in the context of orthogonal cutting. Orthogonal machining is a widely used cutting process in the manufacturing of precision components. In this process, the cutting tool engages the workpiece at a constant angle, which allows for a more straightforward analysis of cutting forces and surface integrity [5]. The interaction between the cutting tool and the workpiece, influenced by cutting speed and feed rate, significantly impacts the resultant surface roughness. Higher cutting speeds can lead to improved surface finishes due to reduced tool wear and efficient chip removal, but excessive speeds may cause increased thermal effects, leading to an adverse impact on surface quality [2]. Despite the critical importance of surface roughness in the performance of machined components, there remains a significant gap in the literature regarding the combined effects of annealing temperature and cutting speed on the surface roughness of orthogonally machined nodular cast iron. This study aims to address this gap by systematically investigating how varying annealing temperatures and a range of cutting speeds influence the surface roughness of nodular cast iron during orthogonal machining.

1.1. Surface Roughness in Machining

Existing research on surface roughness in machining highlights the multifaceted nature of this critical parameter. By understanding the interactions between machining parameters, material propertiesand tool characteristics, manufacturers can optimize machining processes to achieve desired surface finishes. Research on surface roughness in machining has focused on various aspects, including measurement techniques, influencing factors, machining parametersand the effects of surface roughness on performance. Continued research in this area is essential for advancing machining technologies and improving the quality of manufactured components Numerous studies have investigated the relationship between machining parameters and surface roughness across various materials. For instance, El-Rayes et al. [6] examined the impact of cutting speed and feed rate on the surface finish of machined gray cast iron and reported that optimal cutting conditions significantly improved surface quality. Similarly, Kir et al. [7] highlighted the importance of tool geometry and cutting parameters in achieving desirable surface finishes in different cast iron grades.According to Thamizhmanii and Hasan [8], a smoother surface finish is often associated with lower friction coefficients and improved fatigue resistance, which enhances the longevity and reliability of mechanical components. El-Rayes et al. [6] found that increasing the annealing temperature leads to improved ductility and reduced hardness, which in turn enhances machinability and results in a finer surface finish. They further emphasize that heat treatment processes, such as annealing, significantly influence the machinability of nodular cast iron by improving the ductility and reduce hardness.The influence of cutting conditions on surface roughness of ductile iron in turning operation was conducted by Akdemir et al [5]. They reported that the softer matrix results in higher surface roughness due to increased tool engagement and material flow during machining processes, which can lead to the formation of irregularities on the machined surfaces. Annealing and normalizing processes generally reduce the hardness of nodular cast iron, making it easier to machine [9]. Lower hardness levels can result in reduced cutting forces and improved tool life [9]. The studies of Gomes-de-Sousa et al. [10] have shown that normalized nodular cast iron exhibits better machinability compared to as-cast or hardened samples. The surface finish achieved during machining is influenced by the microstructure and hardness of the material [2]. Heat treatments that optimize the microstructure can lead to improved surface finish, as uniform materials produce more consistent cutting conditions [2].The work of Nwosu and Chinwuko [11] has shown that cutting speed, feed rate and depth of cut are critical factors that influence surface roughness. Higher cutting speeds generally lead to improved surface finishes, while increased feed rates are associated with higher roughness values [11].Optimizing these parameters can lead to significant improvements in surface quality.The geometry of cutting tools, including rake angle, clearance angle and edge radius, plays a crucial role in determining surface roughness [12]. The research has demonstrated that tools with positive rake angles produce smoother surfaces due to reduced cutting forces and better chip formation [12]. The research carried out by Shahid et al. [13] have shown that the mechanical properties of the workpiece material, such as hardness and microstructure, influence surface roughness. Harder materials tend to produce rougher surfaces when machined due to increased tool wear and difficulty in chip removal [13].The work of Yurtkuran and Gunay [14] indicates that increasing cutting speed generally leads to a decrease in surface roughness value, at least up to a certain threshold. Higher cutting speeds can reduce the size of the chips produced and improve surface finish due to less tool engagement time with the material [14]. However, excessively high speeds may lead to thermal damage and tool wear, which can negatively affect the surface quality [14].The feed rate is one of the most influential parameters affecting surface roughness according to Polishetty et al. [15]. Higher feed rates typically result in increased roughness due to larger chip formation and more significant tool engagement [15]. The studies of Ramesha et al. [16] have shown that optimizing feed rates can lead to significant improvements in surface finish, especially in turning operations. Parhad et al. [3] observed that the depth of cut influences surface roughness, with deeper cuts generally leading to rougher surfaces. This is attributed to the increased cut area and higher forces acting on the tool, which can exacerbate vibrations and tool wear [3].Ogedengbe et al. [17] concluded that the hardness of the workpiece material is directly correlated with surface roughness. Softer materials tend to produce smoother surfaces, while harder materials may result in higher roughness due to increased tool wear and the difficulty of chip removal [17].The microstructure of the material, including grain size and phase distribution, can also affect surface finish [5]. They concluded that the materials with finer microstructures often yield better surface finishes due to their improved machinability and reduced susceptibility to tool wear.The choice of tool material, such as high-speed steel (HSS), carbide or ceramic, influences wear resistance and heat generation during machining [7]. Carbide tools are generally preferred for machining operations requiring high temperatures, as they maintain their cutting edge longer, leading to better surface finishes [7].The work of Marimuthu and Chandrasekaran [18] ascertained that the tool geometry, including rake angle, nose radius and clearance angle, plays a significant role in determining surface roughness. They concluded that the tools with positive rake angles tend to produce smoother surfaces due to reduced cutting forces and less friction. This studyaimed to considered the combined influence of annealing temperature and cutting speed, particularly under controlled conditions, with the ability to identify optimal machining parameters for achieving superior surface quality.

2. Experimental Procedure

2.1. Nodular Cast Iron Preparation

The study utilized commercial nodular cast iron produced at Nigeria Machine Tools, Oshogbo Osun State in the form of cylindrical bar of diameter of 22cm and average length of 30cm.The composition of the cast iron determined using Optical Emission spectrometer (OES) is depicted in Table 2.1. The cast iron bars were then sectioned into six samples of an average length of 15cm suitable for heat treatment and machining.

2.2. Annealing Process

The samples were heated to five different temperatures; 750°C, 800°C, 850°C, 900°C and 950°C. Each sample was held at the target temperature for 1 hour to ensure homogenization of the material. After the soaking period, the samples were allowed to cool in furnace to room temperature.

2.3. Orthogonal Machining Setup

The orthogonal machining of the as-cast and heat-treated nodular cast iron samples was performed using automatic center lathe machine. High-speed steel (HSS) cutting tools were employed for the machining process.Five different cutting speeds were utilized; 340, 625, 950, 1150, and 1400 rpm. The feed rate was maintained at a constant value of 0.1 mm/rev throughout all machining operations. The depth of cut was set at 2 mm to ensure uniform material removal across all samples. The rake angle was maintained at 10 degree throughout the machining process. Each step was cut at an average length of 74 mm.The turning operation was carried out at different steps and each step represents different cutting speed according to Figures 1 and 2.

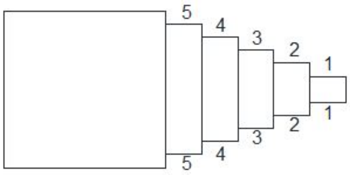

Figure 1: 2D model view of machined sample

Figure 2: Machined sample of nodular cast irons

Table 1: Chemical composition of ductile cast iron in weight percent

Fe	C	Si	Mn	P	S	Cr	Mo	Ni
94.5	3.5	2.3	0.6	0.1	0.03	0.02	0.03	0.03

2.4. Surface Roughness Measurement

Surface roughness was evaluated using a surface roughness tester; Mitutoyo Surftest which employs a stylus method for precise measurement. After machining, the samples were cleaned to remove any debris or cutting fluid that could affect the measurement.Surface roughness measurements were conducted at three locations on each step to ensure representativeness. The average roughness parameter was recorded for each measurement location. The measurements were repeated for each combination of annealing temperature and cutting speed and the average values were calculated for analysis.

2.5. Hardness

Hardness test was carried out on automatic hardness testing machine using Vicker Hardness Number (VHN). The surfaces of the samples were grounded under running water using grinding papers and then polished for better flat surface. The hardness test procedure consists of identing the polished surface with a load of 10kg force applied for 10 seconds.The hardness values were red directly from the machine through a high-powered microscope on the machine. The procedure was repeated for three times for each sample and the average value taken and recorded as the hardness value of sample.

2.6. Microstructural Analysis

The as-cast and samples from annealed condition were prepared for microstructural analysis. This involved standard metallographic techniques, including grinding, polishing and etching. The microstructures of the iron samples were examined using metallurgical microscope. Images of the microstructure were captured at 100x magnifications.

3. Results

3.1. Annealing temperature

As shown in Figure 3, the average surface roughness values decreased initially with increasing annealing temperature, reaching a minimum value at 900°C and then increased again at 950°C for all the samples. The lowest value of 2.62 µm was observed at 900°C. For instance, at a cutting speed of 1150rpm, the average surface roughness values decreased from 2.89µm at 750°C to 2.62 µm at 900°C, demonstrating a clear trend of improved surface finish with higher annealing temperatures. The observed trend can be attributed to the microstructural changes induced by the annealing temperature. This phenomenon is attributed to the refinement of the microstructure which enhances ductility and reduces tool wear leading to smoother cutting conditions and this aligned with the work of Thamizhmanii and Hasan [8]. In as-cast condition, the matrix of the nodular cast iron likely contained a higher proportion of pearlite, which is harder and more prone to brittle fracture during machining and this led to increased surface roughness. As the temperature increased to 900°C, the increased diffusion allowed for more complete transformation of pearlite to ferrite, resulting in a softer, more ductile matrix. This improved machinability, reducing cutting forces and consequently surface roughness as previously observed by El-Rayes et al. [6]. However, it is noteworthy that an increase in surface roughness was observed at 950°C, where the average surface roughness value returned to 3.02 µm at a cutting speed of 1150rpm. The increase in surface roughness at 950°C might indicate excessive grain growth or changes in the graphite morphology, negatively impacting machinability and this is in accordance with the work of El-Rayes et al. [6] which stated that the increase in surface roughness at higher temperature may be linked to excessive grain growth and the onset of adverse microstructural changes which can compromise machinability.

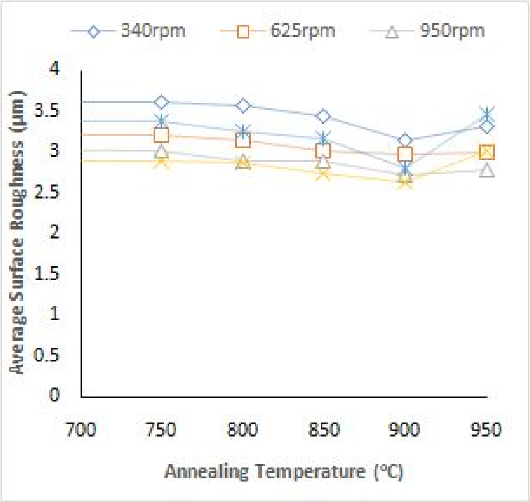

Figure 3: Effect of annealing temperature on surface roughness parameters

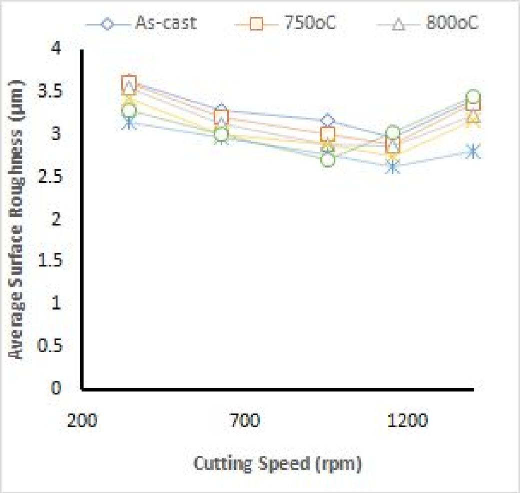

Figure 4: Effect of cutting speed on surface roughness

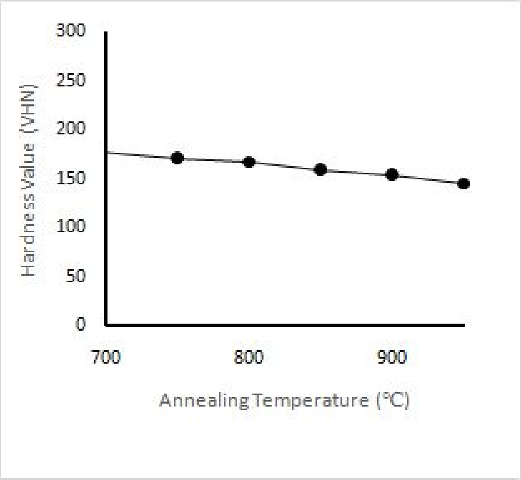

Figure 5: Effect of annealing temperature on hardness value

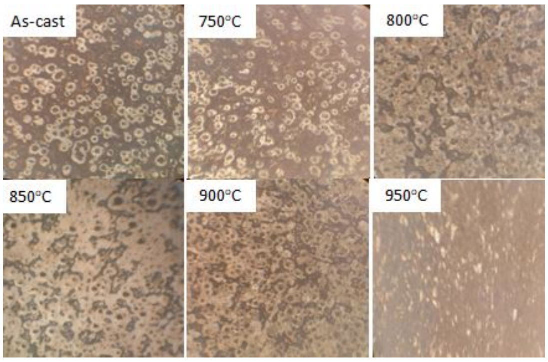

Figure 6: Optical micrographs of as-cast and annealed nodular cast iron at X100

3.2. Cutting Speed

The annealing temperature was identified as the most critical parameter influencing surface roughness. The Figure 4 reveals that surface roughness tends to decrease with increasing cutting speed. For example, for an annealing temperature of 900°C, the average surface roughness values decreased from 3.14 µm at 340rpm to 2.62µm at 1150 rpm. The higher cutting speeds facilitate improved chip removal and reduced tool engagement time, contributing to a better surface finish and this is in accordance with the work of Akdemir et al. [5]. However, the trend indicates diminishing returns at very high cutting speeds. For instance, at 1150 rpm, the surface roughness (2.62 µm) was lower than at 1400rpm (2.8µm) for samples annealed at 900°C, suggesting that excessive cutting speeds may lead to increased machine vibration, thermal effects and tool wear which negatively impacting surface quality and this is in general agreement with Ilori et al. [2].

3.3. Hardness

Heat treatment is a crucial process that alters the physical and sometimes chemical properties of a material. For ductile iron, annealing serves to relieve internal stresses, improve ductility and refine the microstructure. The annealing temperature significantly influences the mechanical properties, particularly hardness (Figure 5), which is essential for applications where wear resistance is critical. As the annealing temperature increases, the hardness decreases, which generally enhances machinability and surface finish [17]. The material in as-cast condition is not subjected to any heat treatment. The recorded hardness of 265VHN indicates that the material retains its properties due to the lack of microstructural changes. At this temperature, the cast iron is in its as-cast microstructure, characterized by a high density of carbides and a mix of ferrite and pearlite. This structure contributes to higher hardness levels resulting in poor surface finish during machining. This high hardness value suggests a brittle state which may lead to poor machinability and increased surface roughness during machining. As the annealing temperatures increases, there is significant drops in hardness. This reduction indicates that the microstructure is undergoing transformation leading to spheroidization of the cementite and this enhances ductility. The decrease in hardness is beneficial for machining processes, as it leads to improved surface finish due to reduced cutting forces and wear on cutting tools. The annealing temperature of 950°C results in the lowest hardness of 146 VHN. The high surface roughness recorded at this temperature was due to the material's excessive softness and build-up edges and machine vibrations. The is in agreement with the finding of Parhad et al. [3] which affirmed that the increased in softness results in highest surface roughness at higher temperatures, as the machining process encounters greater resistance, leading to pronounced tool wear and sub-optimal surface finishes.

3.4. Microstructure

Figure 6 depicts the optical micrographs of as-cast and annealed nodular cast iron at different temperatures. Nodular cast iron, generally consists of a matrix of ferrite or pearlite with spherical graphite nodules dispersed throughout the microstructure [19]. This unique microstructure imparts excellent mechanical properties, including enhanced ductility and strength. The microstructure can be significantly altered through heat treatment processes like annealing, impacting hardness, machinability and surface finish [19]. In as-cast condition, nodular cast iron retains its original microstructure with no changes. However, as the temperature rises, significant transformations begin. The matrix starts to exhibit dissolution of graphite nodules, where carbon-rich particles dissolve promoting ductility. The dissolution of graphite nodules enabling finer cuts and potentially decreasing surface roughness during machining [3]. The refinement of the microstructure at this stage leads to improved machinability. As the annealing temperature increasing, the process of dissolution continues and the matrix transition towards a more ferritic structure with reduced pearlitic content. The microstructure stabilized, leading to a more homogenous distribution of the graphite nodules and a softer matrix and this contribute to better surface finish at higher temperatures. Ramadan et al. [19] reported that as the temperature increases, the dissolution of graphite nodules becomes more pronounced and the matrix structure transitions towards a softer ferritic composition. As the annealing temperature approaches 950°C, the material reaches a near-complete dissolution of graphite nodules whereby the ferrite phase dominates the structure, resulting in a very ductile but soft microstructure. This extreme ductile nature may contribute to poor surface finish observed at higher annealing temperature. This phenomenon is supported by the findings of Shahid et al. [13], who noted that softer materials tend to produce rougher surfaces during machining operations.

4. Conclusion

The results indicate a clear relationship between annealing temperature, cutting speed and surface roughness in orthogonally machined nodular cast iron. Higher annealing temperatures generally enhance surface quality up to a certain point, while increased cutting speeds lead to improved surface finishes. The interaction between annealing temperature and cutting speed significantly influenced surface roughness. As illustrated in Figure 3.1, the optimal surface finish was achieved at an annealing temperature of 900°C combined with a cutting speed of 1150 rpm, yielding an average surface roughness value of 2.62 µm. These findings provide valuable insights for optimizing machining practices in the production of nodular cast iron components, ultimately contributing to improved performance and reliability in industrial applications. This underscores the importance of carefully selecting both parameters to optimize surface quality.

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Conflict of interest

The authors declare there is no conflict of interest

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