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Research Article

Microstructural Characteristics Investigation of CSN 12050 Carbon Steel to Optimize Machinability through Thermal Treatment and Recrystallization

Melesse Workneh Wakjira*

Assistant Professor (PhD), School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Adama, Ethiopia

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Abstract: The aim of the study of this paper is to improve the microstructure characteristics and alloying elements of CSN 12050 carbon steel products through thermal treatment and temperature-dependent characteristics (Recrystallization) to enhance the ease of machinability. The treated and untreated samples change in microstructure characteristics is examined using metallographic microscope equipped with camera. The result showed that an improved microstructure for the ease of machinability obtained in the thermal treatment cycle of annealing and a temperature- dependent (recrystallization) process. Furthermore, by heating the metal to the recrystallization temperature before deformation, the forces and power required to carry out the process are significantly reduced. Analysis of chemical composition has been carried out using Spectro-test TXC25 machine model number 2010, for the required specimens of CSN 12050 carbon steel. Result showed that the improved alloying elements in the chemical compositions of CSN 12050 carbon steel successfully achieved through temperature-dependent recrystallization process. The obtained enhancement in CSN 12050 carbon steel microstructure characteristics and alloying elements is a good implication to comprehend the product sustainability for the ease of machinability in dry condition. The experimentally validated results value using the digital power analyzer shown that 35 % for untreated sample test, 33 % for annealed sample, and for recrystallized sample 32 % of cutting power consumption were recorded. Finally, from the achieved result we can predict that the possibility of economic, environmental and societal benefits of dry machining condition by avoiding the use of cutting fluids.

Keywords: Microstructure; alloying-elements; Machinability; Optimization; metallographic-microscope; Spectro-test TXC25 machine; chemical-composition; digital-power analyzer.

INTRODUCTION

The effect of thermal treatment and temperature-dependent characteristics investigation in-relation to microstructural characteristics of CSN 12050 carbon steel is well conducted to achieve the ease of machinability. This steel is widely used for industrial applications like Shafts, Gears, Bolts, Pins, Connecting rods, Rams, Axles, Crankshafts, Studs, Rams, Guide rods, Spindles and Hydraulic clamps etc. [1]. Among these products the Pin product which is used for cane carrier chains of Sugar Mills is selected to optimize the machinability [1]. It is predominantly manufactured at Hibret Manufacturing and Machine Building Industry (HMMBI) of Ethiopia [1]. Microstructural characteristics investigation of the CSN 12050 carbon steel is commenced to optimize the ease of machinability and minimum power requirement.

Microstructural characterization and modification of chemical component to investigate the effect of alloying elements on CSN 12050 carbon steel is an essential technique to attain the ease of machinability. The microstructure characteristics of CSN 12050 carbon steel can be improved under the effect of thermal treatment and temperature-dependent characteristics. When CSN 12050 carbon steel cooled rapidly (water quenched) the carbon atoms cannot make an orderly escape from the iron lattice. This cause "atomic bedlam" and results in distortion of the lattice, which shows itself in the form of hardness and/or strength [2, 3]. Consequently, a new structure known as martensite is formed, although this new structure (an aggregate of iron and cementite) is in the alpha phase [4]. Most heat treating operations (notably annealing, normalizing, and heating for hardening) begin with heating the alloy into the austenitic range to dissolve the carbide in the iron [4, 5].

Austenite does not ordinarily exist at room temperature in carbon steels. The rate at which steels are cooled from the austenitic range has a profound influence on the room temperature microstructure and properties of carbon steels [6]. It has been reported that the optimization for heat treatment process, microstructural effect on the mechanical behavior, and effect of heat treatment on prior grain size etc. [7-9]. Effect of retained austenite on abrasive wear resistance of carburized SAE 8822H steel and tempered characteristic of quenched alloy spheroid graphite cast iron result of microstructure indications is reported in the previous studies [10-12]. In this study, the effect of temperature-dependent characteristics and cooling medium for properties enhancement of CSN 12050 carbon steel to optimize product sustainability has been examined thorough experimentation. The experimental investigation of microstructure characteristics and chemical composition of CSN 12050 carbon steel has been carried out through thermally treated, untreated and temperature- dependent recrystallization process.

Accordingly, the experimentation result for a lower temperature of $0.5T_m$ (recrystallization) the transformation product coarse pearlite has been obtained. Hence, from the obtained result it has been selected and concluded that a temperature-time dependent recrystallization process is an appropriate process for product sustainability optimization.

Aim

The aim of the study is to improve the microstructure characteristics and the effect of alloying elements to facilitate the ease of machinability for CSN 12050 carbon steel products and to implement product sustainability optimization philosophy.

The objectives of the research are as follows

- To understand and analyze the effect of alloying elements /chemical composition of CSN 12050 carbon steel
- To know the characteristics of alloying elements in the CSN 12050 carbon steel and understand the effect of each alloying elements
- To improve the microstructural effects of CSN 12050 carbon steel
- To enhance the tensile strength, ductility and hardness of the CSN 12050 carbon steel for the ease of machinability
- To optimize the machinability, eliminate the need of cutting fluids or reduce the cost needed for the cutting fluids and reduce the power consumption during machining the CSN 12050 carbon steel.

CSN 12050 Carbon steel chemical composition

The CSN 12050 carbon steel (structural and constructional steel) material chemical composition analysis has been carried out using Spectro test TXC25 machine model number 2010 as given in Figure-1. The samples are finely grinded/polished and suitably etched to provide clearly visible surface for the analysis. The machine is on for 15 minutes to the required amount of temperature from 30 ^{o}C to 40 ^{o}C to flash argon gas for shielding the sample to protect from atmospheric contamination. The untreated and thermally treated spectro test TXC25 machine analysis result of CSN 12050 carbon steel chemical composition weight by percent shown in Table-1.

Fig-1: Spectro test TXC25 machine set up for sample calibrations [1]

Table-1: Results of thermally-treated, recrystallized and untreated CSN 12050 carbon steel samples chemical composition analysis of Spectro test TXC25 machine

Untreated CSN 12050 carbon steel sample mechanical composition weight by percent												
S/N	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**W**	**Fe**
1	0.47	0.24	0.59	0.045	0.085	0.074	0.003	0.017	0.016	0.079	0.040	98.4
Thermally treated CSN 12050 carbon steel sample mechanical composition weight by percent												
Hardened												
S/N	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**W**	**Fe**
1	0.37	0.26	0.63	0.022	0.0075	0.14	0.003	0.016	0.014	0.099	0.040	98.4
Normalized												
S/N	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**W**	**Fe**
2	0.35	0.27	0.60	0.061	0.034	0.13	0.003	0.019	0.017	0.10	0.040	98.3
Annealed												
S/N	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**W**	**Fe**
3	0.34	0.26	0.61	0.064	0.037	0.13	0.003	0.016	0.015	0.097	0.040	98.3
Tempered												
S/N	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**W**	**Fe**
4	0.40	0.24	0.60	0.11	0.067	0.13	0.003	0.020	0.018	0.18	0.040	98.2
Recrystallized												
S/N	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**W**	**Fe**
5	0.41	0.23	0.59	0.17	0.099	0.13	0.003	0.022	0.019	0.10	0.040	98.3

Table-2: Effect of alloying elements on CSN 12050 carbon steel [4]

Alloying elements	Alloying elements and their effects on CSN 12050 carbon steel
C	Carbon has a strong tendency to segregate at the defects in steels (such as grain boundaries and dislocations). Carbide forming elements may interact with carbon and form alloy carbides. Increases hardenability and strength
Si	Silicon is one of the principal deoxidizers used in steel making; therefore, silicon content also determines the type of steel produced. In heat-treated steels, Si is an important alloy element, and increases hardenability, wear resistance, elastic limit and yield strength, and scale resistance in heat-resistant steels.
Mn	Manganese is especially a deoxidizer and desulfurizer. Manganese is beneficial to surface quality in all carbon ranges and reduction in the risk of red-shortness. Manganese is a weak carbide former, only dissolving in cementite, and forms alloying cementite in steels. The presence of alloying element Mn in steels enhances the impurities such as P, as segregating to grain boundaries and induces temper embrittlement.
P	Phosphorous dissolves in ferrite and increases the strength of steels. As the amount of P increases, the ductility and impact toughness of steels decrease, and raise the cold-shortness, also increases hardenability and retards the decomposition of martensite-like Si in steels.
S	Sulfur has a very strong tendency to segregate at grain boundaries and causes reduction of hot ductility in alloy steels. However, sulfur in range of 0.08-0.33% is intentionally added to free machining steels for increased machinability.
Cr	Chromium increases hardenability, corrosion and oxidation resistance of steels, improves high temperature- strength, and high pressure hydrogenation properties. Chromium is the most important alloying element in steels. The addition of Cr in steels enhances the impurities, such as P, Sn, Sb.
Mo	Molybdenum is a pronounced carbide former. The addition of Mo produces fine-grained steels, increases hardenability, and improves fatigue strength. Molybdenum is a very important alloying element for alloy steels.
Ni	Nickel is a non-carbide forming element in steels. Nickel raises hardenability. In combination with Ni, Cr, and Mo, it produces greater hardenability, impact toughness, and fatigue resistance in steels.
Al	Aluminum is widely used as a deoxidizer and a grain refiner. Enhances corrosion resistance and increases wear resistance. Of all the alloying elements, Al is one of the most effective elements in controlling grain growth prior to quenching.
Cu	Copper above 0.30% can cause precipitation hardening. It increases hardenability. Cu improves the atmospheric corrosion resistance (when in excess of 0.20%) and the tensile properties in alloy steels.
Fe	Increase ductility and malleability

Microstructural characteristics experimental investigation on CSN 12050 carbon steel

The microstructural characteristics experimental investigation of the untreated/as casted and heat treated and temperature-dependent characteristics samples are carried out. Totally, six specimens are prepared five of them are subjected to various thermal treatment (*hardening, normalizing, annealing, tempering*) *and recrystallized* process and one is left without heat treatment to compare the treated and untreated CSN 12050 carbon steel. All the five specimens have been subjected to various heat treatment temperatures as shown in Table-5.4 with in an appropriately required holding time. The equipment used for thermal treatment was Muffle Furnace which is ideal for high temperature application up to 1200 °C. The temperature range Amb+5°C to 1000°C (maximum 1200°C) its dimension, width x depth x height: (130 x 250 x 90 mm) and operating temperature is under 1000°C. The equipment used for sample preparation of CSN 12050 carbon steel microstructural examination was RB 206 Metpress-A. It is a hot mounting (*compression mounting*) device using hydraulic power package which consist of upper ram, lower ram, cylinder, heating part, cooling part, and mold. The operating mechanism is automatically mounting press, which is automatically operating pressure, heat, and cooling by water. RB 206 Metpress–A, consists the operating parameters of maximum pressure 4000psi (27579.2×10^3 N/m^2), mold diameter 35 mm of cylindrical type, maximum heating temperature 250 °C, and water cooling by solenoid valve. The consumables used for making mold were Phenolic Resins. The equipment's used for heat treatment and sample preparation shown Figure-2 and 3.

Fig-2: Muffle Furnace

Fig-3: RB 206 Metpress–A

Initially, smoothening was done through silicon carbide water proof abrasive paper electro coated with different grain size (cc-220 CW, cc-800 CW, cc-1200 CW and cc-2000 CW). After smoothening with abrasive paper cleaning with water and air compressor was done. Finally, by using polisher machine the artifacts of grinding is removed to provide an appropriate shine surfaces textures for further CSN 12050 carbon steel microstructural experimentation and validation. The RB 204 Metpol-II machine used for polishing is consisted of motor, Pulsed Width Modulation (*PWM*) method controller, splash ring cover and polishing disc with two wheels (8–12 in. size) system and its rotating speed is 50–500 RPM (10 RPM step).

For carbon and alloyed steel, the following the etching rate rises with the amount of nitric acid. The etching time is from several seconds to a minute. Etching of austenitic steel reveals, the austenite structure and the austenite grain boundaries.

The crystalline structure of the specimens is made visible by using etching reagent: 1 % concentration (*dilute solution*) by mixing HNO_3+100 ml ethyl or 50 ml methyl alcohol and 0.5 ml nitric acid on the polished surface. The finished samples for experimentation categorized as per the thermal treatment order are the hardened, normalized, annealed, tempered and recrystallized the sixth sample required without treatment/as cast. The order of the samples with the corresponding temperature ($^{\circ}C$), handling time (min) and cooling medium showed as in Table-3.

Table-3: Thermal treatment conditions to investigate the test of microstructure characteristic

Conditions	Temperature (^{0}C)	Handling time (min)	Cooling medium
Hardened	850	60	Water
Normalized	850	60	Air
Annealed	850	40	Furnace
Tempered	540	40	Air
Recrystallized	550	60	Air

The testing machines Optical/Metallurgical Microscope (OM), Polisher, Etching process and finished/tested samples are shown in Figure-4, 5, 6, and 7 respectively.

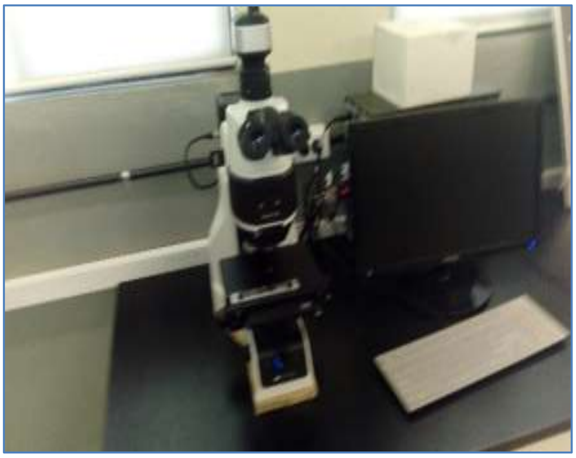

Fig-4: Optical/Metallurgical Microscope

Fig-5: RB 204 Metpol-II Grinders/Polisher

Fig-6: Etching (methyl and nitric acid)

Fig-7: The required test samples

RESULT AND DISCUSSIONS

The hardened specimen microstructure shown that the massive martensitic structure when CSN 12050 carbon steel rapidly quenched from its austenite temperature to room temperature as shown in Figure-8. The austenite will decompose into a mixture of some CSN 12050 carbon steel carbon martensitic and fewer pearlites. Quenched CSN 12050 carbon steel has a metastable structure its morphology shown that plate (*needle*) martensite, the crystals are shaped as thin lenticular plates and the neighboring plates are not parallel to one another. Consequently, in this microstructure there is an increase in hardness, tensile strength, and reduction in ductility as reported in the previous research on different steels [10-12]. The normalized sample result in Figure-9 showed that the size and shape of the original austenite grains were significantly influenced.

It discovered a pearlitic matrix and shorter graphite flakes than in annealed sample. Additionally; many short graphite flakes surrounded with patches of uniformly distributed pearlite grains were observed. The microstructure of the annealed sample in Figure-10 showed that the ferrite grains had go through complete recrystallization and these constituted the major portion of CSN 12050 carbon steel microstructure existed with stress free matrix. The crystal structure at 850 $^{\circ}C$ were fully homogenized and during the slow cooling from austenizing range to room temperature. The final microstructure consisted of large elongation ferrite grains and the pearlite was more uniformly distributed.

Consequently; the result from annealed CSN 12050 carbon steel observed that the possibility of product sustainability optimization by reducing hardness (*brittleness*), altering microstructure so that desirable mechanical properties can be obtained and soften the CSN 12050 carbon steel for improved machinability. The tempered at 540 $^{\circ}C$ is shown in Figure-10. A specific secondary graphite site with white dotted areas of a highly recrystallized ferrite grains was observed. The main processes that take place during tempering are precipitation and recrystallization of martensite. The microstructure of tempered specimen consisted of a number of carbide particles precipitated out from the matrix, which indicated that the precipitate carbide particles decomposed by a process of solution in ferrite matrix [11]. The untreated specimen microstructure characteristic showed that a combination of pearlite (*black*) and ferrite (*white*) features as shown in Figure-12.

Finally; in Figure-13 the formation of new strain-free grains of temperature- dependent process (*recrystallization*), the transformation product microstructure characteristic of coarse pearlitic lamellas has been obtained. The growing coarse carbides increase in the grain size and carbon diffusion from internal parts of grains towards their boundaries are visible very well in it. The recrystallization temperature for CSN 12050 carbon steel is usually specified as the temperature at which complete formation of new grains requires about 1 hour. It is heated to a sufficiently elevated temperature ($0.5T_m$) and then deformed, strain hardening does not occur. Instead, new grains are formed that are free of strain, and behaves as a perfectly plastic; that is, with strain-hardening exponent n = 0.

The microstructure evolution of CSN 12050 carbon steel in the regard of chemical composition experimental results the effect of alloying elements during each cycle of thermal treatments and recrystallization has been identified as shown in Table-3. In this regard, for optimization/product sustainability the selected alloying elements are: Phosphorous retards the decomposition of martensite, Sulfur for increased machinability, Nickel produce impact toughness, fatigue resistance, and Aluminium which is the most effective element in controlling grain growth. Consequently, from all cycle of thermal treatment the recrystallization process which is temperature-dependent characteristic of CSN 12050 carbon steel has been obtained the enriched amount of the selected alloying elements to meet the ultimate goal of product sustainability optimization.

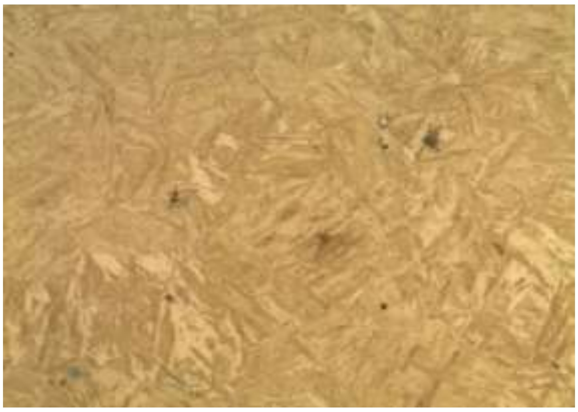

Fig-8: Hardened microstructure feature of CSN 12050 carbon steel 500x

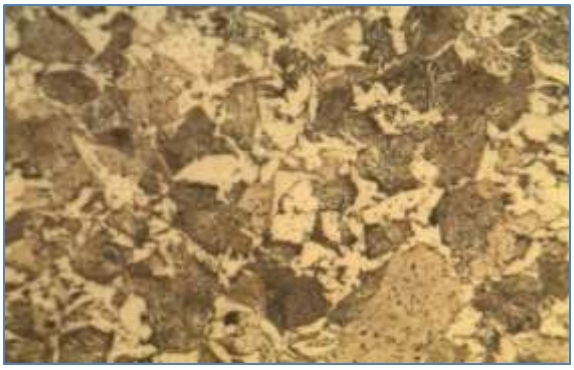

Fig-9: Normalized microstructure feature of CSN 12050 carbon steel 500x

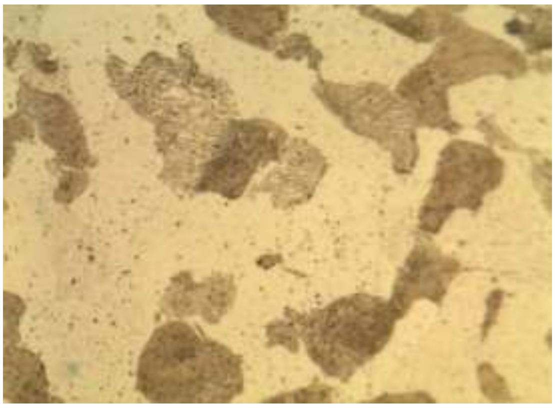

Fig-10: Annealed microstructure feature of CSN 12050 carbon steel 500x

Fig-11: Tempered microstructure feature of CSN 12050 carbon steel 500x

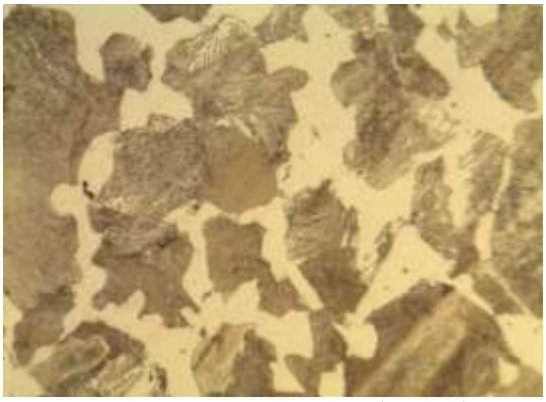

Fig-12: Untreated/As casted microstructure feature of CSN 12050 carbon steel 500x

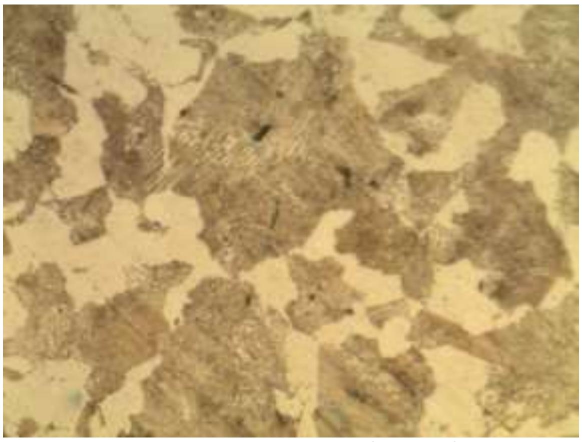

Fig-13: Recrystallized microstructure feature of CSN 12050 carbon steel 500x

Thermally treated/recrystallized and untreated CSN 12050 carbon steel experimentation in turning process, to identify the best minimum cutting power requirement

In this portion the CSN 12050 carbon steel of 200 mm length, and 40 mm diameter workpiece material was used for experimentation in the lathe machine operation. The experimental setup for the experimentation was shown in Figure-14-16. Previously the analysis results of mechanical property enhancement for CSN 12050 carbon steel workpiece material product sustainability optimization has been done [1]. Among the investigated mechanical property enhancement specimens, the thermally treated (annealed), temperature-dependent characteristic (recrystallized) process, and untreated CSN 12050 carbon steel material were selected. The cutting power consumption was measured by using power analyzer and dual digital tachometer as shown in Figure-14 and 15. The machining experiments were carried on the CNC lathe machine and coated carbide cutting tool in dry condition as shown in Figure-16.

The direct reading from the digital power analyzer for the required experimentation results was shown in Figure-17 to 19. The cutting parameters such as spindle speed (rpm), feed rate (mm/rev), and depth of cut (mm) were selected and set as constant to analyze the cutting power consumption in carrying out turning operation. The three selected specimens (Annealed, recrystallized, and untreated) CSN 12050 carbon steel material provided three specimens for each test, a total of 9 experiments were carried out with constant spindle speed (rpm), depth of cut (mm) and feed rate (mm/rev).

The cutting power consumption during turning was measured using power analyzer. From the cutting tests, the cutting power required for each of the selected specimens was plotted in relation to the environment of the required specimen material (Annealed, recrystallized and untreated). Figure-20 shows the results for thermally treated (annealed), temperature-dependent characteristic (recrystallized), and untreated CSN 12050 carbon steel material to realize the product sustainability optimization. The achieved experimental test values reflect the ease of machinability, that is how easy it is to cut CSN carbon steel material at the recrystallization temperature-dependent characteristic and further can be exploited in machining/turning operation of manufacturing industries. From the obtained results observed that, by heating CSN 12050 carbon steel to the recrystallization temperature before deformation the power required to carry out the process are substantially reduced.

Fig-14: DELLRENZO DL2109T29 Digital Power Analyzer setup

Fig-15: VOLTCRAFT DT21JK Dual Digital Tachometer

Fig-16: Experimentally tested sample of CSN 12050 carbon steel

(A)

(B)

(C)

Fig-17: (A) 1st test (B) 2nd test and (C) 3rd test experimental result of cutting power for recrystallized test sample

(A)

(B)

(C)

Fig-18: (A) 1st test (B) 2nd test and (C) 3rd test experimental result of cutting power for annealed test sample

(A)

(B)

(C)

Fig-19: (A) 1st test (B) 2nd test and (C) 3rd test experimental result of cutting power for untreated test sample

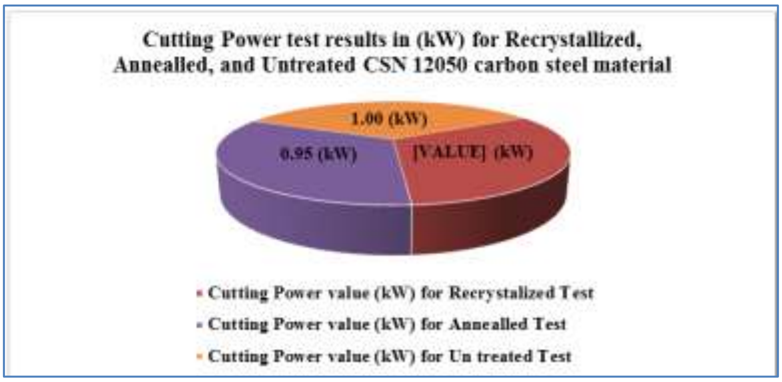

Fig-20: Cutting power experimental test mean result for recrystallized, annealed, and untreated CSN 12050 carbon steel material to achieve product sustainability optimization

The cutting parameters constantly used for the experimentation were 0.25 feed rates (mm/rev), 1.0 depth of cut (mm) and the measured spindle speed using digital tachometer is 640 rpm. When we convert the amount of power consumed from kW into watt, 1000 watts for untreated sample, 950 watts for annealed, and 920 watts for the recrystallized sample test power were consumed during the turning process. Consequently, the optimal temperature-dependent recrystallized sample test result confirmed that about 80 watts of power consumption was reduced than untreated sample test result along with the reduced carbon emission/electric cost, and increased personal health safety for the workers.

Conclusions

The experimentation evolution of microstructure identified as a function of chemical composition and heat treatment history. Accordingly, this study set out to investigate thermal treatment and temperature-dependent characteristics of CSN 12050 carbon steel to optimize machinability some of the key findings are as follows:

- This study has shown that different thermal treatment of CSN 12050 carbon steel gave diverse experimental result of microstructural characteristics. The optimization of machinability depends on the microstructural characteristics of the CSN 12050 carbon steel test result.
- The results showed that the improvement of the microstructural characteristics of the CSN 12050 carbon steel for better quality of machining, high productivity in dry condition and reduced the problem associated with the cutting fluids.
- The summary of experimentation in relation to microstructure evolution showed that graphite flakes in martensite matrix for hardened, graphite flakes in martensite matrix with recrystallized ferrite grains for tempered, and graphite flakes in pearlite matrix for normalized test sample features. Similarly, graphite flakes in ferrite matrix for annealed, and graphite flakes coarse pearlitic lamellas, with growing coarse carbides increase in the grain size for recrystallized process test sample features were observed. Also, graphite flakes in ferrite and pearlite matrix for untreated test sample feature is obtained as shown in Figure-5.8–5.13.
- In the regard of chemical composition, the alloying elements such as: Phosphorous, Sulfur, Nickel, and Aluminium reasonably enriched in the recrystallization process which is temperature-dependent characteristic of CSN 12050 carbon steel. The enrichment of these alloying elements showed that the possibility to improve the ease of machinability as well as to meet the ultimate goal of product sustainability optimization.
- Recrystallization is a temperature-dependent characteristic of metals that can be exploited in turning operation/machining as well as in manufacturing industries. Hence, in this study among the test sample of thermally treated CSN 12050 carbon steel recrystallized sample test result highly enhanced for successful machinability to achieve the goal of product sustainability optimization. From the above experimentally validated results the value for untreated sample test 35 %, annealed sample 33 %, and for recrystallized sample 32 % of cutting power consumption were recorded using the digital power analyzer. Also, as mentioned above about 80 watt of power consumption, carbon emission/electric cost, were reduced along with increased personal health safety for the workers. This is a good opportunity for HMMBI Ethiopia to optimize machinability and manufacture sustainable Pin product for their customer's satisfaction with other surplus benefits.

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