

# Study of the Effect of Quenchants on the Machinability of Heat Treated Mild-Steel

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**ABSTRACT:** Heat treated steels that are quenched rapidly show an increase in hardness and toughness but also show an increase in brittleness which could lead to a higher surface roughness and low material removal rate while machining. Hence, the choice of quenchants has a significant effect on the hardness of low carbon steels. In this research work, the effect of some selected quenchants on the mechanical properties of heat treated and machined mild steel was investigated. Four samples of the carbon steel rods were furnace heated at 850°C and quenched with water, molten salt, potash alum and used engine oil. Central Composite Designs of Design Expert version 12 was used to plan the experiment. Machining factors used were, speed (100-450 rpm), feed rate (0.01-0.03 mm/rev), depth of cut (1-2mm). Surface roughness and material removal rate as well as the results of quenchant characterization were the responses studied. The favored quenchant was oil with the lowest surface roughness, hardness and material removal rate of 0.33µm and 187.78BHN and 0.020133mm<sup>3</sup>/min respectively. This is because the use of oil resulted in the highest reduction in surface roughness and enhanced material removal rate.

**KEYWORDS:** Mild-steel, Machining, Material removal rate, Quenchants, Steel, Surface roughness

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## I. INTRODUCTION

The engineering materials used in various engineering processes are grouped into metals, plastics, ceramics, composite materials and nano-materials (Fadare *et al.*, 2011). Metals are materials which are ductile, lustrous and excellent conductors of heat and electricity, examples include: stainless steels, iron, carbon steels (Abdulrasak *et al.*, 2018). Carbon steels are largely used for a lot of manufacturing processes due to their low cost and ease of fabrication.

Their main compound element is carbon and can be grouped into: low carbon steel, medium carbon steel and high carbon steel depending on the amount of carbon composition (Oduote *et al.*, 2012). Mild steels which are types of low carbon steel have a carbon content of 0.05–0.35 wt% (Nazma-Sultan *et al.*, 2014). They are very ductile and have good weldability. These steels have various mechanical applications as it can be hardened through heat treating and tempering (Eghbali, 2010; Offor *et al.*, 2010; Korad *et al.*, 2011; Park *et al.*, 2012). Common uses of mild steels include fabrication of bolts and studs, they have been found to be used in train railroads, beams for constructing support structures, ship construction, car radiators, cutting tools etc.

The mechanical properties of mild steel can also be increased through heat treatment processes (Nazma-Sultan *et al.*, 2014). When carbon steels are heat treated in a well-managed sequence of heating and cooling, their physical or mechanical properties can be modified for certain desired uses (Zeyad, 2016; Blaoui, 2018, Dauda *et al.*, 2015). Heat treatment is a mixture of heating and cooling, applied to metal

piece to produce certain required micro-structures and mechanical properties such as hardness, toughness, yield strength, tensile strength and elongation. There are various structures in steel such as ferrite, pearlite, bainite, martensite and austenite (Blaoui, 2018).

There are various methods of heat treatment carried out on steel some of which includes; hardening, annealing, normalizing and tempering, case hardening. Hardening is a heat treatment method which includes the heating of metals above their upper critical temperature and quenching rapidly. Rapid cooling is only necessary to lower to temperature and then it is cooled to room temperature in air (Hantosh & Alfatlawi, 2018). Hardened steels are mostly tempered after to reduce internal stresses and reduce the brittleness. Various quenching media gives various results on the hardening of steel.

Quenching is a quick way of bringing a metal to room temperature after heating. Metal workers achieve this by putting the hot metal through a liquid medium. The selection of liquid is known as the quenching medium (Ogedengbe *et al.*, 2021). Popular quenching media include various gases, water, brine, and oil. Water is an adequate medium when the objective is to make the steel sample reach maximum hardness. Nonetheless, making use water as a quenchant can make the metal crack or become distorted. If extreme hardness isn't required, mineral oil, or cottonseed oil can be used as quenchants (Ogedengbe *et al.*, 2021).

Sometimes, quenching after hardening creates distortions in metals which can be corrected with machining. Various machining processes can be carried out on steel after heat treatment and quenching. Mostly, Steels are hardened in order

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to increase its toughness and durability but it also has its disadvantages especially during machining process. Machining hardened steel can be cumbersome and result in high cutting temperature, poor surface finish and reduced tool life.

However, a careful selection could probably result in an improvement of machinability of the steels. Previous researchers have attempted to investigate the possibility of improving the machinability of steel. Abdulkareem *et al.*, (2020), studied the influence of some thermodynamic characteristics of cutting fluid on the machinability of carbon steel. Three machining conditions (dry machining, wet machining with soluble oil and wet machining with used engine oil) were carried out on high carbon steel, with the purpose of finding out how sustainable engine oil would be as an alternative to soluble oil. The machining parameters were cutting speed (750-1750 rpm), feed rate (40-120mm/rev) and depth of cut (0.1-0.3 mm). The experiment was planned using Minitab software version 18, the responses investigated were maximum temperature and surface roughness and tool wear rate.

Thermodynamic characteristics investigated were flashpoint, viscosity, specific heat capacity and density. Results gotten reveal that the cutting temperature was least with soluble oil (from 440°K to 362.6°K) while used engine oil reduced machining temperature from 440°K to 369.8°K. The surface integrity when engine oil was used was 39%. Hence, used engine oil could be a suitable replacement for soluble oil as cutting fluid. Ozcatalbas & Ercan (2003), investigated the effects of heat treatment of the machinability of SAE 1050 mild steel. Two samples of SAE 1050 mild steel were heat treated (annealing and normalizing) were then machined using a Turkish brand engine lathe. The machinability was measured by taking the values of tool life, chip root, morphology, cutting forces, surface finish and tool chip interface temperature. By annealing the material, the ductility and impact energy increased but the decrease in tool life shortened, which decreased machinability.

By normalizing, the hardness, ductility and impact energy increased but the tool life was shortened even more. Alabi *et al.*, (2019), investigated the cutting forces on heat treated carbon steel sample (medium carbon steel) when turning on a lathe machine. Four medium carbon samples underwent heat treatment processes (normalizing, tempering, hardening and annealing). An experimental procedure based on orthogonal cutting was used to quantify the machining forces by means of a dynamometer. It was observed that as  $t_u$  (undeformed chip thickness in mm) increases,  $F_c$  (cutting force in N) shows for all conditions. Rashid *et al.*, (2013) conducted an experiment for the improvement of attainable surface roughness during hard machining process. An AISI 4340 steel (Hardened up to 69 Rockwell C Scale Hardness (HRC)) workpiece was machined on Mori-Seiki CNC lathe. Defects were made on the surface of the workpiece in form of holes using Trumpf (CO<sub>2</sub>) laser machine with peak power of 2.7kW before machining.

Two sets of machining were carried out, the first being standard hard turning and the second being induced surface defect hard turning. Table 1 shows the machining parameters, the diameter and depth of the induced holes. Surface roughness

was measured using a New View 5000 type white light interferometer. It was discovered that these pre-machined holes resulted in lower temperature in the cutting zone, lower average cutting forces and an improved quality of machined surface when compared to standard hard turning.

**Table 1: Experimental parameters (Rashid *et al.*, 2013).**

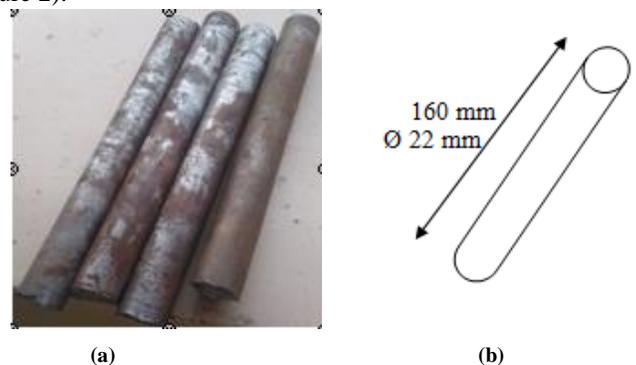
| Parameter                            | Value(s)  |
|--------------------------------------|---|
| Workpiece material                   | AISI 4340 steel hardened up to 69HRC                  |
| Diameter of workpiece before turning | 28.8mm  |
| Tool nose radius                     | 0.8mm   |
| Tool rake and clearance              | 0o and 5o   |
| Feed rate                            | 0.08mm/rev  |
| Depth of cut                         | 0.1mm   |
| Cutting speed                        | 90m/min   |
| Coolant                              | None  |
| Diameter and depth of holes          | 0.9 and 0.1mm, respectively, spaced at 10mm intervals |

Recently, an investigation on the turning of hardened steel using coated carbide inserts by Mondal *et al.*, (2020), was carried out. The machinability of hardened AISI 4340 steel was investigated using groove-type chip breaking coated carbide inserts under different cutting velocities and feed at dry machining conditions. The results revealed that adequate flat continuous chip is gotten at cutting velocity of 231m/min and at a feed of 0.08mm/rev. The possibility of enhancing the surface finish and material removal rate during machining of heat-treated steel through the use of a preferable quenchant is a welcome development. Therefore this research paper investigated the effect of some selected quenching media on the machinability optimization of a mild steel bar.

## II. MATERIALS AND METHODS

### A. Workpiece Material, Machines and Tools

The workpiece material used for this research was mild steel bar of initial diameter 24 mm machined to 22 mm and of length 640 mm divided into four equal parts of length 160 mm each (Figure 1). The sample bar was acquired from the steel market in Akure, Ondo State, Nigeria. The machine used for the turning was a manually operated center lathe made by Colchester mastiff with model number 1400. The cutting tool adopted for the turning operation was an AISI M-42 High Speed Steel (HSS), having the following geometries: nose radius of 0.5 mm, back rake angle of 6°, end cutting edge of 12° and side cutting edge of 12°. A Brother Electric Muffle Furnace model XD – 1200N with the maximum temperature of 1400 °C was used for the hardening of the mild steel samples (Figure 2).



**Figure 1: Acquired Mild steel rod (a) prepared samples before machining (b) schematic for sample.**

**B. Material Preparation and Heat Treatment**

The mild steel samples were prepared by dividing the original parent workpiece material (640 mm by 22 mm) into four equal pieces (160 mm by 22 mm). The pre – experimental compositional analysis of the samples used is presented in Table 2. The heat treatment was done by heating the steel samples in an electric furnace to a temperature of 800°C and soaked for a period of 10 minutes and then each of the four soaked samples were then quenched in pure water, molten salt, used engine oil, potash alum dissolved in water respectively.

**Table 2: Compositional analysis of mild steel bar.**

| Element | %     |
|---------|-------|
| Fe      | 98.34 |
| C       | 0.83  |
| Mn      | 0.63  |
| Cu      | 0.02  |
| S       | 0.02  |
| Sb      | 0.10  |
| P       | 0.01  |
| Ni      | 0.02  |
| Si      | 0.02  |

**C. Experimental Procedure and Tests**

*1) Experimental procedure*

The prepared mild steel samples were hardened by heating them in an electric furnace and then quenched using water, molten salt, used engine oil, potash alum dissolved in water. Each workpiece was mounted on a three jaw self - centering chuck of the lathe machine for turning process (Figure 3) and the workpiece samples were wet machined using a coolant comprising of water mixed with soluble oil and a High Speed Steel, HSS as the cutting tool. The machining parameters considered were cutting speed, depth of cut and feed rate, the responses measured were surface roughness, cutting temperature and material removal rate.



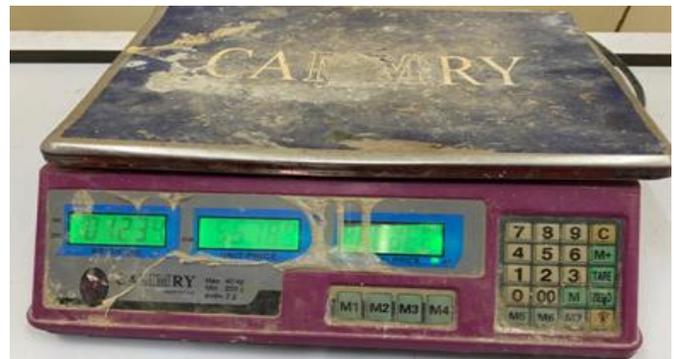
**Figure 2: Muffle furnace employed for the study.**

The machining parameters used were cutting speed (100 - 450 rev/min), feed rate (0.01-0.03) and depth of cut (1.0-2.0 mm). The choice of the selected parameter range was guided by literature and preliminary experiments. The responses measured were surface roughness and material removal rate.



**Figure 3: Machining process of sample.**

The surface roughness, hardness value and material removal rate were measured and recorded using a portable surface roughness profilometer and a weighing balance respectively (Figure 4).Using Atomic Absorption Spectrometry (AAS) method, the quenchants were analyzed and results discussed.



**Figure 4: Machining process of sample.**

The Central Composite Design (CCD) from Design expert version 12.0 was adopted for the design in this experiment. An orthogonal array (Table 3) was developed using CCD which guided the experimental procedure. ANOVA (analysis of variance) was used to analyze the interaction between the machining parameters and responses. A 3D contour and surface plot were developed to further analyze the response interaction.

**Table 3: Machining parameters.**

| Run | Cutting speed (rev/min) | Depth of cut (mm) | Feed rate (mm/rev) |
|-----|-------------------------|-------------------|--------------------|
| 1   | 245                     | 1.5               | 0,03               |
| 2   | 245                     | 1.5               | 0.01               |
| 3   | 135                     | 1.5               | 0.02               |
| 4   | 245                     | 1                 | 0.02               |
| 5   | 100                     | 1                 | 0.01               |
| 6   | 250                     | 2                 | 0.02               |
| 7   | 450                     | 1                 | 0.02               |
| 8   | 330                     | 1                 | 0.03               |
| 9   | 330                     | 1.5               | 0.01               |
| 10  | 330                     | 1.5               | 0.03               |

## 2) Tests

### i) Surface roughness test

Surface roughness of the machined work piece was measured using a portable roughness tester model TR210 made in Beijing having a precision of 0.005-16 $\mu$ m. A number of three readings were taken for each run in every sample and the average was gotten. Clean samples of the specimen were used to reduce error.

### ii) Hardness test

The hardness value of the mild steel samples was determined by using a Rockwell hardness testing machine accessed in the Civil Engineering Department Laboratory at the Elizade University. The sample surfaces were polished prior the test and the indenters were tungsten carbide hard metal balls with load 15 and 100 kgf, respectively. The indenter balls were applied on the steel samples using the Brinell hardness testing machine for a period of 10 seconds each and indentations retrieved. The experiment was repeated three times for each sample and an average value determined.

### iii) XRF analysis

X-ray fluorescence is a method of analysis of metals which involves the measuring the fluorescent (or secondary) X-rays emitted from a sample when excited by a primary X-ray source. Each of the elements present in a sample produces a set of characteristic fluorescent X-rays. A thermo-scientific precious metal analysis Niton XL2 (Figure 5) was used to determine the concentration of elements in the machined hardened samples.

### iv) Atomic absorption spectrometry (AAS)

The AAS method was used to characterize the various quenchants used during the experiment. It works on the principle of absorption of light (radiation) by free atoms present in samples being analyzed. Each sample bar was analyzed and results generated and recorded.



Figure 5: Metal Analyzer model no Niton XL2 by Thermo scientific.

## III. RESULTS AND DISCUSSION

### A. Hardness Value

Table 4 shows the Brinell hardness number for the different quenched steel samples. Water quenched steel sample gave the highest Brinell hardness number of 309.23 BHN while the least Brinell hardness number was gotten from the steel sample quenched in used engine oil. From literature, the cooling rates of the four quenchants affected their hardness

values. The sample quenched in water cooled faster than the other quenchants having a cooling rate of 2.58°C/s, brine quenchant having a cooling rate of 2.25°C/s, potash alum quenchant having a cooling rate of 1.55°C/s and engine oil quenchant having the lowest cooling rate of 0.27°C/s. Brinell hardness value increased with cooling rate.

Table 4: Brinell hardness values for Quenchants.

| Quenchants       | Water  | Potash Alum | Brine  | Used Engine Oil |
|------------------|--------|-------------|--------|-----------------|
| Base-Metal (BHN) | 309.23 | 256.91      | 291.23 | 187.78          |

### B. Surface Roughness

Figure 6 shows that the least surface roughness (0.211 $\mu$ m) was gotten from machining used engine oil quenched steel sample at a cutting speed of 450rpm, depth of cut of 1mm and feed rate of 0.02mm/rev. While the highest value for surface roughness (1.079) was gotten when machining water quenched steel sample at cutting speeds of 245rpm, depth of cut of 1.5mm and feed rate of 0.03mm/rev as shown in Table 4. From Figure 6, the maximum surface roughness gotten for all samples was 1.257  $\mu$ m which was gotten from the water quenched sample and the sample with the lowest surface roughness was the oil quenched sample with a value of 0.229  $\mu$ m.

Also, Figure 6 shows that the water quenched sample had the highest average surface roughness, while oil quenched samples got the lowest average surface roughness, which were the expected results. Samples quenched in potash alum and molten salt also showed high values of surface roughness when compared to the oil quenched sample, this is to be expected as those two quenchants were made by combining water with other substances. It is also worth noting that the worst surface roughness for all samples was gotten during the third machining run indicating that the values of the machining parameters used for that run were not desirable.

The roughness gotten for all runs of the experimental design for the machining of samples quenched in the 4 quenchants is represented by contour plots as seen in Figure 7 (a-d). The response was represented by a three dimensional surface plots of two factors; cutting speed and depth of cut with their corresponding contour plots. Cutting speed had a higher impact on the surface roughness of the machined samples quenched in water and molten salt but its influence was minimal on surface roughness of samples quenched in potash alum and spent engine oil. This could have resulted from the higher hardness value reported with both quenchants. The effect of feed rate on surface roughness values was minimal for all cases.

### C. Material Removal Rate (MRR)

Figure 8 shows the MRR results for machined samples quenched in water, molten salt, potash alum and spent engine oil. The highest MRR values was observed generally for spent engine oil while pure water returned with lowest MRR values. Molten salt and potash alum MRR values were intermediate between spent engine oil and water.

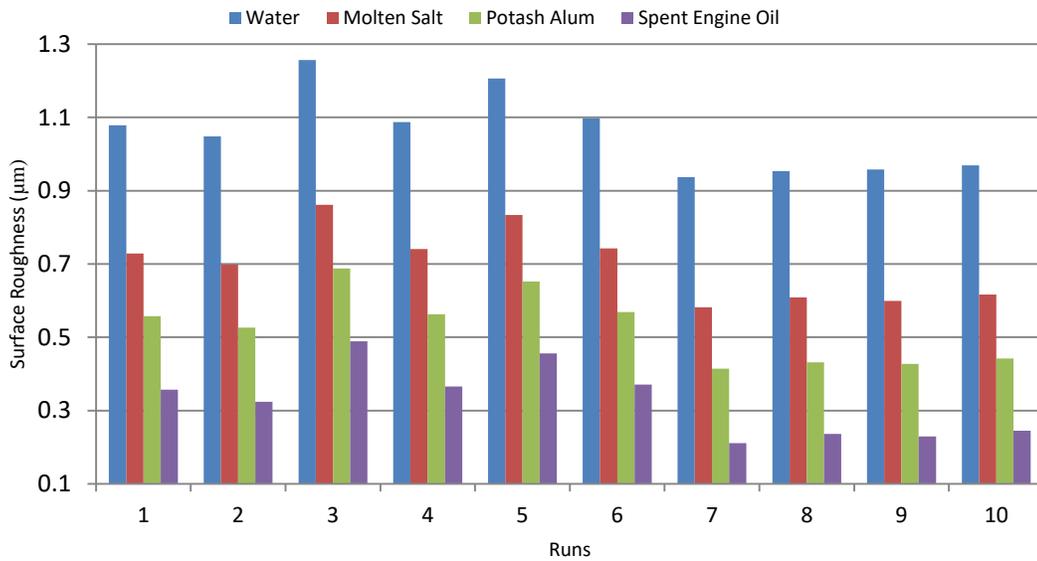


Figure 6: Surface roughness for water quenched steel sample.

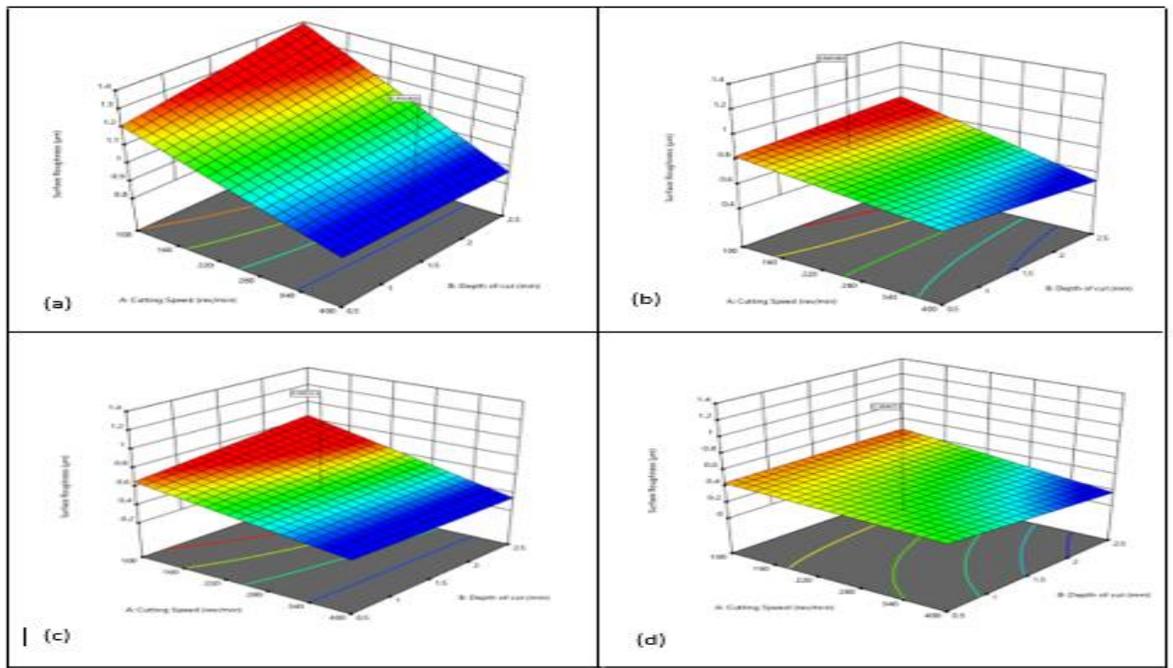


Figure 7: Response surface and contour for machined samples quenched in (a) Water (b) Molten salt (c) Potash Alum (d) Spent engine oil.

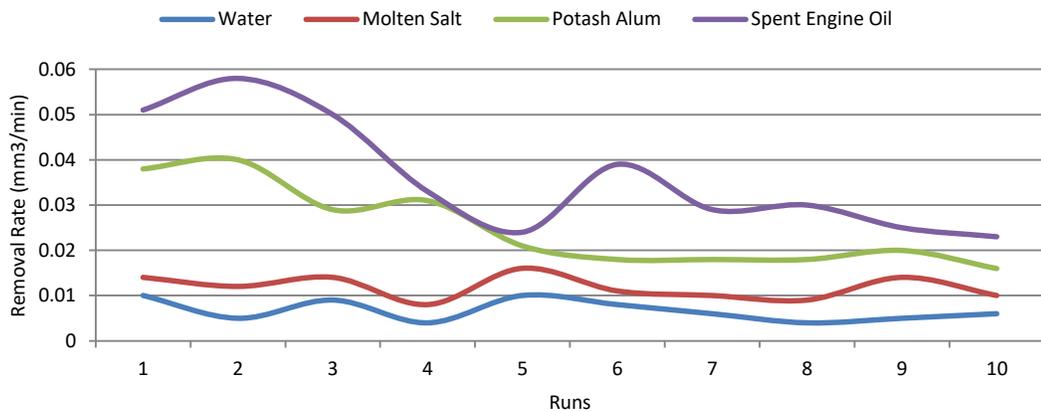


Figure 8: Material removal rate results for machined samples quenched in various quenchants.

This result is in agreement with the hardness value results in Table 3. The water quenched samples with the highest hardness value was the most difficult to machine while the samples quenched in spent engine oil was easiest to machine because of the low hardness value. Hence as hardness value increased, machinability reduced.

#### D. X-ray Fluorescence (XRF) Analyses Results

Result of the XRF analyses carried out on the four quenching mediums is as shown in Table 5. The XRF analyses showed the concentration of elements in the quenched steel samples. Although the water quenched sample had the lowest concentration of iron in it, it had a 0.173% concentration of titanium which none of the other quenched samples had, this explains why the hardness value of the water quenched sample was higher than all other samples.

In the oil, potash alum and molten salt quenched sample, apart from the presence of iron which had the highest concentration and manganese which had the second highest concentration in the three samples, the molten salt sample had a higher concentration of chromium than potash alum and oil quenched samples which accounts for it having a higher hardness value than the two. Oil quenched sample had the lowest concentration in chromium in combination with no presence of titanium and low concentration of rhodium accounts for why this sample had the lowest hardness value. Summarily, alteration in elemental concentrations of steel samples (caused by quenchants) affected the hardness values which eventually affected the machinability of the steel samples.

#### IV. CONCLUSION

The machinability optimization of heat treated mild steel using selected quenchants has been investigated in this study. Results obtained have aided the following conclusions as summarized below;

- (i) The surface roughness of machined steel samples increased as Brinell hardness number increased. Surface roughness was lowest with the spent oil quenched steel sample (0.33 $\mu$ m) which also had the lowest hardness value (187.78BHN), water quenched sample had the highest Brinell hardness number (309.23BHN) but the worst surface roughness (1.0593 $\mu$ m) among machined samples.
- (ii) Material removal rate can be improved by quenching heat treated steel in spent engine oil, than in the 3 other quenching media. The average highest material removal rate (0.020133mm<sup>3</sup>/min) was achieved while machining the spent engine oil quenched sample was the highest while the lowest average material removal rate (0.006381mm<sup>3</sup>/min) was obtained while machining the water quenched sample.

- (iii) The XRF analysis revealed that there were changes in the element concentrations of the steel samples which resulted in the variation of hardness value among the steel samples, which then explains the responses gotten from each sample.

Summarily, it can be concluded that the type of quenching media used during heat treatment could alter (optimize or reduce) the machinability of the steel being heat treated.

#### V. RECOMMENDATION

From the results obtained, water was the preferred choice of quenchant whenever the highest hardness value was required as it gave a Brinell hardness number of 309.23BHN, but whenever it comes to ease of machinability, used oil quenching gave the most favorable results. If a more strength or hardness than that gotten from quenching with used engine oil is required with some increases in difficulty of machining, then potash alum dissolved in water can be used.

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**Table 5: Concentration of elements in each quenched sample.**

| Elements         | Percentage concentration |                   |                      |                      |
|------------------|--------------------------|-------------------|----------------------|----------------------|
|                  | Water quenched           | Used oil quenched | Potash alum quenched | Molten salt quenched |
| <i>Iron</i>      | 98.457                   | 98.773            | 98.633               | 98.778               |
| <i>Cobalt</i>    | 0.443                    | LOD               | LOD                  | LOD                  |
| <i>Chromium</i>  | 0.298                    | 0.245             | 0.28                 | 0.308                |
| <i>Manganese</i> | 0.455                    | 0.57              | 0.512                | 0.486                |
| <i>Titanium</i>  | 0.173                    | LOD               | LOD                  | LOD                  |
| <i>Rhodium</i>   | LOD                      | 0.063             | 0.077                | LOD                  |
| <i>Copper</i>    | LOD                      | LOD               | 0.34                 | 0.159                |

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