Machinability Characteristics of Heat Treated Aladja St60-2 Structural Steel

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ABSTRACT

Normalised and quenched and tempered specimens of ST60-2 structural steel procured from Aladja developed fine pearlite microstructures that improved its machinability and accompanied by good surface finish at various cutting speeds under soluble oil lubrication condition. While the resulting good surface finish in the low-speed range could be attributed to the effectiveness of the soluble oil that prevented the built-up edge formation, the poor surface finish obtained in the intermediate cutting speed range could be linked to the badly broken chips and the observed built-up edge formation in the machining process. However, the improved surface finish at high cutting speed could be attributed to the total disappearance of the built-up edge. From the standpoint of surface finish, better cutting conditions were established based on the prevailing lower tool-face friction being assessed by the observed curl chip formation characteristics in the machining operation.

1.0 INTRODUCTION

The most important aspect of metal cutting is machinability and its influence on the economy of the process. It is a combination of properties in a material which affects its response to removal by tool. Machinability has received much attention from research workers, especially as regards to the development of improved tool materials (ASM, 1961).

Based on considerable experimental and analytical study, it has been established that seven independent variables in addition to the tool-chip interface temperature, are required to completely define machinability. These primary variables include hardness, area ratio at fracture, thermal conductivity, volume specific heat, thickness (feed) of cut, width (depth) of cut, cutting velocity and tool-chip temperature (Datsko, 1966). Many other parameters, which characterize the machining process such as cutting forces, coefficient of friction, shear angle, chip ratio and abrasion are readily dependent upon the aforementioned primary variables. In essence, all these variables should be included in the machinability rating for selecting steels for economy of machining. Many steels, commonly designated free-machining steels, contain special additives such as sulphur in the form of manganese-sulphide particles, for improving their machining characteristics (Shaw, et al, 1957).

In the development of new and improved steel for machining applications, steel producers have developed a number of heat treating processes such as annealing, normalizing, quenching and tempering which have been established to change microstructure of steel thereby enabling the manufacturer to raise cutting speeds, improve surface finish and lengthen tool life (Moody and Felbaum, 1975). Each heat treatment gives the steel different optimum cutting speeds. Different heat treatments produce different microstructures and hardnesses thereby varying their machinabilities. Annealing improves the machining characteristics of the medium and high carbon steels particularly at carbon levels of 0.45 to 0.50 percent and higher. It has been established that quenching and tempering can improve the machinability of low carbon steels with less than about 0.15%C (ASM, 1961).

The objective of the present investigation is to evaluate the machinability of heat treated samples of Aladja ST60-2 structural steel (with a carbon content from 0.35 0.40%), based on the quality of surface finish obtained at various machining speeds after being subjected to annealing, normalizing, quenching and tempering processes and machined orthogonally at various cutting speeds under soluble oil lubrication condition.

2.0 EXPERIMENTAL METHOD

2.1 CUTTING CONDITIONS

In the traditional machining of metals, there is a very wide variety in the type of operations employed and the selection of the most appropriate one for investigation is difficult. It was therefore, decided to select a process which was perhaps typical of all chip removal processes namely orthogonal machining . In orthogonal machining, the cutting edge of the tool is perpendicular to the direction of relative work tool motion. From an industrial viewpoint, it could be argued that a process such as end milling or shaping has greater utility than orthogonal machining. However, it was believed that in a complex process such as machining, the number of independent variables should be kept as small as possible and the simpler orthogonal process was preferred. In orthogonal machining, factor such as tool forces, the type of chip produced and the temperatures generated can be determined readily. Moreover, conditions of plain strain deformation can be machined. In other types of machining (end milling, turning) such determinations are difficult if not impossible to carry out.

2.3 EQUIPMENT

All cutting tests were carried out on a lathe machine with a wide range of spindle speeds from 22.4 to 2000 rev.

min^{-1} and feeds in the range from 0.040 to 2.032 $mmrev^{-1}$. A high-speed steel tool with a rake angle of 6°, approach angle of 45° and a clearance angle of 8° with a sharp nose was used in this investigation. A carbolite furnace with a maximum temperature of 1200°C was used to austenise the steel samples for immediate purpose of heat-treating.

2.4 MATERIALS

The principal experimental material was a bar stock of Aladja ST60-2 Structural Steel whose chemical composition is given in Table 1. It was supplied by the Katsina Steel Rolling Mill. A soluble oil, a good commercial cutting fluid which contains emulsifiers based on sulphonate fatty oils and resin soaps to permit the formation of a stable emulsion readily in water was used in the orthogonal machining of heat treated samples of the Aladja Structural Steel. Quenching of the steel samples was accomplished by immersion into brine, water and in Super V Engine oil with a viscosity value of 40.5×10^{-3} Ns/m^2.

2.5 METHOD

The as-received (hot rolled) 40mm diameter bar stock of Aladja ST60-2 Structural steel was power sawed into six bars 16cm long for heat treatment operations. Choice of this bar geometry was to eliminate end effect (Spalding and Afgn, 1981). Additionally, a bar of similar geometry was prepared from the as-received stock for hardness and metallographic examinations.

Before subjecting to various heat treatment operations, the steel samples were packed in cast iron chips in a steel box to prevent surface decarburisation and heated to an austenizing temperature of 950°C. After holding at this temperature for two hours, a sample each was then quenched in brine, water and oil. To accomplish both the annealing and normalizing operations, a sample each was furnace cooled and air cooled respectively after holding at the austenising temperature of 950°C. On holding the last steel sample at the austenizing temperature for two hours, it was brine quenched and tempered at 450°C.

Orthogonal machining, as illustrated in Figure 1, was conducted on one end of each heat treated and as-received samples of Aladja ST60-2 Structural steel at an interval of 2cm with various spindle speeds at a feed rate of 0.053mm rev^{-1} and a depth of cut of 3mm under soluble oil lubrication condition. The tool was sharpened after machining each specimen under various investigated cutting speeds to maintain constant tool geometry.

Surface roughness measurements of the machined specimen surfaces at various cutting speeds were determined by the subtronic stylus probe method (Tuplin, 1959 and Reece, 1962).

2.6 HARDNESS TESTS AND METALLOGRAPHIC EXAMINATION

Vickers pyramidal hardness tests were made on one end of each of the heat treated and as-received steel samples by the application of full load of 30 kgf along the axis of the diamond indenter for 30 seconds.

Metallographic examination of the steel samples in the heat-treated and as-received conditions was made. Sample for metallographic examination was carefully ground progressively on grades of silicon carbide papers (220,320,400 and 600 grit) and properly rinsed with water to ensure temperature regulation of the sample while grinding. Polishing was carried out afterwards on a rotating wheel covered with cloth pad using aluminium oxide powder. The surface was degreased by swabbing with cotton wool soaked in benzene and acetone before being etched in 3 percent Nital and held in this etching agent for 30 seconds. Microscopic examinations of the etched surface of various specimens were undertaken using a metallurgical microscope with an in-built camera through which the resulting microstructures of the heat-treated and as-received steel samples were photographically recorded.

3.0 RESULTS AND DISCUSSION

3.1 RESULTS

The average hardness values determined for the heat-treated and as-received samples of Aladja ST60-2 Structural steel are given in Table 2. Machined hardness value for each cutting speed regime in the orthogonal machining of the heat-treated steel specimens is also given in Table 2.

Surface roughness readings of the finish machined specimens and the observed chip formation characteristics in machining the heat-treated steel specimens at various cutting speeds are appended in Table 3. The various microstructures developed by subjecting the Aladja steel specimens to various heat treatment operations are presented in plates A G.

3.2 DISCUSSION

It has been established that in order to increase the rate at which steel can be machined, proper heat treatment is required. This step often permits higher cutting speeds and assures maintenance of more uniform production rates. Ability to choose the proper heat treatment however requires a good working knowledge of the relationships between microstructures of the metals and machining characteristics. Since compositions are fixed by physical and mechanical requirements, the microstructure is the only remaining factor that can be altered to provide the best machinability.

The micrograph of the normalized specimen of Aladja ST60-2 Structural steel (Plate B) shows a fine pearlite in a ferrite matrix structure. The uniformly distributed hard fine pearlite structure contributed to the reduction of ductility of the normalized steel specimen and resulted in an improved machinability.

Annealing in general is a process carried out for the purpose of permitting the steel to be machined relatively easily. The medium carbon grades to which the Aladja ST60-2 Structural steel belongs machine best in annealed condition. The improved machinability experienced in the orthogonal machining of the annealed sample could be attributed to the presence of fine pearlite structure as revealed by the micrograph of Plate C.

The micrograph of the brine quenched Aladja ST60-2 Structural steel (See Plate D) reveals structures, which is mainly martensite. The martensite present was not tempered and as such the specimen could not develop good machinability.

The micrograph of water quenched specimen in Plate E shows untempered martensite structures, which exhibited poor machining characteristics. Also the micrograph of the oil quenched specimen (See Plate F) for which the quenching was slow enough to permit formation of some grain boundary ferrite, and some unbroken martensite structure, which enhanced the machinability.

In conformity with earlier observation that high elastic limit of the martensite crystals is the fundamental cause of high hardness of quenched steel (Kurdjumov, 1960), the quenched specimens revealed a considerably high hardness values in the range 158 250 VHN as against the as-received hardness value of 123 VHN.

The micrograph of brine quenched and tempered Aladja ST60-2 structural steel (See Plate G) reveals fine tempered martensite and ferrite. Based on this, the specimen was able to develop a good machinability.

In support of earlier observations (Moody and Felbaun, 1975 & Clark and Varney, 1962) fine microstructure produced better surface finish as revealed by the normalized, and quenched and tempered micrographs of the steel specimens with surface roughness values of 3 and 5m CLA respectively when machined at highest cutting speed of 250 rpm. Among the group of quenched specimens, the best surface finish was obtained on the brine quenched and tempered specimen both at low and high cutting speeds. It is noteworthy that the degree of fineness of the developed microstructure as shown by the micrographs of both the normalized and the quenched and tempered specimens (see Plates B and G) was almost the same and hence the closeness in the value of surface roughness obtained on the machining of these specimens.

On comparative basis, the degree of fineness of the pearlite structure was highest in the normalized specimen (see Plate B) thereby yielding the best surface finish. Better surface finish was obtained in the annealed specimen when a less fine pearlite structure was produced.

The poor surface quality obtained on the machining of oil quenched, brine quenched and water quenched specimens at highest cutting speed (surface roughness of 6, 6 and 7m CLA respectively) could be attributed to the presence of martensitic microstructure in each specimen of Aladja ST60-2 structural steel. Among the group of quenched specimens and quenched and tempered specimen of Aladja ST60-2 structural steel, the best surface finish was obtained on the brine quenched and tempered specimen both at low and high cutting speeds.

The best surface finish was obtained in the machining of the quenched and tempered specimen at low cutting speed of 22.40 rpm due to the fine microstructure of tempered martensite, which has been claimed to improved machinability (Clark and Varney, 1962). Deterioration in the surface quality at high speed could be attributed to the gumming characteristics caused by the increase in temperature with increase in cutting speed. Poor surface quality with a surface roughness value of 7m CLA was obtained in the water quenched specimen machined at the highest cutting speed probably due to the presence of martensite in the microstructure.

In the low cutting speed range (22.4 31.5 rpm), fairly good surface finishes were obtained in machining of the heat treated specimens due to good performance of soluble oil to prevent the formation of built-up edge. However, the best surface finish in this cutting speed range occurred in the quenched and tempered specimen.

With the exception of the brine quenched and tempered specimen, discontinuous chip formation characterized the machining of the remaining heat treated specimens in the intermediate cutting speed range 45 125 rpm. In agreement with previous work (Sullivan et al, 1978), the badly broken chip and in essence, the presence of built-up edge in this speed range contributed to the poor surface finish obtained in the machined surfaces of the heat treated specimens of Aladja ST60-2 structural steel.

In the high cutting speed range 180 250 rpm, a semi-discontinuous to fully continuous chip formation characteristics became evident. An improved surface quality was attained due to gradual disappearance of built-up edge resulting from the heat generated that reduced the bonding energy between atoms thereby reducing the required energy to shear the material. It has been established that the greater the chip curl, the better the quality of the surface (Arshinov and Alekseev, 1973).

In this investigation, the greater chip curl prevailing in the machining of the normalized, annealed, quenched and tempered specimens of the structural steel at higher cutting speed did enhance the production of superior surface finishes. The best surface finish obtained in the machining of the normalized specimen could therefore be attributed to the greatest chip curl produced at highest cutting speed.

4.0 CONCLUSION

Surface quality, an important contributing factor to the evaluation of machinability of metals in general, has been quantitatively determined for heat treated specimens of Aladja ST60-2 structural steel in the range of speed 22.4 250 rpm. Although, carbon content has a predominant effect on machinability of carbon steels chiefly because it governs strength, hardness, abrasiveness and ductility, the fine pearlite structure developed in the normalized and quenched and tempered specimens of the Aladja ST60-2 structural steel contributed immensely to the improvement of the machined surface.

The good surface finishes obtained at the high cutting speed range had been

Attributed to the disappearance of the built-up edge and the greater chip curl, which occurred during machining. Greater chip curls gives an evidence of low friction and generally better cutting conditions from the standpoint of surface finish.

From the practical point of view, the results of the present investigation on the machinability characteristics of heat-treated specimens of Aladja ST60-2 structural steel revealed the vital role heat treatment processes could play in enhancing the quality of the machined surfaces.

5.0 ACKNOWLEDGMENTS

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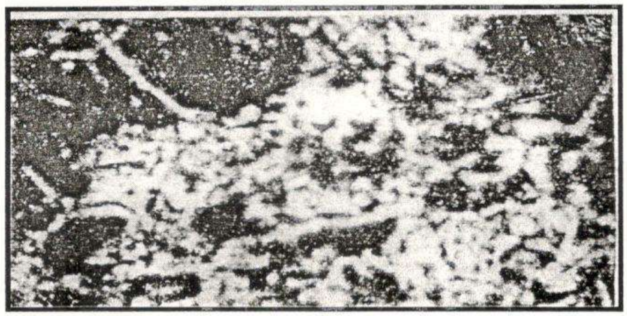

Plate A: As-rolled ST60-2 Aladja structural steel. The structure shows ferrite (White) with outline of prior austenite grain(White) in pearlite matrix (Black). (X200).

Plate B: Normalised ST60-2 Aladja structural steel. The structure consists of pearlite (Dark gray) and ferrite matrix (White). (X200).

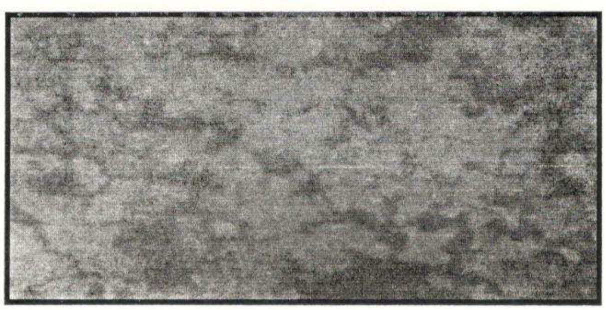

Plate C: Annealed ST60-2 Aladja Structural steel. The structure indicates little pearlite in ferrite matrix. (x200).

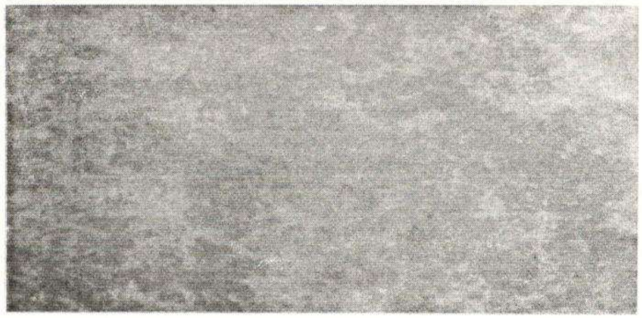

Plate D: Brine quenched ST60-2 Aladja Structural steel. The structure reveals high level Martensitic structure (White). (X200).

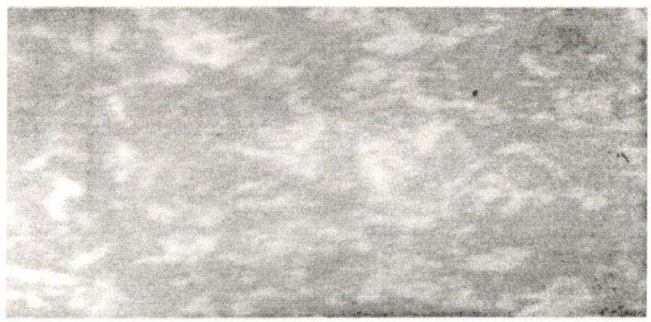

Plate E: Water quenched ST60-2 Aladja Structural steel. The structure reveals martensitic structure (White). (X200).

Plate F: Oil quenched ST60-2 Aladja Structural steel. The structure consists of grain boundary ferrite (White) and martensite (White patches) (x200).

Plate G: ST60-2 Aladja Structural steel brine quenched and tempered at 450°C. The structure shows tempered martensite (Grey) with patches of ferrite. (x200).

TABLE 2: Grade and Composition of the Aladja Structural Steel.

Chemical Composition (Wt.%)					
Grade	C	Mn	Si	P	S
ST60-2	0.35-0.42	0.90-1.20	0.20 - 0.30	0.04	0.04

Other Elements such as Copper, Chromium, Nickel and Aluminium are in trace amounts

TABLE 2: Variation of Hardness Values with Cutting Speeds in the Orthogonal Machining of Heat Treated Specimens of Aladja ST60-2 Structural Steel.

Type of Heat Treated	Hardness Value (VHN)	Hardness Values (VHN) of Machined Surfaces of the Heat Treated Specimens at a Cutting Speed (rev. Min^{-1}) 22.40	31.50	45.00	63.00	90.00	125.00	180.00	250.00
Annealing	118.00	135.60	134.20	133.10	131.90	131.50	130.70	130.70	130.70
Normalising	129.00	177.70	177.70	177.10	175.80	173.40	170.90	170.90	170.90
Oil Quenching	158.00	201.50	191.90	189.80	188.40	185.60	184.90	184.90	184.90
Brine Quenching	250.00	329.50	325.50	322.00	319.00	315.50	313.00	312.50	313.00
Water Quenching	221.21	273.00	262.00	261.00	258.00	256.00	254.00	254.00	254.00
B/ B/Quenched And Tempered	186.00	266.50	249.00	247.00	245.00	242.30	239.80	239.80	239.90
As-received (Hot rolled)	123.00	171.70	171.70	171.10	169.60	167.00	164.60	164.60	164.60

TABLE 3: Variation of Surface Roughness Reading and Chip Formation Characteristics With Cutting Speed in Orthogonal Machining of Heat Treated Structural Steel

Types Treatment Operation	Cutting Speed (Vrpm)	Surface Finish (um) CLA	Observed Chip Formation Characteristics
	22.40	3.00	Large Discontinous Chip without b.u.e
	31.50	4.00	Large Discontinous Chip without b.u.e

Annealing	22.40	3.00	Large Discontinuous Chip without b.u.e.
	31.50	4.00	Large Discontinuous Chip without b.u.e
	45.00	7.00	Small Discontinuous Chip without b.u.e.
	63.00	8.00	Small Discontinuous Chip without b.u.e.
	90.00	9.00	Small Discontinuous Chip without b.u.e.
	125.00	12.00	Small Discontinuous Chip without b.u.e.
	180.00	5.00	Large Discontinuous Chip without b.u.e.
	250.00	4.00	Large Discontinuous Chip without b.u.e.
Normalising	22.40	4.00	Small Discontinuous Chip without b.u.e.
	31.50	8.00	Small Discontinuous Chip without b.u.e.
	45.00	7.00	Small Discontinuous Chip without b.u.e.
	63.00	7.00	Small Discontinuous Chip without b.u.e.
	90.00	7.00	Small Discontinuous Chip without b.u.e.
	125.00	10.00	Small Discontinuous Chip without b.u.e.
	180.00	9.00	Large Discontinuous Chip without b.u.e.
	250.00	3.00	Large Discontinuous Chip without b.u.e.
Oil quenching	22.40	4.00	Small Discontinuous Chip without b.u.e.
	31.50	5.00	Small Discontinuous Chip without b.u.e.
	45.00	7.00	Small Discontinuous Chip without b.u.e.
	63.00	12.00	Small Discontinuous Chip without b.u.e.
	90.00	11.00	Small Discontinuous Chip without b.u.e.
	125.00	10.00	Small Discontinuous Chip without b.u.e.
	180.00	7.00	Small Discontinuous Chip without b.u.e.
	250.00	6.00	Small Discontinuous Chip without b.u.e.
Brine Quenching	22.40	4.00	Small Discontinuous Chip without b.u.e.
	31.50	6.00	Small Discontinuous Chip without b.u.e
	45.00	8.00	Small Discontinuous Chip without b.u.e.
	63.00	5.00	Small Discontinuous Chip without b.u.e.
	90.00	7.00	Small Discontinuous Chip without b.u.e.
	125.00	10.00	Small Discontinuous Chip without b.u.e.
	180.00	12.00	Small Discontinuous Chip without b.u.e.
	250.00	6.00	Small Discontinuous Chip without b.u.e.

Water Quenching	22.40	4.00	Small Discontinuous Chip without b.u.e.
	31.50	5.00	Small Discontinuous Chip without b.u.e.
	45.00	6.00	Small Discontinuous Chip without b.u.e.
	63.00	8.00	Small Discontinuous Chip without b.u.e.
	90.00	8.00	Small Discontinuous Chip without b.u.e.
	125.00	10.00	Small Discontinuous Chip without b.u.e.
	180.00	8.00	Small Discontinuous Chip without b.u.e.
	250.00	7.00	Small Discontinuous Chip without b.u.e.
Brine Quenching and Tempering	22.40	3.00	Small Discontinuous Chip without b.u.e.
	31.50	5.00	Small Discontinuous Chip without b.u.e.
	45.00	10.00	Small Discontinuous Chip without b.u.e.
	63.00	10.00	Small Discontinuous Chip without b.u.e.
	90.00	7.00	Small Discontinuous Chip without b.u.e.
	125.00	8.00	Small Discontinuous Chip without b.u.e.
	180.00	6.00	Small Discontinuous Chip without b.u.e.
	250.00	5.00	Small Discontinuous Chip without b.u.e.

*** CLA Centre Line Average.**

Figure 1: Orthogonal machining on end of steel bar.