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Effects of Plasma Cutting on Surface Integrity of Mild Steel

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Abstract:

Persistent fatigue failure observed in vibrating screen side plates motivated this investigation to determine the effects of plasma cutting on the surface integrity and hence fatigue performance of mild steel plates. Fatigue crack initiation and propagation was reported to have occurred in a number of vibrating screen side plates in which bolt holes had been produced using plasma cutting. This cutting technique had been introduced to reduce bolt hole production times thus replacing the traditional hole drilling technique previously used. This inadvertently modified the surface conditions of the material. Since fatigue is largely a surface phenomenon due to a number of factors such as stress concentration and surface roughness, fatigue strength was unintentionally compromised. A proper assessment is always required to test the effect of new processing techniques on service performance before implementation. Although full scale fatigue testing is too expensive, low cost surface integrity tests can be conducted to assess the impact of the new technique on anticipated fatigue performance. Experimental assessments done on the plasma-cut mild steel plate using microstructure and micro-hardness testing techniques revealed clear evidence of material hardening. Since increased hardening implies increased notch sensitivity, it was therefore concluded that plasma cutting has the effect of reducing the fatigue strength of mild steel components hence the observed fatigue failures in vibrating screen side plates.

Key words: Plasma cutting, Fatigue failure, Crack initiation, Crack propagation, Microstructure, Mild steel

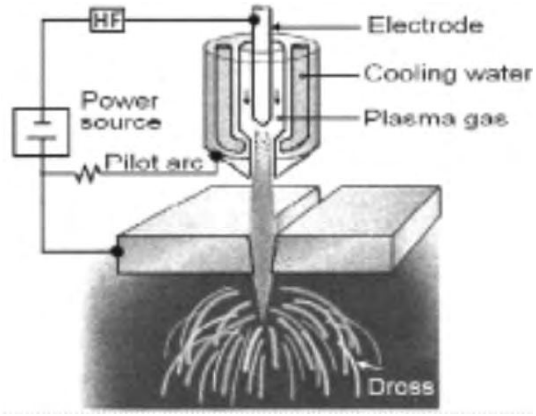
1. Introduction

Fatigue failure of metals has been of major engineering concern ever since the dawn of mechanization and industrialization . Despite subsequent and extensive research and experiential accumulation of knowledge on fatigue failure of materials over the decades, this phenomenon continues to be a major cause of component failure in mechanical systems today. This is more prevalent in cases where new materials are introduced or new manufacturing techniques are applied. Such cases require special investigation in order to effectively develop mechanical systems with sufficient fatigue strength to survive the rigors of in-service loading conditions. The factors that affect fatigue performance are numerous [2] .

Fatigue failure is predominantly a surface phenomenon, characterized by crack initiation, crack propagation and eventually fast fracture [1]. For pure crystals, crack initiation occurs on slip planes driven by shear stresses. In most materials, heterogeneities such as inclusions, welding defects, manufacturing defects etc. become the stress concentration points from which cracks initiate. Other surface integrity parameters that govern crack initiation and growth include material hardness, yield strength, residual stresses and surface roughness. It follows therefore that processing techniques which modify the surface condition of a component such as turning, milling, grinding, flame cutting, plasma cutting, water jet cutting and others, have an influence on the fatigue performance of the component in service.

Companies are always under pressure to cut down on production costs. In the mining industry this translates to operators demanding bigger machines with larger production rates at lower costs . Equipment suppliers face demanding delivery times and are therefore pressured to cut down on production times. Particular production processes are therefore introduced to cut production times without paying due attention to their effects on the service performance of components produced by such processes. Replacing an established drilling process with plasma cutting in the manufacture of side plates for vibrating screens is a case in point.

Plasma cutting is a very flexible technique which utilises ionised gas (plasma) to cut conductive materials. It has been used to cut high strength materials since the 1960s. The process generates a high energy stream of ionised gas which heats the material to be cut . Although any gas can be used, most applications use air. The ionised air conducts electricity between an electrode and a work piece which heats the material to melting point. The high speed plasma then blows the molten metal away thus severing the material. This process is schematically illustrated in Figure 1.



Although plasma cutting is not a new technology, it is a technique still under development for cutting various materials using different gases and varying process parameters , , . Salonitis and Vatousianos recently investigated the process parameters that affect the plasma cutting of mild steel . They concluded that the cutting speed, the cutting current, the plasma gas pressure and the distance of the plasma torch from the work piece surface (cutting height) are the main parameters that affect plasma cutting performance. In addition they also reported that surface roughness and the conicity are mainly affected by the cutting height while the heat affected zone (HAZ) is mainly influenced by the cutting current. Conicity also suggests a possible difference in surface integrity effects on the opposite surfaces of the component being cut. Numerical modelling of these processes has been investigated by Narimanyan using moving boundary methodology . This provided better understanding of the physical process involved in the thermal plasma cutting process.

Although the plasma cutting process can be controlled manually, most industrial processes employ CNC machines to control the process. Because of the number of processes that affect the finished product, process control is a key element of plasma cutting. Deli and Bo developed a fuzzy neural network process control strategy aimed at improving the quality and precision of the plasma cutting process . This approach achieved better control of the current leading to better control of process performance. Using this approach, it was demonstrated that better surface finish with lower ripple effects could be obtained when compared with traditional closed loop control strategies.

A number of studies have been done on the effect of plasma cutting on surface integrity. Hoult, et al investigated the high tolerance plasma arc cutting on 2124 aluminium-copper alloy . They reported significant influence of cutting speed on surface quality and recommended cutting speeds in the range 55-60 mm/s. The maximum size of heat affected zone (HAZ) was measured to be of the order of 140 micrometres. Bhuvenesh, et al applied manual plasma arc cutting on standard AISI 1017 steel . Results obtained indicated that the surface roughness produced on the cut surfaces was directly proportional to the material removal rate. At material removal rates of 3500 mm^3/min, maximum surface roughness was found to be 80 micrometres. This was also found to be dependent on the size of dross produced during cutting.

Vibrating screens used in mining operations can be as big as 4 m by 11 m. These units typically have capacities of about 15000 to 20000 tonnes per hour . Vibrations in these machines are induced by rotating out of balance masses mounted either on the bottom or upper part of the machine frame. This subjects the side plates, on which most machine components are mounted, to severe cyclic bending stresses. In the case under investigation, cracks initiated from one of the bolt holes close to the bottom of the machine and propagated almost vertically up to the point of almost complete fracture.

The objective of this investigation was therefore to determine the potential effects of plasma cutting on the fatigue performance of mild steel plates cut using plasma.

2. Experimental Setup

2.1 Aim

The purpose of this experimental investigation was to establish the effects of plasma cutting on the surface integrity of a mild steel component. This was done with a view to qualitatively assess the consequent effects of this manufacturing technique on the fatigue performance of the component in service. The approach adopted in this investigation was a low cost alternative to conducting a full set of fatigue life assessment tests.

2.2 Materials

The material used in the production of the 3 m by 6 m vibrating screen side plates was selected for this investigation. The 350W mild steel was supplied in 8 mm thick hot rolled plate with chemical composition as given in Table 1.

Table 1: Chemical composition of 350W mild steel

	C	Si	Mn	P	S
Content (%)	0.23	0.4	0.50-1.50	0.04	0.05

The corresponding mechanical properties for this material are given in Table 2.

Table 2: Mechanical properties of 350W mild steel

Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
350	450-620	22

(a) Method 1 (b) Method 2 (c) Method 3

Figure 2: Bolt hole preparation techniques applied.

2.3 Specimen Preparation

In order to capture the actual conditions in the failed plates, specimens were prepared using the three techniques used to produce the 20 mm diameter bolt holes in the vibrating screen side plates. The three techniques are shown in Figure 2.

Figure 2(a) illustrates the technique in which the plasma cutting starts at the centre of the hole and proceeds outward in a spiral fashion to cut the bolt hole profile. This approach does not leave a notch on the hole profile. In Figure 2(b), the cutting begins at a point on the circumference and the profile of the hole is traced out. This technique leaves a notch at the starting point of the cutting. For the last case, Figure 2(c), plasma cutting is used to produce a hole with a smaller diameter than what is required (similar to Method 1) and then the required diameter and finish are then obtained by drilling.

All the specimens were prepared by the vibrating screen manufacturer using typical industrial parameters. For each technique illustrated in Figure 2, four specimens were produced. Each specimen was 200 mm square with the 20 mm diameter holes cut at the centre. This ensured that the test pieces were not influenced by any edge effects.

Test pieces used for hardness measurement and microstructure analysis were then extracted from the specimens using a configuration shown in Figure 3. The overall dimensions of the test pieces are also given.

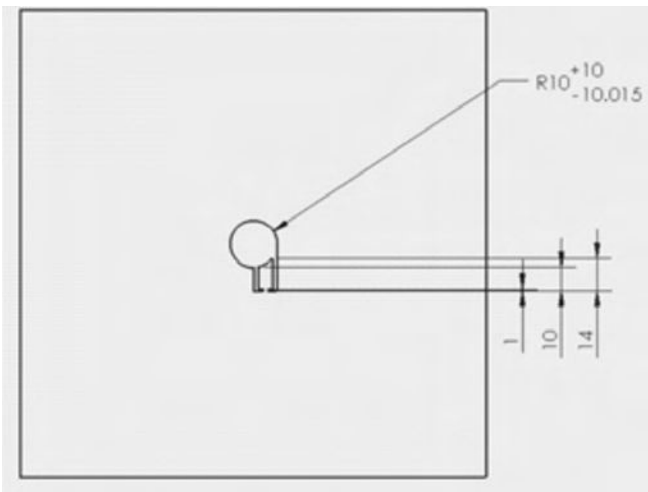


Figure 3: Test piece extraction method.

Water jet cutting was used to extract the test pieces as this minimised the formation of heat affected zones (HAZ) which can alter the test piece properties. Each test piece was then mounted on a polymeric resin using a Leco PR-25 mounting machine. Mounted test pieces were then ground and polished. Microstructure observation required specimens to be further etched for 18 seconds using Nital, a solution composed of 100 ml ethanol and 100 ml of nitric acid. Prepared and mounted test pieces are shown in Figure 4.

Figure 4: Mounted test pieces.

2.4 Experimental Protocol

Hardness Testing

Vickers hardness testing was done along the centre of the specimen using a TIME MH-6 digital semiautomatic micro hardness tester. Testing was done in compliance with ASTM E384-99 standard. A 100 mg indentation load with a dwell time of 10ms was applied. Measurements were recorded as a function of distance from the cut end. Special care was taken to avoid edge effects. Multiple readings were taken for each specimen to average out data.

Microstructure Analysis

Microstructure observations were conducted using an Olympus SZX 16 stereo microscope. This also provided the ability to measure grain sizes and grain distortion angles. Observations were made at varying magnifications.

3. Results

3.1 Micro hardness Testing

For each cutting technique, three test pieces were mounted and hardness tested. The fourth specimen was used for microstructural analysis. The results were then averaged for each manufacturing technique. The averaged results of the micro hardness testing are presented in Figure 5.

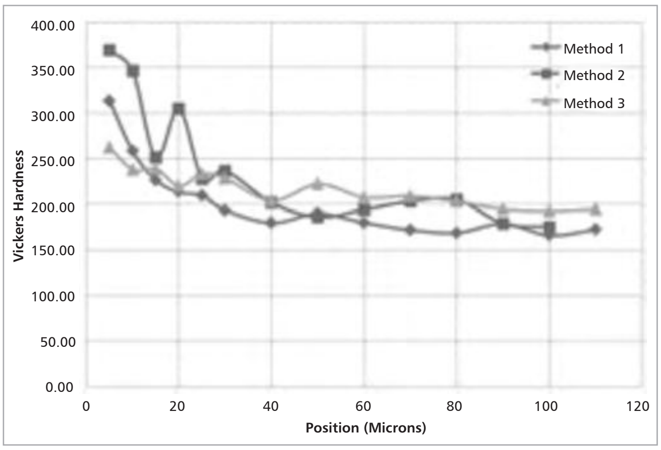


Figure 5: Average hardness values as a function of distance from processed edge.

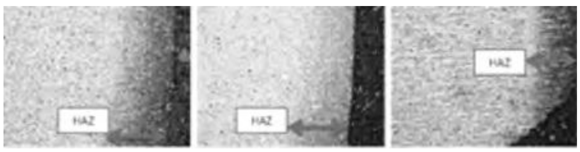
3.2 Microstructure Analysis

Microstructural observations were made at varying magnifications in order to capture the various features of the specimens produced. For example, low magnifications enabled a clear view of the extent of the HAZ penetration into the bulk test piece material. Higher magnification levels provided sufficient detail on grain size changes and grain distortion. Quantitative grain size and distortion changes could be measured and compared with the undisturbed parent material.

The microstructure of the parent material as obtained from one of the specimens is shown in Figure 6.

Figure 6: Parent material microstructure

Figure 6 also shows the grain morphology resulting from the plate rolling process and the grain sizes. Figure 7 is a low magnification image showing the general extent of the HAZ.



(a) (b) (c)

Figure 8 shows a micrograph of a sample produced using method 1 captured at a magnification of 100×.

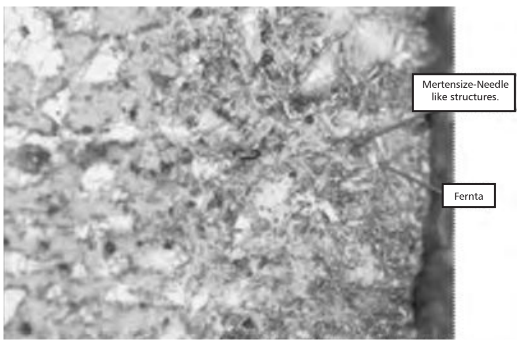


Figure 8: Microstructure of specimen made using Method 1

Figure 9 shows the microstructure for a specimen produced using Method 2 produced at a magnification of 100×.

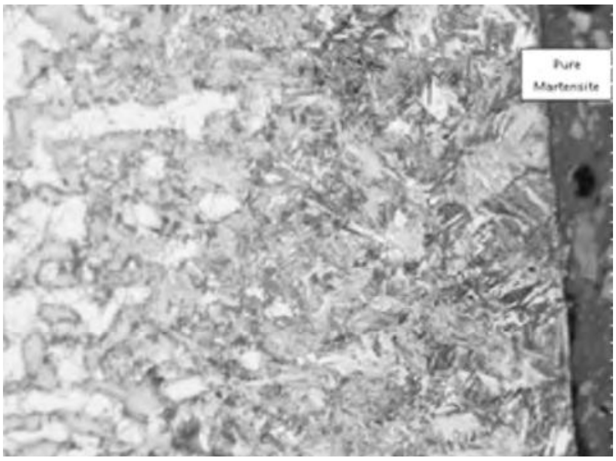


Figure 9: Microstructure of specimen made using Method 2

Figure 10 presents the micrograph for a specimen produced using Method 3 produced at a magnification of 100×.

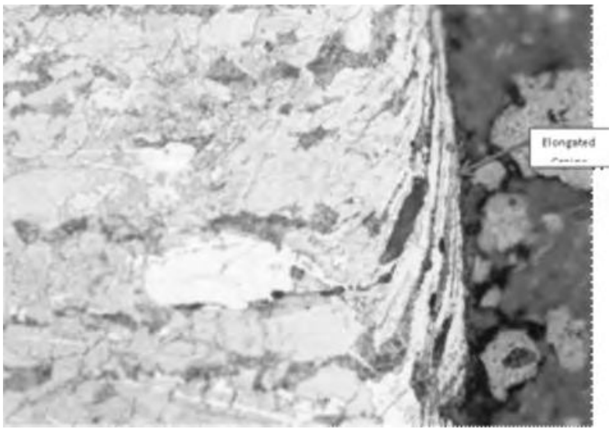


Figure 10: Microstructure of specimen made using Method 3

4. Discussion

4.1 Hardness Profile

Hardness profiles presented in Figure 5 show that the three methods under investigation have very different effects on hardness. Method 2 has the worst hardening effect on the material. This is a result of the heating that was applied during the initiation of the cutting process. This has the effect of changing the microstructure in the heat affected zone.

Method 1 has the second highest hardness values in the HAZ. In this method the cutting process was initiated at the centre of the hole. Since less heat was applied to the hole profile during cutting, there was lesser chance of microstructural changes hence the lower hardness values.

Method 3 had the best performance in terms of hardness profile. The result was the same as the technique that has always been used. Although drilling as a final cutting method induced great metal shearing, this was limited to a very small region close to the surface. There was therefore no significant change in microstructure leading to the lower hardening in the measurement resolution compared to plasma cutting alone. However the two techniques used in method 3 (plasma cutting followed by drilling) mean that the production process becomes too expensive. The first plasma cutting operation might have an effect of slightly improving cutting time but has minimal effect on the material.

The higher the metal strength, the higher is the notch sensitivity of the metal to fatigue. Since the two plasma cutting methods used, produce the same surface roughness on the cut surface, it can be deduced that the elevated hardness profile recorded for the plasma cutting technique leads to compromised fatigue performance due to the hardening effect.

4.2 Microstructure Evaluation

Figure 7 shows that plasma cutting produces a HAZ in the cutting region. This was a result of the heat input during the cutting process. As a result there is significant recrystallization during plasma cutting. This was evidenced by the existence of needle like martensitic structures appearing in Figures 8 and 9 compared to the parent material structure shown in Figure 6. The different heat input levels in the two plasma cutting methods investigated, produce different levels of recrystallization and hence hardening. It follows that the changes in hardness discussed in section 4.1 was mainly as a result of changes in microstructure.

The microstructure for Method 3 as shown in Figure 10 indicates that although there was significant grain distortion, there was no change in the composition of the microstructure. The distortion was limited to a zone which is about the size of a single grain. In addition, the severe plastic distortion of the surface grains tends to induce compressive stresses in the surface layer which have been reported to improve fatigue performance.

5. Conclusions

Although drilling is expensive compared to plasma cutting, it has a lower effect on fatigue performance of the component. Drilling results in a highly distorted surface but the hardness profile remains close to the parent material hardness. Plasma cutting induced a lot of heat in the material which led to microstructural changes. The amount of microstructure changes as shown by the presence of martensite depends on the amount of heat input. Cutting that was initiated on the hole circumference induced more heat to the hole surface than that which was cut from the centre and hence has the largest hardness resulting in the hardness increasing from 200 VH to 370 VH.

It can therefore be concluded that the plasma cutting method introduced in the production of the bolt holes in vibrating screen plates had the effect of reducing the fatigue strength of mild steel. Of the two plasma cutting techniques that were used, Method 1 was the most ideal as it has the least impact on fatigue.

Where plasma cutting is used, it is recommended that the cutting be initiated at the centre of the hole and gradually extended outwards. It is further recommended that the plates be annealed after cutting the holes to reduce hardening and minimise the effect on fatigue performance.

6. References

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