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Fatigue Crack Initiation in Powder Metallurgically-Processed Tool Steel Material under Cyclic Loading

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ABSTRACT

The cyclic behavior of P/M steel has been evaluated at different tempering conditions. Heat treatment is found to significantly affect the hardness, microstructure and fatigue response of the material. Optimum tempering temperature is found to give the highest hardness and better fatigue life compare to as-received material. This heat treatment also characterizes the mechanisms of fatigue crack initiations. Three mechanisms are found in this material: (1) crack initiated from broken particle, (2) crack initiated from open pore and (3) crack initiated from interfacial debonding between particle and matrix. It has been observed that, by carefully designing the heat treatment this steel can be beneficially used in fatigue loaded components.

Keywords: *P/M material, Sintered steel, Crack initiation, Fatigue life, Tempering treatment.*

Introduction

Fatigue crack initiation has received considerable attention in fatigue research because of the critical role such knowledge can play in mitigating against catastrophic failures. It is well established [1-2] that even the initially smooth surface becomes roughened upon the repeated application of stress or strain and that these surface irregularities become cracks over many cycles. For common metallic materials and their alloy, the fatigue failure process consists of the following stages [3]:

a) Cyclic deformation during which the repeated applications of stress or strain condition the metal for the subsequent stages.
b) Crack initiation during which microcrack initiate and coalesce to form macrocrack.
c) Macrocrack propagation.
d) Final failure.

Powder metallurgy (P/M) material offers designers and users a versatile and efficient method of producing engineering parts and component. The process is versatile as it is applicable for simple as well as complex shapes and a full range of chemical, physical and mechanical properties are achievable. The process is efficient because it produces moderate to high volume net or near-net shapes, with almost no raw material loss economically [4]. The fatigue behavior of alloyed P/M material is determined by the mixed influence of their porosity and microstructures. Depending on the pore morphology, chemical composition and homogeneity of the microstructures, either microplastic deformation or early crack initiation and propagation dominate the fatigue process [5].

Microcrack propagation rate increase when the pore content increase. This is because pores lead to crack extension, despite the possible retarding effect of the pores. Thus, in the presence of porosity, the local stress amplitude is higher than the nominal one and localized microplastic deformation dominate the fatigue initiation behavior and enhance microcrack propagation adjacent to the pore [6]. For crack initiation, three reasons are stated [7], first the weakening effect of the pores on the fatigue crack resistance is partly reduced by the creation of non-propagating short cracks, at the main propagating crack front. Secondly, cracking at the crack tip occurs mainly by shear mode instead of the severe tensile mode. Thirdly, the overall crack path is not straight and gives rise to closure effects.

As the utilization of P/M steel for structural application expands, the demand to develop materials with improved processing and mechanical properties to meet the critical design parameters and performance the post-heat-treatments are introduced. This included the quenching and tempering processes. The tensile or fatigue strength may be adjusted by different tempering condition. It is evident [8] that knowledge of these relationships will provide relevant insights for improving their performance as structural materials. Although there are a few studies devoted to evaluate the correlation existing among basic mechanical properties, material parameters, sintering variables for sintered steel, very little information has been published on the influence of tempering operations on such properties [8]. However, the influence of high density (< 2% porosity) structure with varying heat treatment or microstructure on the cyclic properties still requires further investigation for better understanding of the fatigue response of P/M materials. The aim of this investigation is therefore to evaluate the fatigue crack initiation of a high density HAP10 sintered steel under different heat treatment conditions. This material is categorized as high density material with 7.25g/mm^3. This alloy is presently developed for use in aerospace and automotive related area.

Experimental Procedures

Material and Heat-treatment

Alloy powders are produced by atomization process where a stream of molten metal was broken into particles by a high pressure jet of water to obtain powder of size typically less than 10μm. Then, powder material is blended mechanically to ensure material homogeneity. The mixture is heated at temperature 1140°C. In this process, the particles adhere together thermally as a result when heating temperature exceeds the melting point of constitutive materials, the chemical composition of this material in the percentage of weight 1.3Fe-0.6C-5.0Si-3.0Cr-6.0W-4.0V-3.0V [9]. The hardened P/M material is forged and subsequently followed by cold rolling. Stress relief annealing treatment at temperature range 650 – 750°C is performed in order to remove residual stresses occurred by this cold working process. P/M material received with 1m long and 35mm diameter then it is machined into circular cylinder 2.5mm thick. Prior to fatigue tests, special heat-treatment schedule is designed. Firstly, all set of specimens are austenitized at 900°C for 2 hour, then, the material heated is cooled down to room temperature in industrial oil. Four different tempering temperatures are selected namely 300, 400, 500 and 600°C. These treatments are conducted to induce various material surface hardness and microstructures. A standard series of metallographic polishing is followed to ensure perfect observation of these microstructures and to avoid misinterpretation between stretches and crack initiation. Optical microscope is used to do this observation. Figure 1 shows the microstructure of as-received and heat-treated sintered steels and it is also show typical defect found in P/M materials such as surface porosity. Furthermore, the shape of pore is quite regular with noticeable no sharp tips around the pores. Regardless of the tempering treatment applied, microscopic examination revealed that the microstructure mostly consisting of martensite with some retained austenite.

Bending Fatigue Test

Mechanical characterization was performed in terms of material hardness and four point bending moment fatigue test. Hardness test is evaluated by standard Rockwell test using 10kg load. Fatigue testing conducted on circular shaped specimen with 2.5mm thick and 35mm diameter under four-point bending. A circular forcing tool is specially designed so that loads are transferred uniformly and biaxially to the specimen at radius R_1. Tests are carried out using servo-hydraulic testing machine at loading ratio, R of 0.333 and working frequency of 15 Hz. Maximum and minimum load are 12kN and 4kN, respectively. Generally, loading ratio is defined as:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{F_{\min}}{F_{\max}} \tag{1}$$

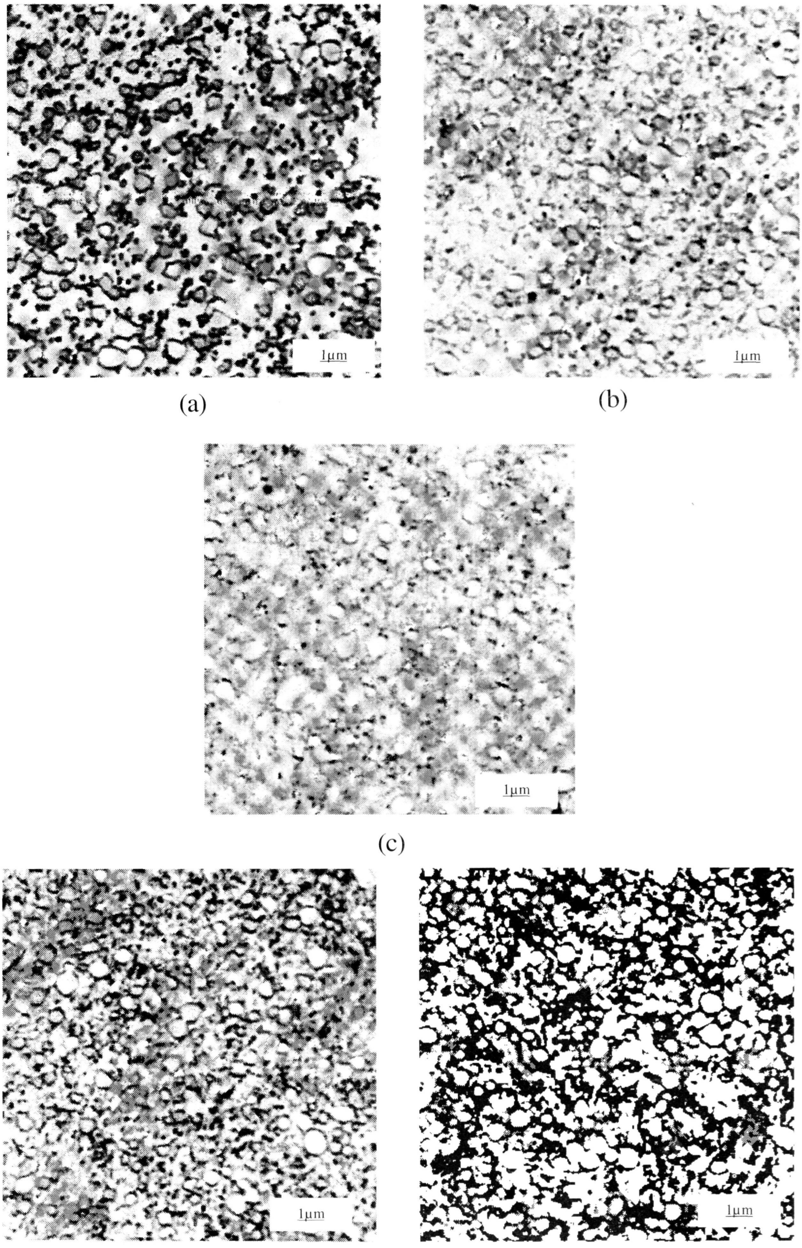


Figure 1: Heat-treated Sintered microstructures (a) As-received, (b) Tempered at 300°C, (c) Tempered at 400°C, (d) Tempered at 500°C and (e) Tempered at 600°C.

All experiments are conducted at room temperature and in air. The specimen has a smooth surface and there is no notch presence on the specimen surface providing maximum bending fatigue stress to the specimen. The fatigue tests are carried out according to interrupted-testing-technique where every 10% of the fatigue life, the testing are ceased in order to observe the behavior of fatigue crack initiation. Normally, fatigue crack initiation occurred at 10% of total fatigue life [1, 2]. A few specimens are fatigued to fail in order to obtain its total fatigue life before further fatigue testing is performed. The stress at a bottom point on the surface of a bending specimen varies between maximum and minimum tensile stresses. For elastic material, Figure 2 shows the method of load application:

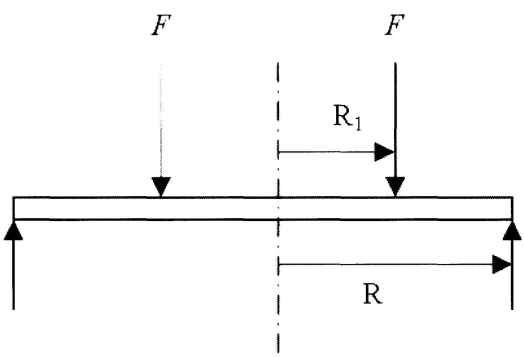


Figure 2: Circular Specimen is Subjected to Circular Loading, F at Radius, R_1.

$$\sigma_r = \frac{3F}{4\pi h^2}\left[2(1+\upsilon)In\frac{R}{R_1} + (1-\upsilon)\frac{(R^2 - R_1^2)}{R^2}\right] \tag{2}$$

Where ó$_r$ is the radial surface stress, *F*, *h*, *R*, R_l and í are applied load, specimen thickness, outer radius, loading radius and poison's ratio, respectively. Equation (2) is used to convert the maximum and minimum loads into stress values.

Results and Discussion

Microstructure and Hardness

As-received sintered material hardness is about 89HRA [9]. The hardness values determined may be described, once the apparent porosity of the investigated material is taken into account. The hardness differences seen among the four variants must be a direct consequence of the distinct tempering conditions.

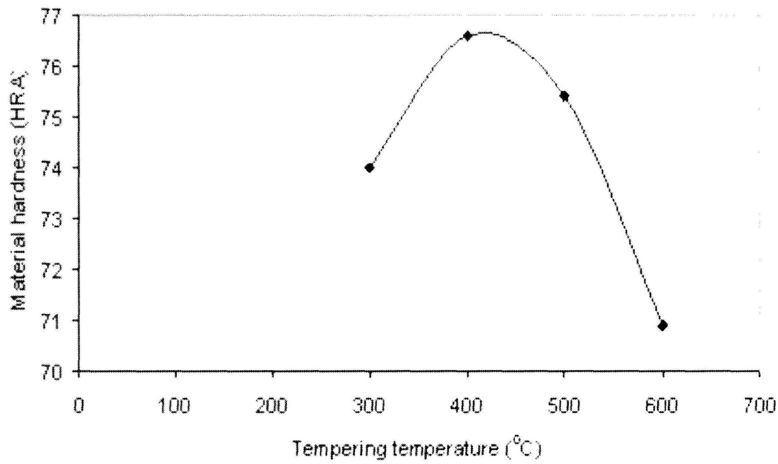


Figure 3: Effect of Tempering Temperatures on Sintered Surface Hardness (HRA)

According to Fig. 3, the hardness reached the maximum value when tempering temperature conducted at 400°C, this finding is also reported in [8]. The hardness changes should be related to pore morphology condition and they are also induced by the austenite to martensite transformation during the quenching process. Figure 1(a) and 1(b) show the microstructures of tempered sintered materials at different tempering temperatures 300 and 400°C. It is seem that the total number of pores have decreased significantly. This is can be related to porosity content within sintered materials. When indenter penetrates into porous structures, it is easily go through into the structure.

Fatigue Life

Figure 4 generated from four point bending moment fatigue testing for all set of circular specimens. It is readily seen from this Figure 4, material that is tempered at 400°C exhibits maximum fatigue life among other types of material conditions. Therefore, introduction of tempering treatment can improve fatigue life and increasing material hardness. The improvement of fatigue life of tempered material at 400°C is almost double. But further increasing tempering temperature results a reduction in fatigue life and hardness as well. This is can be related to the change of microstructural morphology, where the microstructure seen relatively coarser than as-received material. This change will provide a site for stress concentration and hence reducing the overall fatigue life. Higher stress concentration produces larger plasticity region and therefore creates a new surface so called crack initiation.

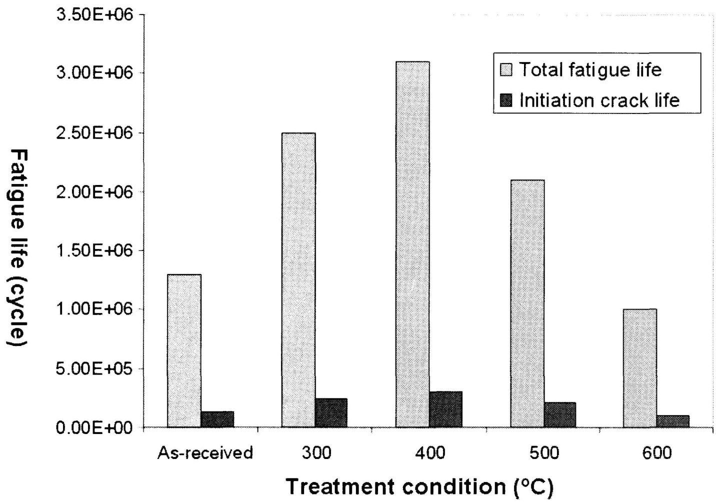


Figure 4: Total Fatigue and Crack Initiation Life of Sintered Materials.

Fatigue Crack Initiation

Fatigue crack initiation in polycrystalline materials is governed by the occurrence of various stress raisers such as fatigue slip bands, inclusions, precipitates, notches and others. In the case of P/M materials, the effect of these stress raisers is superimposed on the pore density, size, shape and the interpore distance. Accurate description of the crack initiation process in P/M materials is more difficult compared with fully dense materials [10]. Three different types of fatigue crack initiation found in this work: crack initiated from particles broken, crack initiated from open pore and crack initiated from particle and matrix debonding. These crack initiations are found to be a function of tempering temperatures, which is tempering treatment characterizes the crack initiation mechanisms. High cycle fatigue testing of P/M steels has reveled that crack initiation is frequently localized at pore clusters, mostly at or near specimen surface [10].

As-received Material

As-received material which is annealed to remove residual stresses during fabricating process, these stresses are assumed not to play a significant role in affecting the fatigue crack initiation behavior. At 10% of total fatigue life, cracks initiate from the broken hard-particles as shown in Figure 4. This is may be due to higher interfacial strength between particle and matrix. In this case of high cycle fatigue (fatigue life > 10^6 cycles), where the applied stresses are too low to cause localized cyclic plasticity on the smooth specimen surfaces, therefore at the site especially notch-like region (interface between matrix and particle) which induces higher stress concentration, and the formation of localized plasticity increases and then initiating the fatigue crack.

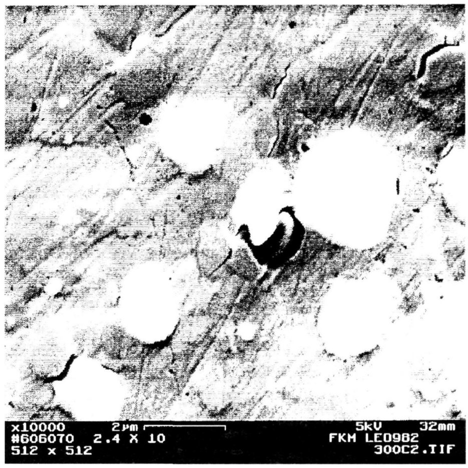


Figure 5: Fatigue Crack Initiation in As-received Sintered Steel.

C.D Liu [12] reported fatigue crack initiation occurs only after either leading to formation of holes or notches at the specimen surfaces. There is no literature found discussing that crack initiated from the broken particles. Normally, for sintered material, fatigue crack initiates from pore [12], surface defect [13], sintering neck [14] and inclusion/particle debonded [15]. Cold forging and stress-relief treatment are known to be one of the influential factors that contributing to the high interfacial strength between matrix and particle [16].

Tempered at 300^{0}C and 400^{0}C

It is well known that the influence of the pore geometry on the cyclic properties of a P/M material dominates the initiation of fatigue life. Irregular pore reduced the fatigue life while regular pore improves [5]. Figure 6 depicts the typical defect found on the surface of this material. It has been found that from experimental observation, fatigue crack initiates from the open pore as shown in Figure 7. As expected, regular or round pores have lower stress concentration factor [3], therefore, they delay the formation of plasticity region of the pores. These specimens also accumulate the highest fatigue life among others. Pores only exist as the stress concentrators, where there are no others defect. Most of the pores are round in shapes. As a result, longer fatigue life required to straining and damage the pore morphology and then promotes the crack initiation process, crack propagation and final rupture. Work [3] also stated that the greater the porosity content, the earlier the crack developed. Another factor they stated that the shape of pore also must be taken into account in determining the mechanism of fatigue crack initiation that affects the overall fatigue life.

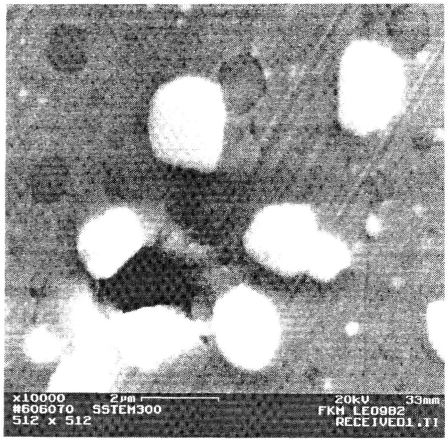
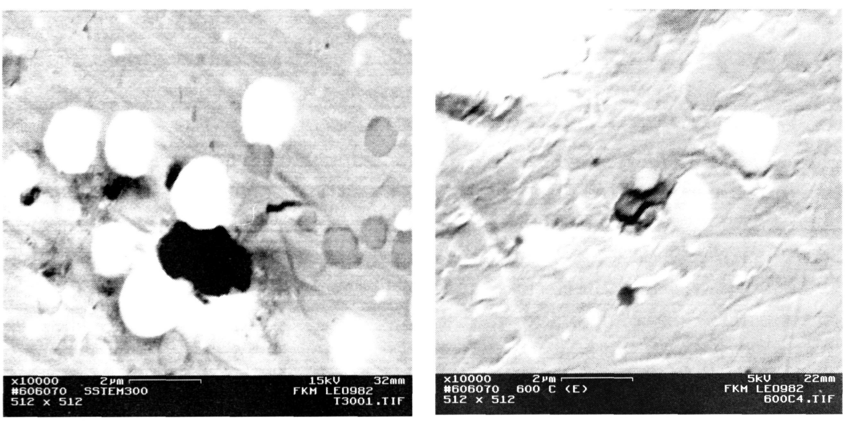


Figure 6: Typical Defect (Surface Pore) Found on the Surface of Sintered Steel

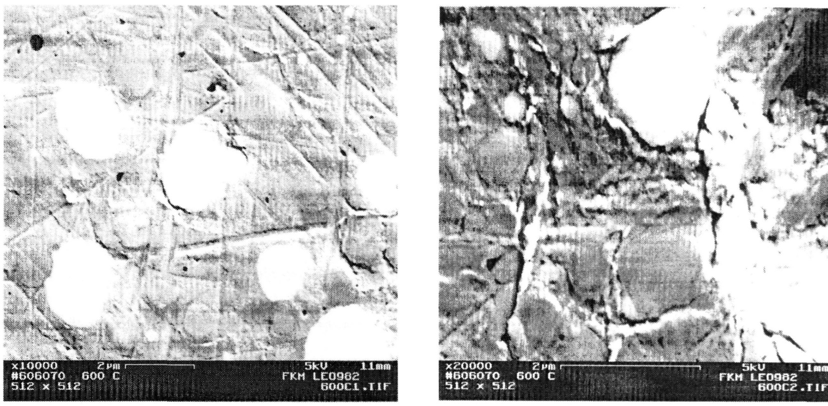


(a) (b)

Figure 7: Fatigue Crack Initiation in (a) Tempered Specimen at 300°C, (b) Tempered Specimen at 400°C.

Tempered Specimens at 500°C and 600°C

The interaction of the plastic zone with the interface between matrix and particle leads to changes in the initiation of fatigue crack mechanisms and in the effective driving force for crack propagation. This study has shown that for tempering temperature greater than 500°C, fatigue crack initiates at the interface boundary as depicted in Figure 7. It is found that the crack initiation path is perpendicular to the direction of fatigue loading. A defect such as notch-like effect takes place in increasing the stress concentration around the particles. In this work, notch-like is define as the interface between matrix and particle. This notch-like effect also plays an important role in initiating the fatigue crack by inducing localized plasticity region around the particles.



(a) (b)

Figure 8: Fatigue Crack Initiation in (a) Tempered Specimen at 500°C, (b) Tempered Specimen at 600°C.

SEM examination on the surface of the tempered specimen at 600°C shows that the fatigue crack begins at interface boundary. The early stages of initiation and growth of this fatigue crack is illustrated in Figure 8(b). For both tempered specimens, debonding is evident at the interface between the matrix and particles. Once the interface has been separated, a crack forms along the particle, thereby causing the stress concentration ahead of the particle to increase. Further fatigue loading will result the crack propagating into the matrix. It can be seen that a crack has extended to the matrix ahead of the particle with some unbroken matrix. No damage has occurred in the particles.

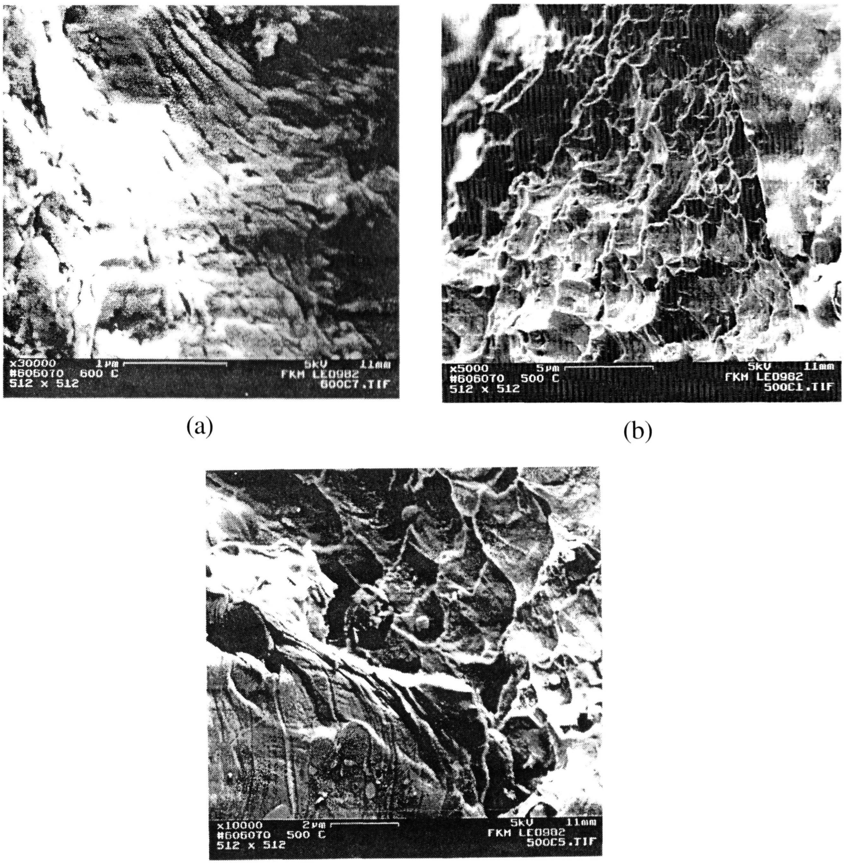
Pores, inclusions and hard particles on the specimen surface and in the interior can be found as sites for crack initiation. Apparently, the stress field around these things influences the crack path [11]. It has been associated that residual stresses play an important role in the fatigue of engineering materials, these stresses are dominant when fatigue crack initiates at the specimen surface. Compressive stresses in high stress areas are usually considered beneficial because they impede crack formation and growth while tensile residual stresses are detrimental because they aid crack initiation. The works of Mc Clinton et al. [17] suggested heat treatment of metal produces differential contraction which causes strain transformation as shown in equation (3):

$$\varepsilon^T = 3(\alpha_M - \alpha_P)\Delta T \tag{3}$$

Where á is the linear thermal coefficient and the subscript *M* and *P* denote metal and particle. ÄT represents the difference between the highest and the lowest temperature during heat treatment processes. When higher austenitizing temperatures are applied to the sintered specimens and then they are suddenly cooled down to room temperature. These two constitutive materials (matrix and particle materials) have different chemical composition. Therefore, during austenitizing treatments both materials expands but after a period of time, these specimens are quenched, both of them contract. This contraction occurs at different rate due to different thermal coefficient. As a result, this phenomenon provides a space between these two constituent materials due to thermal mismatch. This space also provides a site for stress raiser for stress concentration. In a fracture mechanics review, when applied surface energy exceeds a critical localized surface energy, it will create a new surface or crack.

Fracture in Sintered Steels

The as-received specimen exhibits lower fatigue life than heat-treated specimens (300 and 400°C) but further heat treatment shows lower fatigue life (600°C). Figure 9(a) shows the sequence of as-received, tempered specimens 400°C, 500°C and 600°C, respectively. These fracture surfaces are taken after the specimens are completely failed. The fatigue life of all set of as-received and heat-treated sintered steel is shown in Figure 3. Obviously, tempering treatments have characterized the fatigue crack growth mechanisms. Figure 9(a) display appreciable striations. Actually one line of striation contain thousands of striations. The striation forming by a plastic crack tip blunting mechanisms during loading and unloading portion of the fatigue cycles. However, the striation rather dispersed throughout the fracture surface and not be seen clearly because substantial surface rubbing and pounding during repeated loading. There is no significant distinct feature of fracture surfaces between Figure 9(b) and 9(c). This dimples fracture mechanism is considered a lower energy process and therefore an undesirable fatigue crack growth mechanism. The dimples are also attributed largely to the interfacial cracking between hard particles and the surrounding material matrix. Figure 9(c) clearly showed the hard particle at the center of micro-voids. This mechanism may be influenced by the presence of residual stresses after heat treatment and interfacial weakness between particle and matrix.



(a) (b)

(c)

Figure 9: SEM Observations of Fracture Surfaces, (a) Striation Formation (Specimen Tempered at 400°C), (b) Dimples (Specimen Tempered at 500°C) and (c) Dimples (Specimen Tempered at 600°C).

Conclusion

In this present study, the surface condition and quality of sintered steel is very important since fatigue crack initiated in the area where there are pore cluster or inhomogeneous microstructural during mixing and poor interfacial strength between matrix and particles. Crack initiation in sintered steel is found to have the following features:

i) Crack initiated from broken particles.
ii) Crack initiated from open pores.
iii) Crack initiated from interfacial debonding between particles and matrix.

This study also found that fatigue crack initiation mechanisms are characterized by tempering temperatures. Material hardness and microstructures also changed significantly after experiencing heat treatment. Obviously, this particular grade of P/M steel holds good potential for achieving better fatigue life by suitably designing heat treatment schedules. This would be highly beneficial for optimizing the design and manufacturing of fatigue components using this sintered steel.

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