CRACK INITIATION AND CRACK PROPAGATION IN COPPER POWDER MIXED PM STEEL

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Abstract
This paper presents a detailed study of the crack initiation site and initial crack walk in two copper containing PM steels sintered at 1120°C. Material A is plain copper – carbon PM steel Fe2Cu0.8C. Material B is based on 1.5% Mo pre-alloyed powder mixed with Ni, Cu and C. Material A contains pearlite, fine pearlite and a small amount of ferrite. The crack initiation and crack walk in material A is mainly obtained through the relatively coarser pearlite and along the interface between fine pearlite and pearlite. The upper/lower bainitic particle cores of material B are stronger, and crack initiation and crack walk is mainly obtained along the interface between the Cu-rich martensite and bainite, but also through the martensite or bainite.

Keywords: fatigue, crack initiation, crack propagation, microstructure

INTRODUCTION
The porous microstructure of PM steel implies stress concentrations around the pores during loading. The surrounding sinternecks are possible sites for crack initiation during cyclic loading. Different techniques to “reinforce” the sinterneccks have been developed over the years. One of the most frequently used is mixing with copper. Copper melts at 1080°C, and 1120°C sintering implies liquid phase sintering. The melted copper will wet the base particles and is well distributed on the contact surfaces between the particles due to the capillary forces. Fine pearlite or a Cu-rich martensitic phase are formed. These microstructures are strong reinforcements of the sinterneccks. The study presented here focuses on the initiation of the fatigue crack and crack path in relation to the microstructure. Which are the strong and the weak parts of the microstructure in copper powder mixed PM steel?

It is easy to detect the crack path by light optical microscopy, LOM, in polished surfaces. Several investigations on the crack path in relation to the pore structure have been presented in literature. However, very few are presented on the relation between crack path and the metallographic phases. Plastic replicas [1] or direct SEM [2] or LOM observations of the specimen surface or of metallographic sections [3] have been used. In this work, the challenge has been to study the fatigue crack initiation of PM steel without disturbing the original as-sintered surface. The morphology of an as-sintered surface does not allow direct observations of small cracks through single particles with either of these methods. A new way to analyze cracks through the microstructure has therefore been introduced. The specimens included in this investigation are processed along different routes. The illustrations are chosen in order to show good representative examples of crack initiation and crack walk features. It was shown that the mechanisms do not depend on the density in the investigated intervals, nor on the compaction route.

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MODIFIED SPECIMEN DESIGN

Tests with the ISO 3928 fatigue test specimen with rectangular cross section, have shown crack initiation in one of the corners in the majority of the tests, see Fig.1.

A recent close investigation into the origin of the fatigue cracks has shown that particles along one edge were partially torn away due to the processing of the specimen green body after compaction. This phenomenon is not relevant for a PM component, and the specimen design was modified in order to avoid this effect. The modified corner geometry is shown in Fig.2.

Fig.1. Crack initiated at a corner pore along the die-punch edge caused by processing of the green body.

Fig.2. Modified specimen corner design.

Specimens with the original rectangular cross section as well as the modified geometry are included in this study. With two exceptions (Fig.1 and Fig.6), all micrographs showing Fe2Cu0.8C are from tests with the modified corners. All Fe4Ni2Cu1.5Mo0.7C micrographs are from tests on rectangular specimen cross-sections.

MATERIALS

Two copper powder mixed PM steels are included in this investigation. Material A is plain copper-carbon Fe2Cu0.8C based on ASC100.29 in the density interval 6.9 to 7.3 g/cm³ achieved by conventional and warm compaction. Material B is based on Astaloy Mo, a 1.5% Mo pre-alloyed base powder admixed with 4% Ni, 2% Cu and 0.7% graphite. All material B samples are warm compacted to densities between 7.0 and 7.3 g/cm³. The temperatures of 150°C and powder temperature of 130°C are used. A 0.6% lubricant is used for the warm compacted materials, and 0.8% Amide wax for those cold compacted.

Both materials were sintered for 30 min in 90/10 N₂/H₂. All specimens were tested in the as-sintered condition. No machining or polishing had been done prior to the fatigue tests. Detailed information about densities and compaction mode for each example is not included in this report.

FATIGUE TESTS

Plane bending fatigue testing with a load ratio R=−1, i.e. fully reversed loading at 25 – 30 Hz was performed. Specimens which survived 2 million cycles were considered as run outs.
The tests are done in displacement control. Test termination was controlled by either reaching the run out number of cycles set to two million, or 1.5% increase of specimen compliance. The compliance increases when the crack starts to grow and test termination could be obtained shortly after crack initiation. The recording system also allowed evaluation of the crack initiation surface (top or bottom). Stress levels slightly above the fatigue endurance limit have been used, and typically the number of cycles to test termination was 0.5 – 1 million.

**METALLOGRAPHY AND FRACTOGRAPHY**

After test termination, about 5 – 10 μm of the cracked surface was polished away. LOM observations were made of unetched and etched micrographs in order to evaluate the surface crack walk in relation to the microstructure. SEM fractography was used to find features of the crack surface. However, LOM and SEM could not be used on the same sample. The pore sizes found on the LOM micrographs are larger than the real pores. The particles are slightly convex on the as-sintered surface, and the amount of polishing is not deep enough to reach the narrow sinternecks.

**RESULTS**

Material A, ASC100.29+2%Cu+0.8%C

Pearlitic grains partly surrounded by fine pearlite, and a small amount of ferrite forms the microstructure. Figure 3 shows the pore structure of the crack initiation area.

![Fig.3. Material A. Crack initiation close to the edge. The outline of Fig.4 is marked.](image)

![Fig.4. Same sample as shown in Fig.3. Initiation crack and crack walk downwards through pearlite and along the pearlite - fine pearlite interfaces.](image)

Figure 4 shows the initiation through a pearlitic grain. Note that the pore sizes are exaggerated especially close to the edge due to the small degree of polishing. The crack starts at a pore close to the edge on one of the maximum loaded surfaces. The crack passes through pearlitic grains or along the interface between pearlite and fine pearlite. Generally, one or two cracks with crack lengths of a few hundred microns were found in material A.

A detailed study of the initiation and the crack propagation is shown in Fig.5. Also here, the crack walk passes through pearlite or along the fine pearlite – pearlite interface. The micrograph indicates that the preferred crack walk, in many cases, passes through the particles and does not follow the pore structure.
Fig. 5. Material A. Overlay of two micrographs. Crack initiation and crack walk through pearlite, P, and the interface between fine pearlite and pearlite, FP-P. Crack walk is found in both directions from the initiation. The arrows through pores are introduced to make it easier to follow the crack path.

The last example of material A is a SEM fractograph from the crack initiation area, see Fig. 6. The exact initiation point cannot be identified here. Transgranular fracture is found dominated by striations. Note the low fraction of open pores. This is because the fine pearlite surrounding the pores is stronger than the pearlitic cores of the particles, and the crack in many cases passes through pearlite or follows the fine pearlite – pearlite interface and circumvents pores.
Fig.6. Material A. SEM fractography. The lower left corner is deburred. Crack walk close to the initiation area. The exact initiation site could not be detected in this sample. The arrows indicate crack propagation evaluated from the striations. Double arrows indicate possible crack propagation directions.

Material B, Astaloy Mo + 4%Ni + 2%Cu +0.7%C
Also in material B, copper is found along the sinter necks. The copper-rich areas are martensitic. The cores of the particles are, however, different as compared to material A. The material B base particles are pre-alloyed with 1.5% Mo which, in combination with graphite, gives a stronger metallographic structure.

Fig.7. Material B. Complete crack walk from initiation at an edge pore to crack arrest. Rectangular cross section.

Fig.8. Etched sample, same area as in Fig.7.

Generally, several cracks were found in each sample of material B. The crack lengths are about 100 – 200 μm, which is smaller than in material A. In Figure 7 and Fig.8,
it is seen that crack initiation is found at the interface between martensite and bainite at a notch formed by a pore. The crack walk is initially through martensite. Multiple cracks are found when the crack enters a bainitic grain. The crack walk continues along the martensite – bainite interface. Finally, crack arrest is found in the Ni-rich area in the lower end of Fig.7 and Fig.8. Figure 9 also shows crack arrest in a Ni-rich area.

![Crack Walk and Arrest](image)

**Fig.9.** Material B. Martensite-bainite interface crack walk and crack arrest in a Ni-rich area. M: martensite. B: bainite.

Figure 10 shows crack walk through different microstructures and along interfaces. The crack is initiated in bainite and continues through martensite. In the lower half of the figure, also along the interface between coarse and fine bainite and along the martensite – bainite interface.

Figure 11 shows a SEM fractograph of a crack initiation area. It has earlier been shown that crack arrest has been found in Ni-rich areas. Here the crack initiation is found in a Ni-Cu agglomerate. The initially slow crack propagation, through the interface between a ductile and a very hard phase, have resulted in striations in many different directions. However, alternate loading means that also compressive stresses act on the crack surface, and detailed traces from the striations probably are destroyed due to plastic deformation. It is seen from previous figures that the surface crack walk also partly goes through martensite. It is, however, hard to distinguish slow propagating cracks through martensite in the SEM fractographs.
Fig. 10. Material B. Arrows indicate the crack walk through bainite, B, martensite, M, along the interface between coarse, CB and fine, FB, fine bainite and along the interface between martensite and bainite.

Fig. 11. Material B, deburred corner. SEM EDS analysis indicates high content of Ni and Cu in the marked initiation area. The slow crack propagation close to the initiation is characterized by striations. The arrows indicate local crack propagation directions.
DISCUSSION

The investigation presented here is focused on the fatigue crack initiation and crack formation in relation to the microstructure. Great effort has been put into finding a method to trace the early surface cracks in as-sintered surfaces. It is easy to detect the crack initiation in a polished PM steel surface by plastic replica. Replicas, however, cannot be used to detect early cracks on as-sintered surfaces. In addition, the method is very time consuming. It was necessary to find a new way to analyze early cracks and we developed a method based on the combination of mechanical features during testing and successive polishing and LOM analysis. The bending fatigue test system allowed us to measure the compliance of the test bars, and to terminate the tests very early after crack initiation. The crack initiation surface (top or bottom) could be detected from the shift of the mean moment (positive or negative) acting in the specimen mid-section when the termination criterion was reached. The cracked surface was inspected in LOM after a very shallow polish. The crack initiation and early crack walk was detected in relation to both the pore structure and the metallographic microstructure. The method does not allow inspection of successive crack propagation, and therefore the detection of the exact initiation site might seem to be arbitrary. However, the inspected cracks were, as mentioned, very short and in most cases clearly related to a dominating pore. The crack initiation could, in the majority of the cases, be related to a stress raiser formed by the pore.

Typical crack lengths detected in material A are 400 – 500 microns, and one or two cracks were found in each sample. The crack depth is estimated to be of about the same size as the crack length, and a single 400-micron crack can well be detected by the compliance based test termination system. The crack lengths found in material B are about 100 – 200 microns. A single crack of this length most probably cannot be detected during the fatigue test. However, several cracks were found in each sample, and the cumulative influence can be detected.

The two PM steels exhibit different fatigue performance. Material A is a medium-performance material. Material B is a high-performance material with a fatigue endurance limit about 20 – 40% superior to the copper carbon material. Similarities and differences considering the crack behavior that can be related to the different microstructures are found. Different features of the crack initiation and crack walk through the material, reflect the difference in fatigue performance during cyclic loading.

Both materials have heterogeneous microstructures. Different metallographic phases, which indicate concentration gradients of the alloying elements, are found in the micrographs. The microstructure in material A consists of fine pearlite, pearlite and a small amount of ferrite. The microstructure of material B is formed by martensite, bainite and Ni-rich areas with retained austenite and surrounded by martensite. Both fine and coarse bainite are found. These metallographic phases have very different mechanical characteristics. A possible explanation for the interface crack walk is based on the difference in yield stress of the two phases involved. Mechanical loading of an interface between a high yield stress material (martensite) and a lower yield stress material (pearlite or bainite) gives very localized plastic deformation at the interface when the yield stress of the low performance constituent is reached. The crack walk follows the localized plastic deformation.

The particle cores in material A are pearlitic. No surface crack initiation in fine pearlite is found and also very few cases of cracks through fine pearlite. Initial crack walk is found through pearlite or along fine pearlite – pearlite interfaces. The preferred crack walk is often through the pearlitic core, and does not necessarily follow the pore structure. An interesting feature here is that very few pores are found in or close to the initiation area,
with the exception of the stress raiser itself. The crack is guided away from the pores immediately after crack initiation.

The higher strength of the molybdenum pre-alloyed base powder of the high performance material is displayed by the fact that the crack initiation and the crack walk is mainly obtained along the interface between the bainitic particle core and the Cu-rich martensite. In some cases, crack walk along interfaces between coarse and fine bainite or through bainite are found. Crack initiation and early crack walk has also been found through martensitic grains. Several short cracks were found in each sample of material B. In some cases, surface crack arrest was observed also in Ni-rich areas. This has been reported already during the eighties for diffusion alloyed D.AE with 0.5% graphite sintered at 1120°C [4]. All cracks most probably reach Ni-rich areas along the crack front where they will be arrested or delayed. However, a possible large crack propagation mechanism is that the Ni-rich area is circumvented and the crack continues on the other side. The Ni-rich areas slow down parts of the crack front, but cannot arrest the entire crack.

CONCLUSIONS
The modified ISO 3928 fatigue specimen has shown to be less sensitive to corner pores as compared to the original design with rectangular cross section. More focus on the material is obtained with the modified design.

The method developed to find early surface cracks allow detection of the initial crack walk in relation to the pore structure and the etched microstructure. One of the most important features of the method is that no preparation of the specimen is needed before the fatigue test is performed. All fatigue tests can be made on as-sintered specimens, and any of the tested samples can be analyzed. The microstructure of material A is characterized by fine pearlite, pearlite and a small amount of ferrite.

Trans-granular crack propagation through pearlite dominates the crack initiation and early crack propagation in material A. Some crack propagation is found along the interface between fine pearlite and pearlite, and also through fine pearlite. The fine pearlite is an effective reinforcement of the microstructure. The microstructure of material B is characterized by Cu-rich martensite around the pores, bainite and Ni-rich areas.

Crack initiation and crack propagation in material B is mainly along the interface between martensite and bainite. Some crack propagation goes through martensite and through bainite. I.e. the main part of the crack propagation is between metallographic phases with different yield stresses. Arrest of surface cracks is found in Ni-rich areas. There is no indication of surface crack walk through Ni-rich areas.

REFERENCES