3D Crack Walk in Copper-Nickel-Molybdenum Alloyed PM Steel

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ABSTRACT. *A detailed 3D crack walk study is made on Ni-Cu alloyed PM steel with Mo pre-alloyed base powder. Surface crack walk has earlier been observed not to pass through islands of Ni-rich austenite. The aim of the study is to find the crack walk in relation to the Ni-rich austenite. Successive grinding in steps of about 20 μm is made and the surface crack in each level is recorded by light optical microscope. The main part of the crack walk is found through high temperature bainite or along the interface between martensite and high temperature bainite. Ni-rich austenite is surrounded by martensite that hinders the crack to enter into austenite. The result indicates that austenite as such is not a strong crack stopper.*

INTRODUCTION

Powder metallurgy, PM, steel is a near net shape process widely used in production of parts for the automotive industry. The annual consumption of iron powder for the PM steel industry is about 800.000 tons (2002). On average every European or Asian produced car contains about 8 kg PM parts, American cars about the double.

Premixed powder is pressed in dies at up to 1000 MPa. The porosity is normally of the order 5 – 15% depending of compressibility of the powder and amount of graphite and lubricant added to the iron base powder. Pure iron or low alloyed iron base powder with low yield stress are preferred. The pressed parts are normally sintered at 1120^{o}C in a reducing sintering atmosphere. Dew point down to – 40^{o}C is needed in order to avoid oxidation and decarburisation. The development of the PM materials has successively increased the mechanical performance and PM steel is today also used for fatigue-loaded components. Typical examples are gears and synchronizer hubs.

PM steel is a porous material. The pores are possible initiation sites for cracks and also leads propagating cracks through the material. The possibility to design clever microstructures by adding small amount of alloying elements that creates a network of strong microstructures has been a way to compensate for the micro-notches formed by the pores.

Copper is by far the most common alloying element in PM steel. Copper is added as powder and mixed together with the base powder, lubricant and graphite. The influence of Cu on the mechanical performance is strong. Copper melts at 1080°C and solid solution hardening is obtained. Copper rich very fine pearlitic phase is formed around the pores in PM steel based on pure iron base-powder. Molybdenum and Nickel may either be pre-alloyed to the base powder or added as elementary powder in the premix. Pre-alloyed Mo has a relative small influence of the yield stress and high performance base powder grades typically contains 1 – 1.5% Mo. Nickel pre-alloyed base-powders have low compressibility and relatively low fatigue performance microstructures are obtained at normal cooling rates.

Nickel has been shown to increase the ductility of PM steel. Another feature of Nickel addition is to utilize the slow diffusion rate of Nickel in Iron at the sintering temperature 1120°C. A heterogeneous microstructure is formed around the Nickel particles with austenite in the core surrounded by martensite. The best effect is obtained with Ni mixed with Mo pre-alloyed base powder. The martensitic network has been found to increase the fatigue performance. The combination of Mo pre-alloyed base powder mixed with Ni and Cu has been shown to give high fatigue performance.

New applications of PM steel are mostly found in competition with wrought steels. The macroscopic ductility of PM steel is lower than for solid steels. Designers are conservative and the properties of rod steel have more or less defined acceptable material characteristics also for PM steel.

Ductility and toughness are important target parameters. Nickel is one way to combine improvement of ductility and of fatigue performance. The aim of this study is to find the possible mechanisms of the positive influence of Nickel. The investigation is made to find further ways to close the gap to homogeneous steels.

Bergmark et.al. [1] have investigated surface cracks with special attention to the crack walk in relation to the microstructure. Lindqvist [2] has investigated the cracks in cross-sections and mapped the Nickel content along the crack path. In both cases, PM steels with pronounced heterogeneous microstructures and about the same alloying content were investigated. However, the results are of limited value as only one plane was studied. The investigation presented here is an extension of the paper by Bergmark et.al. [1] from 2D to 3D.

MATERIALS

The investigated PM steel is based on water atomized AstaloyMo™, a 1.5%Mo pre-alloyed base powder from Höganäs AB. The base-powder is premixed with 4%Ni +2%Cu + 0.7%graphite + 0.6% lubricant. The mix is bonded and warm-compacted to density 7.3 g/cm^3. Sintering is made at 1120°C for 30 min in 90%/10% N_2/H_2 sintering atmosphere. The cooling rate in last section of the belt furnace is crucial for the formation of the different microstructures. Typically, a cooling rate of about 0.8°C/sec is obtained. Liquid phase sintering is obtained from Cu. Cu will be well distributed along the capillaries. The microstructure contains (high temperature) bainite, Cu-rich martensite and Ni-rich austenite surrounded by a shell of Ni-rich martensite. Cu-rich martensite is found along or surrounding the pores. The Ni-rich austenite and martensite is limited to the original place of Ni as the Ni diffusion rate is slow in iron. No or only minor amounts of low temperature bainite is found. The cross-section microstructure is shown in Figure 1.

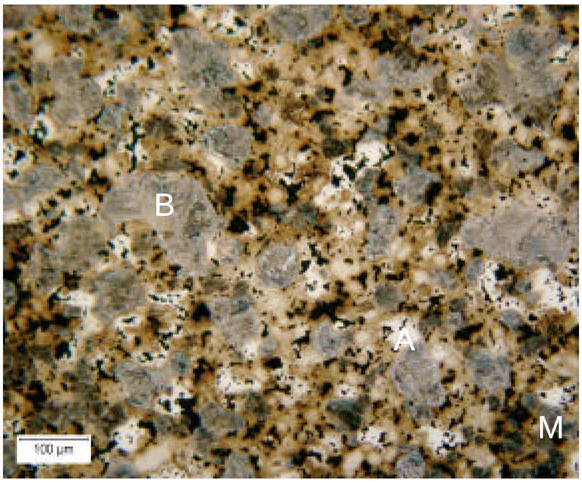

Figure 1. Cross-section microstructure of Fe+4%Ni+2%Cu+1.5%Mo+0.7%C. Black areas indicate pores. Typical maximum pore size is about 50 µm. A: Nickel-rich austenite. The white Ni-rich areas are surrounded by martensite. B: High temperature bainite base powder particle, M: Cu-rich martensite. The microstructure is pronounced heterogeneous with mainly martensite surrounding the pores.

FATIGUE TESTS

Plane bending displacement controlled fatigue tests have been made on as sintered PM steel fatigue bars ISO 3928.

Detailed crack walk will here be shown for one specimen tested at 220 ± 220 MPa initial stress, i.e. load ratio R=0. A fully instrumented data sampling system is used and the specimen compliance is evaluated continuously. The test was terminated when the compliance had increased 1.5% after 91 kilocycles.

3D CRACK WALK

Crack initiation at R=0 is always found on the tensile loaded specimen surface. The preparation of the samples for crack walk investigation is made by cutting about 155 mm of the specimen midsection and molding with the cracked surface visible. A very shallow (about 10 µm) grinding followed by polishing was made to make the surface crack visible in a LOM (Light Optical Microscope). This level is referred to as level zero in the following. Successive grinding and polishing in steps of about 20 µm is made to detect the 3D crack walk. In total, 4 levels at 0, -20µm, -42µm and -59µm are studied.

Crack initiation is obtained at the right specimen edge seen in Figure 2. Two positions where the visible cracks are interrupted by Ni-rich areas are investigated. The specimen width is 5 mm. Position one is placed about 1 mm from the right edge. Position two is placed about 2.5 mm from the right edge.

RESULTS

Position 1

Figure 2 shows the crack walk at level zero. Parts of the convex particle top surfaces remain due to the shallow initial grinding and polishing. Some of the pores shown in this figure are therefore much larger than pores normally seen in cross-sections.

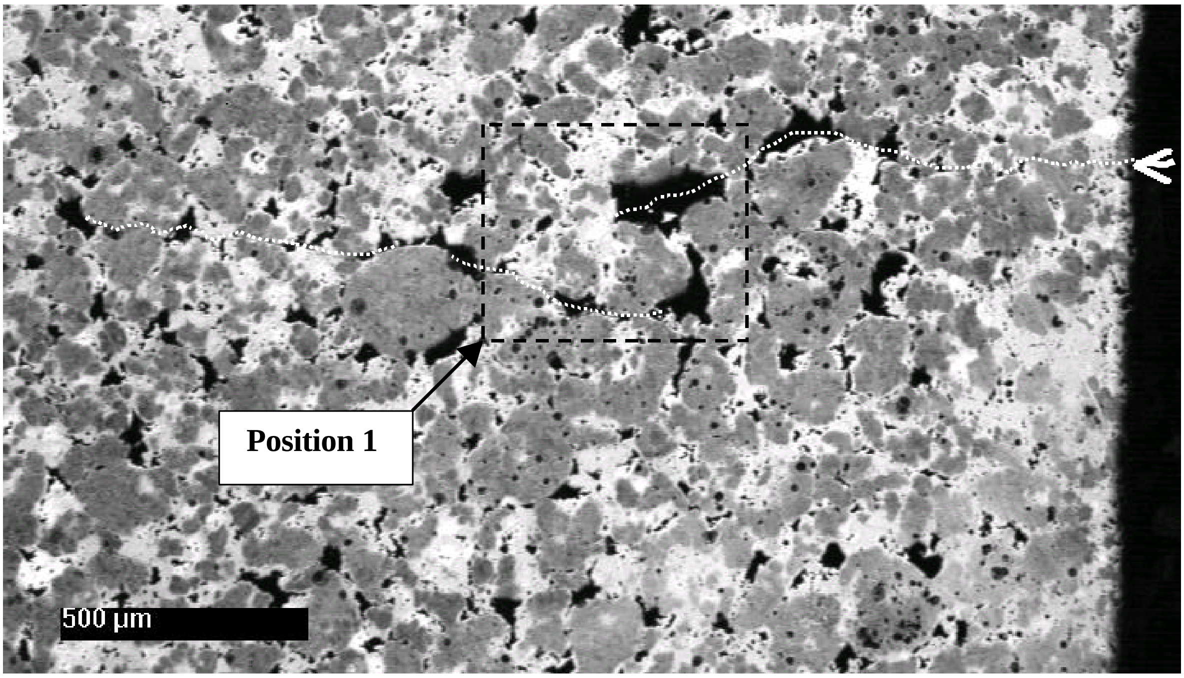

Figure 2. Overview of position 1. Crack walk is indicated by the dotted lines. Two crack branches are found and there are alternate interpretations of how the crack was developed. The arrow indicates one possible crack initiation. See further text. The large pores visible in the center of the figure are an effect of the shallow grinding of the top surface. See further text.

Position 1 is marked in Figure 2. Position 2 is placed just outside the left edge of the micrograph. Two crack branches are found in Figure 2. The cracks might have been developed independently and later linked together. Another interpretation is a continuous crack that has started at the arrow along the right edge and circumvented the particle in center of position 1. Surface crack propagation is found along interfaces between martensite and high temperature bainite, through the bainitic base powders and to some extent also through martensite.

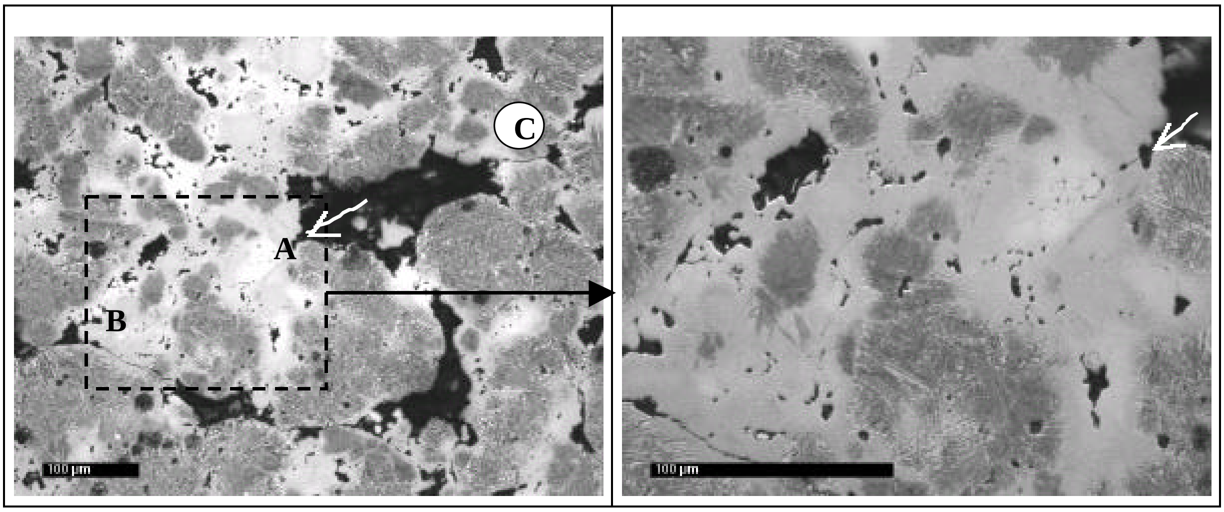

Figure 3. Position 1, level zero. Two magnifications. The marked rectangle in the left figure outlines the borders of the figure to the right. The main crack is visible in the lower left corner close to B and at C. A short crack through martensite is visible at the arrow in figure right. The visible crack disappears in austenite. This area was chosen in order to see how the short crack is linked from A to B, i.e. to the continuation of the main crack in the lower left corner.

Figure 3 shows details of position 1 at level zero. Figure 4 shows position 1, level – 20 µm. The Ni-rich area between A and B visible in Figure 3 is almost completely ground away is replaced by a bainitic base powder particle. A visible crack is present from A to B.

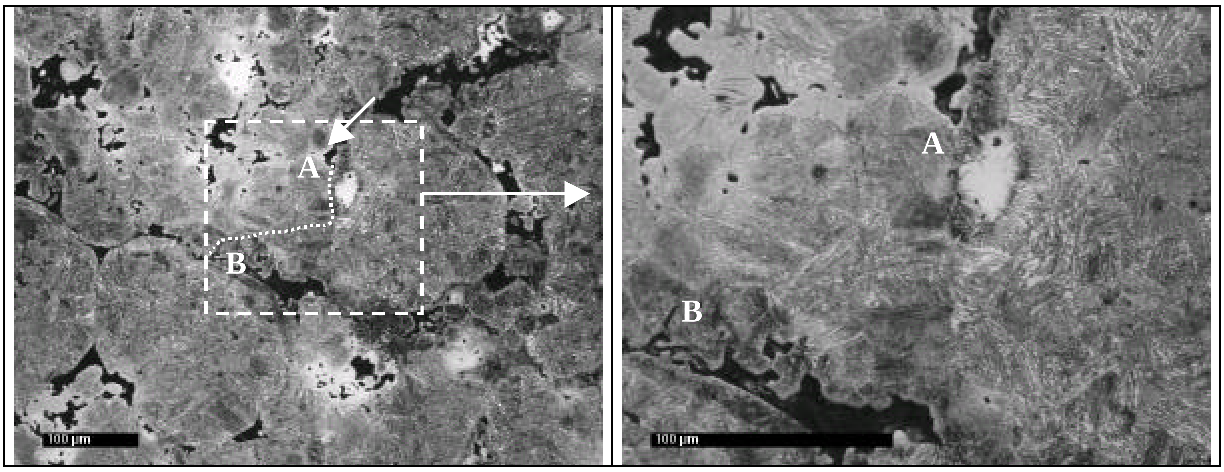

Figure 4. Position 1, level -20µm. Surface crack walk in two different magnifications. The broken line rectangle in the left figure indicates the outline of the right figure. Almost all martensite and austenite between A and B is ground way and the linking crack is visible. The linking crack is very narrow and cannot, however, be seen in the figures reproduced here

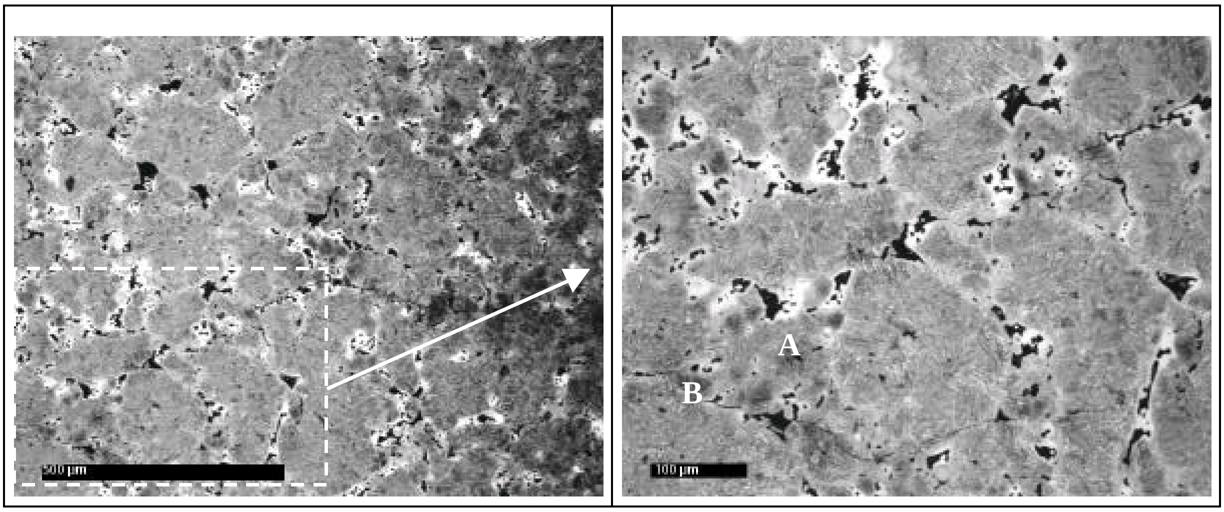

Figure 5. Position1, level -42µm. Here the visible crack from A to B has disappeared. An extension of the crack is seen from B and further right in the lower part of the right figure.

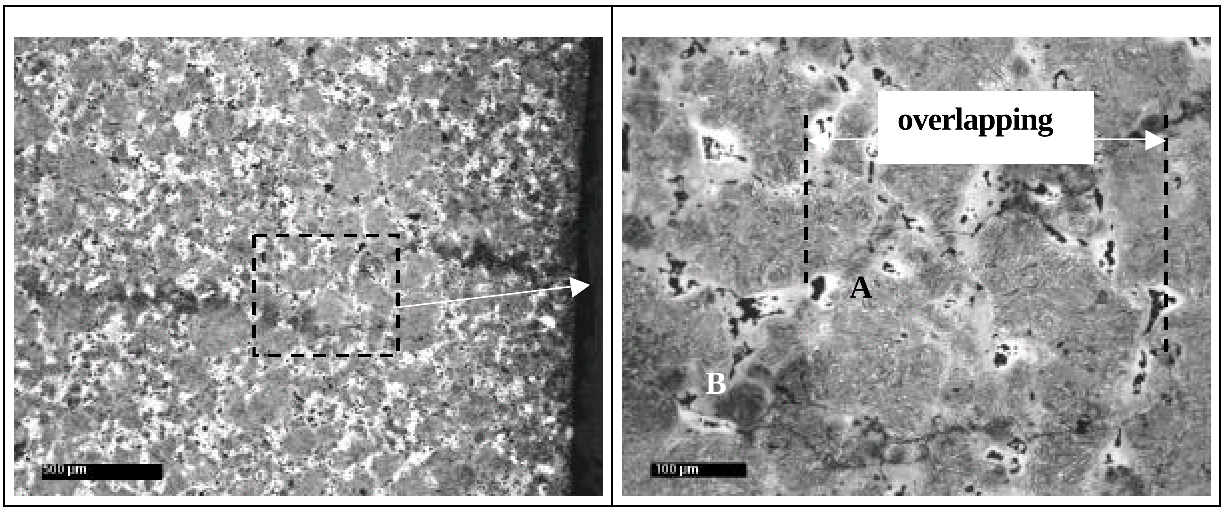

Figure 6. Position 1, level–59 µm. The cracks are contained in the dark bands obtained from slight over-etching due to etch liquid soaked into the cracks. No visible crack linkage between A and B is seen. The extension of the overlapping cracks is marked in the right figure.

The linking crack from A to B has disappeared at level -42µm. Two overlapping cracks have developed see Figure 5. Figure 6 shows level –59 µm.

Position 2

The crack walk in relation to Ni-rich austenite at position 2 reveals the same features that have been found at position 1. One example from position 2 is shown in Figure 7 where micrographs from levels -20µm and -42µm are shown. Figure 7 also shows typical interface crack walk between martensite and bainite.

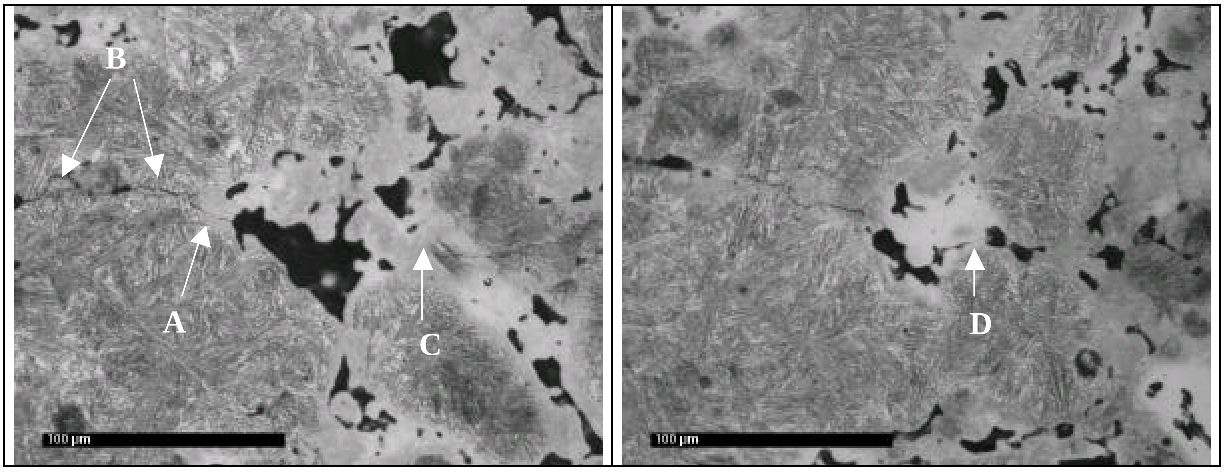

Figure 7. Position 2 at two levels -20μm (left) and -42μm(right). A: crack walk along interface between Ni-rich martensite and high temp bainite. B: Crack walk along interface between Cu-rich martensite and high temperature bainite. C: Possible crack arrest in Ni-rich martensite close to austenite as indicated at level-20μm. D: The crack at level-42μm indicates continuous crack walk below the -20μm arrested visible crack at C.

DISCUSSION

The method to find the 3D crack walk is based on successive grinding and polishing. The microstructure consists of hard phases with high yield stress (Cu-rich and Ni-rich martensite respectively) as well as soft phases with low yield stress (austenite and bainite). The possibility to detect small cavities like pores and cracks presumes that they are not smeared and filled because of plastic deformation during the preparation. The methods to detect pores in most types of PM steel are well developed. Choosing well-tested parameters for the different steps in the polishing process opens the pores. Hard phases are most easy to detect. Crack walk through martensite will be seen very clearly with the method used here. Crack walk through a soft phase like austenite, however, might be shadowed by plastic deformation and smearing. This might be a reason why no crack walk through austenite is seen. The austenite areas are almost everywhere surrounded by a shell of martensite. Crack walk through austenite, therefore must be combined with crack walk also through martensitic. Actually, such crack walk is found at the both investigated positions. Furthermore, crack walk is present through bainite around a Ni-rich austenitic area with no visible crack. Ni-rich austenite can accept high levels of cyclic plastic strain and must not necessary be fractured even if the surrounding material is cracked. The conclusion is drawn that Ni-rich austenite in PM steel most probably does not have possibilities to arrest cracks. It is known that addition of Nickel raises the fatigue performance of Mo pre-alloyed PM steels. The suggested mechanism based on this study is the crack resistance of the martensite formed around the Ni-rich areas.

Two crack branches were found along the right edge of the specimen. The cracks were separated at level zero, linked together along a very narrow crack through a bainitic base powder particle at level –20μm and separated again at level -42μm and -59μm. Earlier investigation in the same material [1] has revealed crack lengths of up to 300 μm at 1.5% increased compliance. The total crack length shown in Figure 2 (zero level) and Figure 6 (level -59μm) is about 2.5 mm. A continuous crack grows along the surface as well as down. The relatively small increase in compliance indicates shallow cracks. Most probably, at least two cracks have developed independently of each other. The Ni-rich austenite surrounded by martensite revealed between A and B in Figures 3, 5 and 6 have probably stopped linkage of the main cracks. The narrow linking crack revealed in Figure 4 is probably a local fracture of one particle. The crack walk revealed at four levels in position 1 indicates that presence of Ni-rich areas surrounded by martensite is a strong reinforcement of PM steel.

CONCLUSIONS

Crack walk in the Fe+4%Ni+2%Cu+1.5%Mo+0.7%C PM steel investigated is found along interfaces between Cu-rich or Ni-rich martensite and through the bainitic base powder particles. The Cu-rich martensite is an effective shelter around the pores and the Ni-rich martensite around the austenitic areas. The conclusion can be drawn that austenite as such is not a crack arrest candidate in PM steel. The important phase is the martensitic shell surrounding the austenite. Many small Nickel rich areas characterize an optimized distribution of the heterogeneous microstructure in order to form more or less a continuous 3D martensitic network by means of the combination of Copper and Nickel.

REFERENCES

1. Bergmark, A., Persson, U. and Alzati, L. (2002) In: *Advances in Powder metallurgy & Particulate Materials – 2002*. **5**, 95-103. Compiled by Arnhold et.al. MPIF Princeton, USA
2. Lindqvist, B. (1988) In: *Modern development in Powder Metallurgy*. **21**, 67-82. Compiled by Gummesson and Gustafsson., MPIF Princeton, USA