FATIQUE PROPERTIES OF CU-C ALLOYED PM STEEL AT TWO DENSITY LEVELS

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Abstract
A full factor test of the axial fatigue properties of Cu + C alloyed PM steel is performed. The three variables are: density (approx 7.15 and 7.4 g/cm^3 obtained by single and double compaction), Cu content (0 and 2%) and C content (0.2% and 0.8%). The greatest influence on the fatigue endurance limit was found for Cu (+53 MPa) followed by density (+33.5 MPa) and C (+25 MPa). The greatest combined influence was found for Cu and C (+12.5 MPa in addition to the individual effects). The high cycle fatigue properties of cold compacted double pressed and sintered Fe2Cu0.8C are compared with warm compacted material with the same composition. Fractography, displaying the sizes and origins of the initial faults, is performed on double pressed/sintered and warm compacted Fe2Cu0.8C.

Introduction

Copper - Carbon alloyed PM Steel is a real workhorse in the PM steel industry. It is a competitive and well-known alternative for medium loaded components. The static mechanical properties are good. In this investigation, the focus is on the dynamic mechanical properties. The high cycle fatigue endurance limit, FEL, at constant amplitude loading is determined. A full factor test with three variables is performed. The variables are density, carbon content and copper content.
The investigation is made on cold compacted powder mixed Cu+C PM steel. Cu(-100 mesh) particles were used to avoid the potential problem with segregation of Cu. The Cu particles melt during sintering and typically pores with a diameter of 150 – 200 µm can be found in the microstructure. Premixing with finer Cu particles in combination with bonding opens the possibility to avoid segregation. In addition to the full factor test, one set of test specimens was manufactured using the Densmix route with Cu (-200 mesh) particles and warm compaction.

Materials

All materials were based on ASC100.29 water atomized iron powder. The graphite powder was UF-4 from Graphitwerk Kropfmühl. Cu (-100 mesh) was used for the full factor test materials and Cu (-200 mesh) for the warm compacted material. 0.8% zinkstearate was used as lubricant.

Factor test
The full factor test matrix is presented in Table 1.

Nr	Material	Density g/cm^3	Compaction
1	Fe0.2C	7.14	Single
2	Fe0.2C	7.37	Double
3	Fe0.8C	7.10	Single
4	Fe0.8C	7.35	Double
5	Fe2Cu0.2C	7.00	Single
6	Fe2Cu0.2C	7.20	Double
7	Fe2Cu0.8C	7.05	Single
8	Fe2Cu0.8C	7.38	Double

Table 1. Factor test matrix.

Sintering
Single compacted materials were sintered at 1120^{o}C for 30 minutes in endogas with carbon activity. Double compacted materials were presintered at 750^{o}C for 20 minutes in 90/10% N_2/H_2. The sintering after the second compaction was made with the same parameters as for the single compacted materials.

Specimen
The specimen design is shown in Fig 1. The specimen thickness is 5 mm.

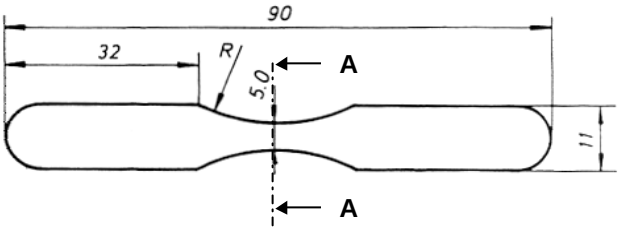


Fig. 1. Fatigue test specimen

Stress concentration in axial loading
A linear 3D FEM calculation was performed in order to find the theoretical tensile stress concentration. The result is presented in Fig. 2. Note that the maximum principal stress is considered and not the equivalent stress. Maximum stress was found in the smallest cross section in the middle of the concave surfaces facing the die corresponding to a stress concentration of +6%. Minimum stress was found in the center of the flat surfaces facing the punches. The stress concentration is + 4% in the corners.

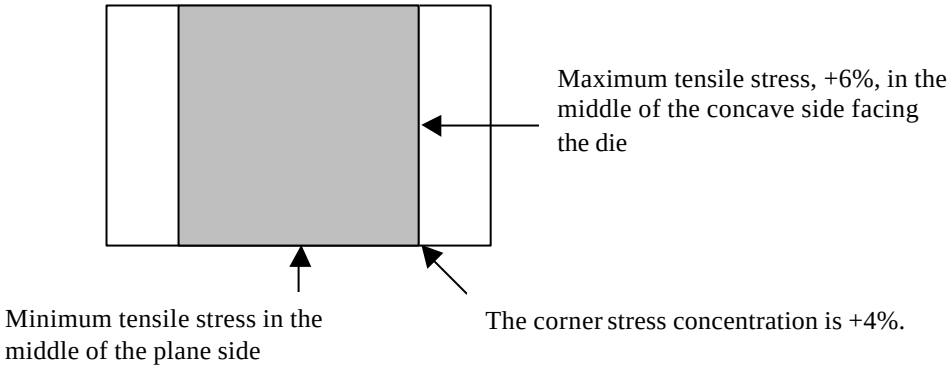


Fig. 2. Cross section A-A marked in Fig. 1. Tensile **s**tress distribution in the minimum cross section**.** The **s**tress concentrations are given relative to the nominal stress.

Fatigue testing.
All fatigue test were performed in axial loading with load ratio R=-1. The staircase method with 15 samples was used to find the 50% fatigue endurance limit and standard deviation at 2 million cycles. The tests were run in a servo hydraulic MTS frame with Instron 8500+ control system at frequencies between 25 – 37 Hz. Aluminium inserts were used to avoid stress concentration along the edges of the hydraulic grips. Details about the testing are reported earlier (Bergmark 1999).

Fractography.
SEM fractography was used to investigate the Fe2Cu0.8C high density and warm compacted materials. The purpose was to find the crack initiation site and to determine the size of the fault related to the initiation.

Microstructure
The pore morphology was investigated in a light microscope. Cross sections were ground and polished and the pore size distribution was recorded.

Results

Factor test.
The three factors are

Factor	Low	High
Density	Approx 7.1 g/cm^3	Approx 7.4 g/cm^3
C-content	0.2%	0.8%
Cu-content	0	2%

The results of the fatigue tests of the materials included in the factor test are presented in Table 2.

Nr	Material	Density	Cu	C	FEL MPa	Std dev MPa
1	Fe0.2C	Low	Low	Low	105	-
2	Fe0.2C	High	Low	Low	131	24
3	Fe0.8C	Low	Low	High	109	4
4	Fe0.8C	High	Low	High	152	5
5	Fe2Cu0.2C	Low	High	Low	143	4
6	Fe2Cu0.2C	High	High	Low	174	9
7	Fe2Cu0.8C	Low	High	High	179	18
8	Fe2Cu0.8C	High	High	High	213	10

Table 2. Fatigue endurance limits, FEL, and the corresponding standard deviations. The standard deviation is not included in the evaluation of the factor test. The information is included here in order to allow a simple comparison between the calculated effects and the scatter.

The result from the evaluation of the factor test is shown in Table 3.

Variable(s)	Density	C	Cu	Density + Cu	Density + C	Cu + C	Density + Cu +C
Effect MPa	+33.5	+25	+53	+5	-1	+12.5	-3.5

Table 3. Individual and combined effects in MPa of the variables included in the factor test.

The largest influence, +53 MPa, is found for addition of Cu followed by +33.5 MPa for the density and +25MPa from C. The largest combined influence, +12.5 MPa, is found for the combination of Cu and density. The other combined influences are small.

Warm compacted Fe2Cu0.8C.
The density of the warm compacted specimens was 7.23 g/cm^3. The 50% fatigue endurance limit was 216 MPa with a standard deviation of 7 MPa.

Fractography.
SEM fractography was performed on two series, namely cold double compacted and warm compacted Fe2Cu0.8C. All broken specimens from the staircase series were examined. The initiation sites and sizes of the initiation faults were determined. The results are presented in Table 4 for the cold double compacted material and in Table 5 for warm compacted material.

Specimen Nr	Nominal load MPa	Life cycles	Size (µm)^2	Placement
8-52	220	413459	9052	Corner
8-53	210	1 063 202	27941	Corner
8-55	210	201 774	23865	Corner, punch surface
8-58	220	462 397	33900	Punch surface, 0.4 mm from corner
8-91	230	425 920	9942	Corner, punch surface
8-92	220	1 266 490	38040	Die surface, ca 0.9 mm from corner
8-94	220	564 523	7821	Die surface, ca 50 µm from corner
	Mean fault size		21509	

Table 4. Results from fractography of cold double compacted Fe2Cu0.8C.



Fig. 3. Two corner placed initial faults, double compacted Fe2Cu0.8C. Left specimen 8-52, size 9052(µm)^2, right specimen 8-53, size 27941(µm)^2, shown in about the same scale. Compaction left right. The figures are hand drawn from SEM photos.

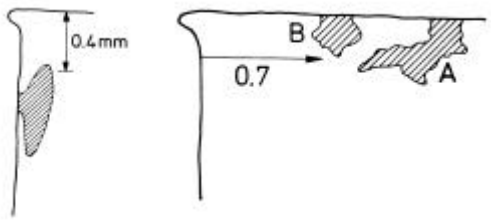


Fig. 4. Surface initial faults, double compacted Fe2Cu0.8C. Left specimen 8-58 size 33900 (µm)^2 , right specimen 8-92 size 38040 (µm)^2 (surface A), shown in about the same scale. Compaction left – right.

The results from fractography of warm compacted Fe2Cu0.8C are shown in Table 5. Note that one initiation fault is considerably larger than the others. Also note that the cases where the sizes of the initiation faults are difficult to detect are combined with the highest nominal loads.

Specimen Nr	Nominal load MPa	Life cycles	Initial fault $(\mu m)^2$	Placement
11-1	210	536 778	46348	Corner
11-4	220	693 996	7058	Corner
11-6	220	737 872	7160	Corner
11-8	220	1 827 950	6319	Corner
11-10	220	1 414 920	5860	Corner
11-13	230	565 278	5606-122 56	Corner, hard to detect, possible interval
11-15	230	628454	-	Site and size cannot be detected
	Mean fault area		14549 (6599)	13,15 (1,13,15) excluded

Table 5. Results fromfractography of warm compacted Fe2Cu0.8C.

Microstructure

A few big pores characterized the pore morphology of the single as well as the double compacted materials with Cu with a size close to the largest copper particles. Most probably the largest pores are due the elementary copper particles that were melted during sintering.

Discussion

The factor test shows that the highest influence on the FEL of Fe+Cu+C PM steel is obtained from introducing 2% Cu followed by increasing the density from low to high, i.e. approx 7.15 to 7.4 g/cm^3 and increasing the carbon content from low, 0.2%, to high, 0.8%.

The FEL found for Fe2Cu0.8C double compacted to 7.38 g/cm^3 is 213 MPa with standard deviation of 10 MPa. The FEL of Fe2Cu0.8C warm compacted to density 7.23 g/cm^3 is 216 MPa, with a standard deviation of 7 MPa, i.e. slightly superior to the cold compacted material in spite of the difference in density.

The initiation faults were of about the same size as the largest copper particles. The difference in size of the initiation faults found in double cold compacted and warm compacted material respectively are most probably caused by the difference in copper particle sizes and the initiation faults also most probably are placed at the pores left after melted Cu. However, one of the initiation faults found in warm compacted material was considerably larger than the others. This fault was placed in a corner and the size corresponds to a 215x215 um2 square. No indication is available whether it is caused by an extremely big Cu particle that normally could not pass the (-100) mesh or some other reason.

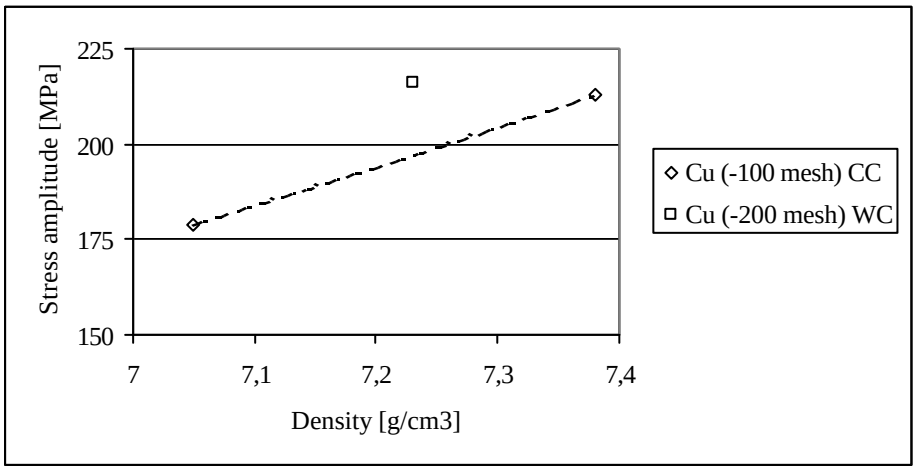


Fig. 5. Fatigue endurance limits of cold and warm compacted Fe2Cu0.8C.

The fatigue endurance limits of double cold and warm compacted material are almost the same. According to the literature, the Youngs modulus of PM steel proportional to the density raised to about 3.4. Obviously the warm compacted material accepts higher strain at the FEL as compared to the double compacted.
The results for Fe2Cu0.8C are shown in Fig. 5. The power law trendline introduced for the results of the cold compated material has the exponent 3.4 i.e. the same as the relation between density and the Youngs Modulus. The result indicates that the FEL is proportional to the Youngs Modulus. A comparison of the FEL for warm compacted material and the trendline at the same density indicates a 10% difference.
The theoretical maximum tensile stress calculated by FEM is found in the middle of the concave side of the cross section (+6%) followed by the corner (+4%). The crack initiation was in the majority of the specimens found in the corner of the cross sections. A few specimens showed initiations on the concave sides.

Conclusions

The highest influence on the high cycle fatigue performance of cold compacted F+Cu+C PM steel with Cu (-100 mesh) particles is obtained from the introduction of 2%Cu followed by increasing the density from approx 7.15 to 7.4 g/cm and increasing the carbon content from 0.2 to 0.8%.
Indications are found for the conclusion that the fatigue crack initiation starts in pores left from melted big Cu-particles.
The fatigue endurance limits of single and double compacted Fe2Cu0.8C based on Cu (-100 mesh) particles are approximately proportional to the Youngs Moduli of the materials.
Warm compacted single compacted Fe2Cu0.8C with Cu (-200 mesh) particles at the density 7.23 g/cm^3 has slightly superior fatigue performance as compared to cold double compacted Fe2Cu0.8C Cu (-100 mesh) particles at density 7.38 g/cm^3.
A comparison between warm single compacted and the trendline for cold compacted Fe2Cu0.8C indicates that the warm compacted alternative has approximately 10% higher FEL at the same density.

References

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