NEW MATERIALS FOR POWDER FORGED CONNECTING RODS

Roland Warzel III, Ian Howe, Nagarjuna Nandivada, North American Höganäs
Sven Bengtsson, Anders Bergmark, Höganäs AB

ABSTRACT

The iron-copper-carbon material system is well established in the manufacture of powder forged connecting rods. Utilizing this system takes advantage of the brittleness of the material to fracture split the large end of the connecting rod streamlining the shape and reducing the weight of the final component. Recent advancements by competing technologies have shown similar fracture splitting properties while increasing the fatigue strength. This paper explores new material systems for powder forged connecting rods which exhibit compressive yield strength and machinability properties similar to or better than the competing technologies.

INTRODUCTION

For several years, development of new powders for high performance powder forge applications has been an ongoing project at Höganäs AB. This paper is a collection of data for some of the most promising materials developed so far.

Modern materials for connecting rods have a high fatigue strength, high yield strength, good machinability and the possibility to fracture split the large end. The fracture split capability is achieved by limiting the plastic deformation in the fracture surface. This feature was first introduced for powder forged connecting rods[1]. Development of materials has subsequently facilitated this process for drop forged connecting rods using high carbon micro alloyed steel (C70S6)[2]. Micro alloyed steels (with medium carbon) for connecting rods have existed for quite some time, but they have traditionally been too ductile for fracture splitting. The connecting rods are also traditionally heat treated in order to reach the high performance required in the heavy duty segment. Recently, the development of micro alloyed steels for forging with the fracture split capability has provided a competitive edge compared to powder forged connecting rods in this segment.

Lee et al showed new forged materials with yield strength in the 760-840 MPa (110,000 – 122,000 psi) range depending on the thermal history[3]. These figures should be compared to conventional micro alloyed steel were the yield strength is in the range 520-560 MPa (75,000 – 81,000 psi). The authors claim an improvement in machinability while maintaining fracture split capability. These differences are reflected in the fatigue strength that reaches 450 (65,000 psi) and 350 MPa (51,000 psi) for the improved and conventional steels respectively.

Another forging steel development was reported by Kate et al where they compared C70S6 and conventional micro alloyed steel with a new micro alloyed steel for which ductility has been kept low to allow fracture splitting capability[4]. The proof stress and fatigue strength were increased above that of C70S6 and to the same level as the micro alloyed steel.

Ilia et al reported on an optimization of the copper and carbon contents of materials for powder forged connecting rods[5]. By increasing the copper content from 2.0 % to 3.25% and the carbon content from 0.50% to 0.57% the yield strength increased from 550 to 740 MPa (80,000 to 107,000 psi). Increasing carbon above this level severely impairs the machinability of the material. The yield strength is above C70S6 and very close to 36MnVS4 micro alloyed steel. The fatigue performance of the powder forged material is significantly better than C70S6 and even slightly better than 36MnVS4, at least in one of the conditions.

The current work is a report of an ongoing effort to develop powders for powder forged connecting rods. The goal is to increase the buckling resistance (Compressive Yield Strength, CYS) and the fatigue strength while maintaining machinability and fracture split capability.

A full set of mechanical performance information would include data from tensile tests (yield strength, ultimate tensile strength, and elongation) as well as impact and fatigue tests. Explicit investigations of tensile strength and fatigue performance are, however, not included in this study. There are two main reasons for this. In order to evaluate a number of different material alternatives, small test bars were used for hardness and CYS. This significantly reduced costs for tooling and forging. The second reason is the close relationship between tensile yield stress and CYS for isotropic materials with plastic flow controlled by the von Mises criterion and also the close relation between hardness and fatigue performance for metals with hardness less than about 400HV10 as displayed by the Murakami model.[6] Hardness and CYS are simply well suited mechanical performance data for development of materials for powder forging. Complete material properties will be evaluated from the most promising material systems. Another important issue is that the mechanical performance of connecting rods to a large extent is controlled by features introduced in the forging operation. Machined test bars from blanks will normally not show the same type of factors responsible for a fracture initiation process as connecting rods.

EXPERIMENTAL PROCEDURE

Materials

Four pre-alloyed base powders for powder forging plus the Fe-Cu-C system (as reference) are included in this investigation. Separate machinability tests were made on two of the four base powders and with Fe-Cu-C (reference).

Three of the four materials are new materials developed at Höganäs AB. The experimental materials were manufactured in the 250 kg (550 lb) laboratory atomization/annealing plant at Höganäs AB. The fourth base powder is AstaloyCrL (FL-52XX), a standard product from Höganäs AB. The pre-alloying elements in the four materials are shown in Table I below.

Table I. Pre-alloyed compositions of materials included in the investigation.

Material	Cr, %	Mn, %	Mo, %	V, %	Cu, %
FA	0.30	0.90	-	0.11	-
FB	0.26	0.56	-	-	0.25
FV	-	-	-	0.15	-
AstaloyCrL	1.50	0.15	0.20	-	-

Base powders were mixed with graphite (Asbury 1651), lubricant (Kenolube®) and Copper (AcuPowder Cu-165). In total 11 variations were investigated. The compositions are shown in Table II below. Carbon analysis was performed according to ASTM E1019 to determine the as forged carbon.

Experiments

Cylinders with a diameter of 24 mm (0.944 in) and height of 30 mm (1.18 in) were compacted at 490 MPa (71,000 psi). Sintering was conducted at 1120°C (2050°F) for 40 min in 100% H_2 (FA, FB and FL-52XX) or in 90%/10% N_2/H_2 (FV and ASC100.29) for 40 minutes. The cylinders were then removed from the furnace one by one and forged. The transfer time from the furnace to the press including forging was 8 – 10 s. After forging, the cylinders were left to cool on steel plate in air. The final dimensions of the forged cylinders were diameter 24.7 mm and height 25.3 mm.

Table II. Mixed compositions included in the investigation.

Mix ID	Base Iron	Cu-165, %	Graphite 1651, %	C Forged, %
FA-1	FA	2.1	0.60	0.52
FA-2	FA	3.3	0.60	0.53
FB-1	FB	2.3	0.60	0.53
FB-2	FB	3.5	0.60	0.56
FV-1	FV	3.0	0.58	0.57
FV-2	FV	3.0	0.68	0.66
FV-3*	FV	3.0	0.65	0.57
FL-52XX-1	Astaloy CrL ®	-	0.70	0.61
FL-52XX-2	Astaloy CrL®	-	0.80	0.71
FL-52XX-3	Astaloy CrL®	1.1	0.40	0.34
FC-0205**	ASC100.29	3.0	0.65	0.57

*Mixed also with 0.40% MnS (Höganäs AB) to improve machinability

**Reference material

Mechanical tests

Determination of the compressive yield stress was conducted according to ASTM E9 – 89A. Cylinders with a diameter of 11 mm and length of 16.5 mm were manufactured from the forged slugs for a length/diameter ratio of 1.5. Vicker hardness was measured in the core of the slugs. Two hardness scales were used: HV1 and HV10. All hardness measurements were made on full or almost full dense materials and Vicker hardness with different applied load (1 or 10 kg) will in this case show very similar figures.

Machinability tests

Seven (7) mm deep holes were drilled in the forged slugs after grinding off the decarburized surface layer. Dormer A002 diameter 3.5 mm high speed steel drills (PVD coated with TiN at the point) were used in the machinability tests. The drill point angle was 118°. A constant feed rate 0.06 mm/rev was used in all tests. Cutting velocities $V_c = \pi d \cdot n$, where n is revs/min between 27 to 143 m/min corresponding to n = 2500 to 13 000 rev/min were used. The very high cutting speeds were used with the purpose of minimizing the machinability test time.

RESULTS

CYS and HV1

Compressive yield stress and Vickers hardness of all 11 variants included in the investigation are shown in III and Figure 1. Data for 36MnVS4 are also presented. HV1 data (also converted to HRC) are included in Table III for comparison.

Table III. Vicker hardness and compressive yield stress (CYS)

Mix ID	HV1/HRC	CYS [MPa (10^3psi)]
FA-1	288 / 29	660 (96)
FA-2	333 / 33	852 (123)
FB-1	335 / 33	666 (97)
FB-2	372 / 38	882 (128)
FV-1	374 / 38	891 (129)
FV-2	401 / 42	938 (136)
FV-3	397 / 41	885 (128)
FL-52XX-1	344 / 34	902 (131)
FL-52XX-2	373 / 38	996 (144)
FL-52XX-3	373 / 38	766 (111)
FC-0205**	361 / 37	723 (105)
36MnVS4	332 / 33	820 (119)

**Reference material

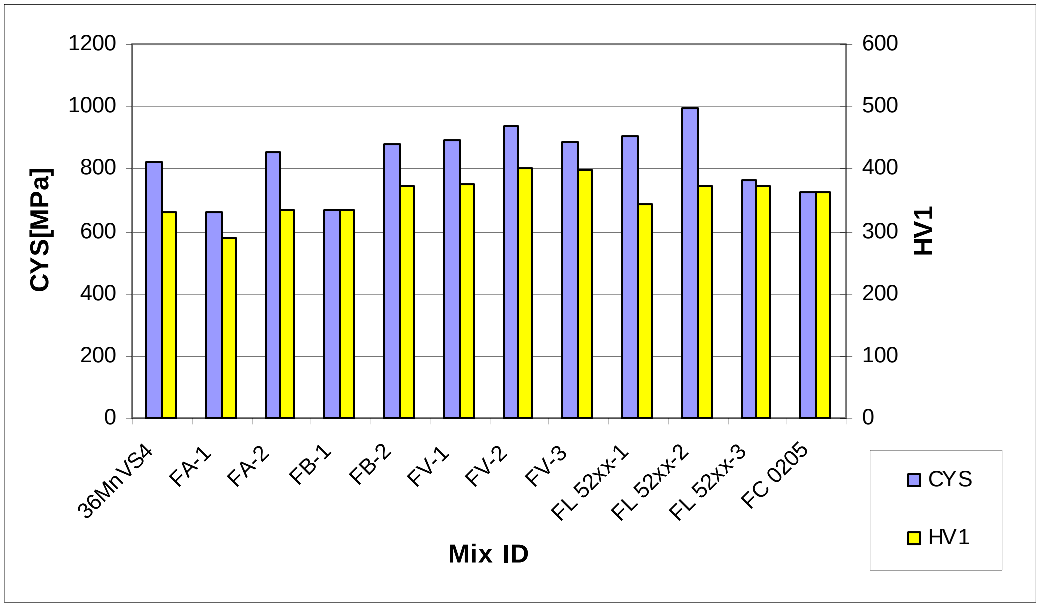

Figure 1. Compressive yield stress (CYS,) and Vicker hardness (HV1)

Metallography

A detailed characterization of the microstructures is made below.

Mix FA-2: FA + 3.3%Cu + 0.53%C

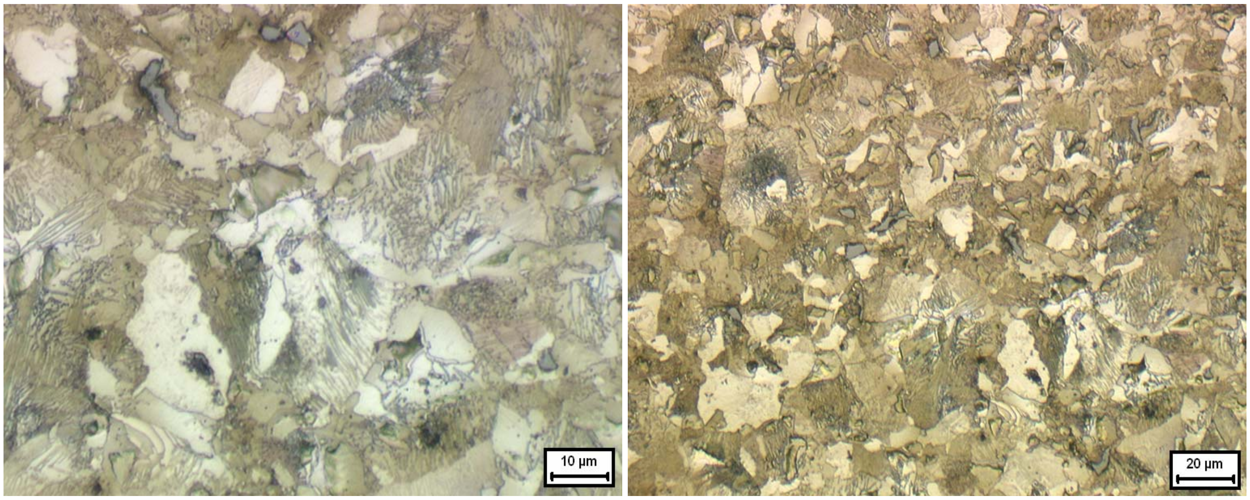

Figure 2. Mix FA-2 microstructure

The microstructure consisted of fine and coarse pearlite with about 10 – 15% ferrite. Cu-diffusion was observed in austenite grain boundaries. The typical grain size was 10 – 20 µm.

Mix FB-2: FB + 3.5%Cu + 0.56%C

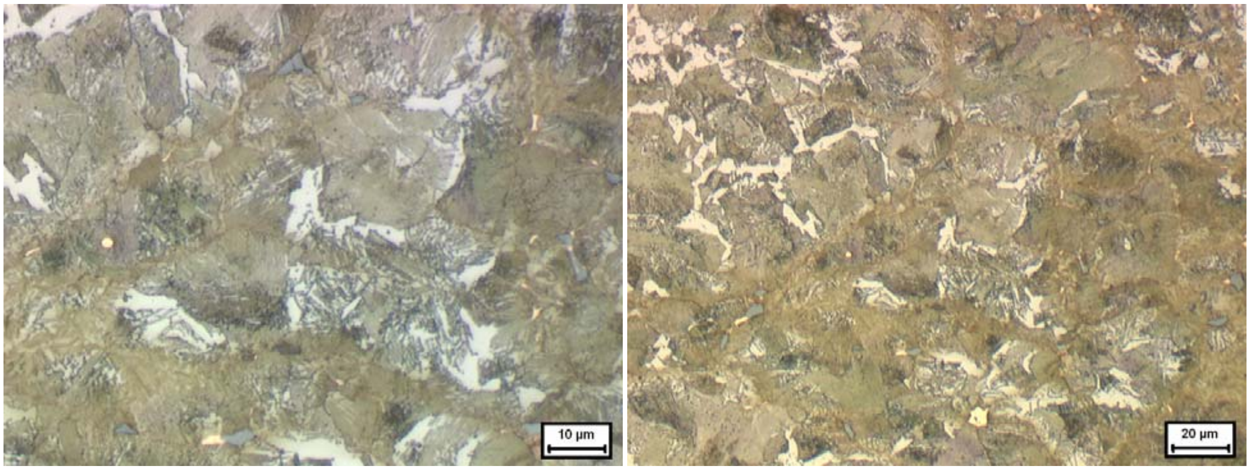

Figure 3. Mix FB-2 microstructure

The microstructure of FB-2 consisted of pearlite with a small amount of ferrite (2-3%). There was also approximately 10% martensite. A small amount of grain boundary cementite was found.

Mix FV-3: FV + 3%Cu + 0.55%C + 0.4% MnS

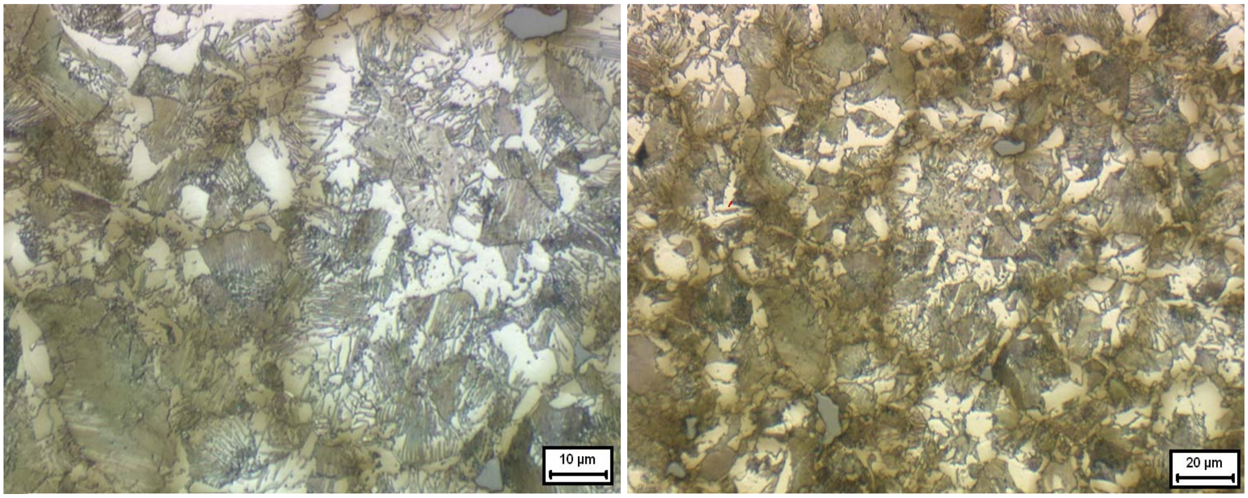

Figure 4. Mix FV-3 microstructure

The microstructure of FV-3 was a mixture of ferrite and pearlite. Brownish Cu diffusion areas were also observed. The typical grain size was 10 – 25µm.

Mix FL-52xx-1: Astaloy CrL® + 0.61%C

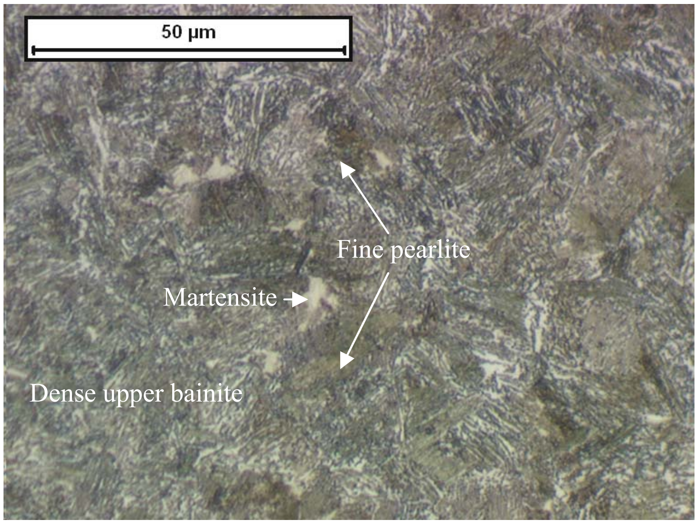

Figure 5. FL-52xx-1 microstructure

The microstructure consisted of dense upper bainite with some very fine pearlite. About 1 – 2% of martensite was also found. When the carbon content was increased carbon to 0.71% the amount of martensite increased to about 3%.

Mix FC-0205: ASC100.29 + 3%Cu + 0.57%C

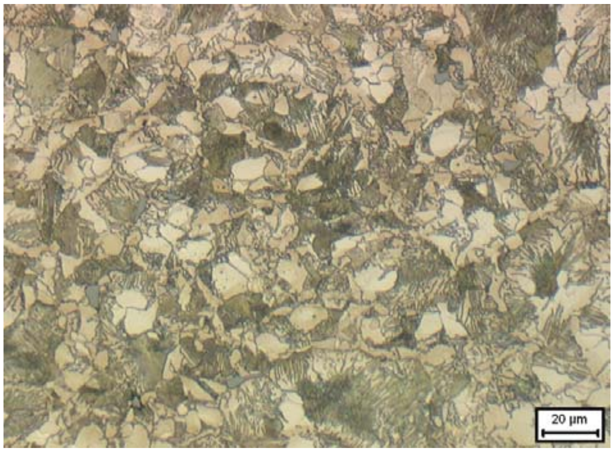

Figure 6. Mix FC-0205 microstructure

The microstructure was typical of a FC-0205 material system: fine and coarse pearlite and ferrite.

Machinability

Machinability tests have been performed on materials FA and FB with a slightly different composition of the pre-mixed alloying elements compared to the materials included in the CYS and HV1 study. The reference material in this part of the investigation is Fe-Cu-C. An overview of the materials is given in Table IV. All materials in the machinability tests were mixed with 0.32% MnS. Vicker hardness was measured with the HV10 scale.

Table IV. Overview of materials for machinability tests.

Mix ID	Base Iron	Cu, %	C,% (analyzed)	HV10 (HRC)
FA-3	FA	3.25	0.55	239 (24)
FA-4		3.25	0.63	262 (26)
FA-5		3.25	0.71	289 (29)
FB-3	FB*	3.25	0.51	295 (30)
FB-4		3.25	0.60	291 (17)
FB-5		3.25	0.70	312 (31)
FC-0205-1	AHC100.29	2.00	0.48	212 (22)
FC-0205-2		3.25	0.48	264 (26)

*FB is pre-alloyed with 0.25%Cu. Total Cu content is 3.5%

90 x 38 x 21.5 mm green parts were delubricated at 700^{o}C for 15 min followed by sintering in 90%/10% N_2/H_2 for 15 min at 1230^{o}C and then forged. The blanks had dimensions 92.5 x 39.8 x 18 mm with densities 7.74 – 7.80 g/cm^3. Note that different sintering temperatures have been used in the two studies. The cooling rate of the blanks for machinability tests is estimated to about half of the cooling of the slugs used to machine samples for CYS tests. This is displayed by the lower hardness of the machinability test blanks (compare Table III and Table IV).

Machinability tests

Holes with diameter 3.5 mm were drilled to the specified depth 7 mm. The number of holes until breakage of the drill was evaluated for different cutting speeds. The results are shown in Figure 7 and Figure 8.

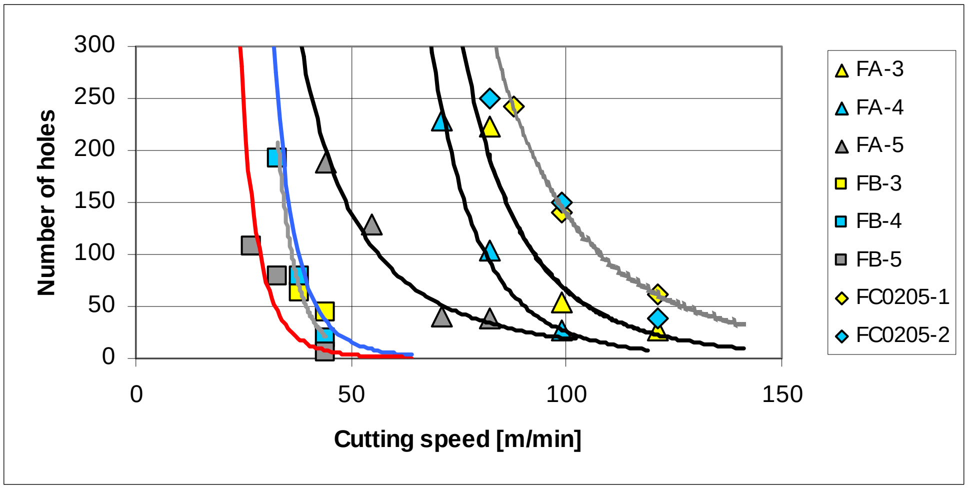

Figure 7. Results from machinability tests. Number of holes with one drill as a function of cutting speed. The powders were mixed with 0.32%MnS. Trendlines are introduced to allow easy interpretation of results. The three broken lines to the left show results for FB. The three solid lines in the middle show FA. The two FC 0205 materials show very similar results as shown by the gray rightmost line.

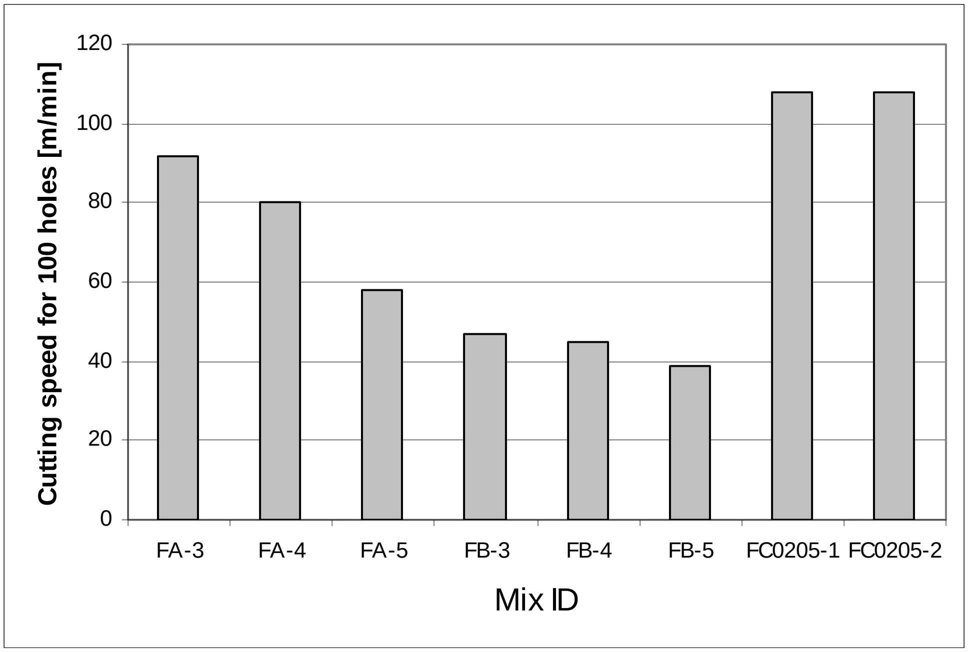

Figure 8. Results from machinability tests. Allowed cutting speed for 100 holes with one drill as estimated from the trendlines in Figure 7. The materials were mixed with 0.32%MnS

As expected, increasing the hardness of the materials (through more carbon or alloying) increased the difficulty of machining. The FB material systems had the highest apparent hardness values and were also more difficult to machine.

Hardness influence on machinability

Cutting speed for 250 holes was evaluated from Figure 7 and combined with HV10 data from Table IV. The results are presented in Figure 9. The trendline is calculated from the results for the FA and FB materials.

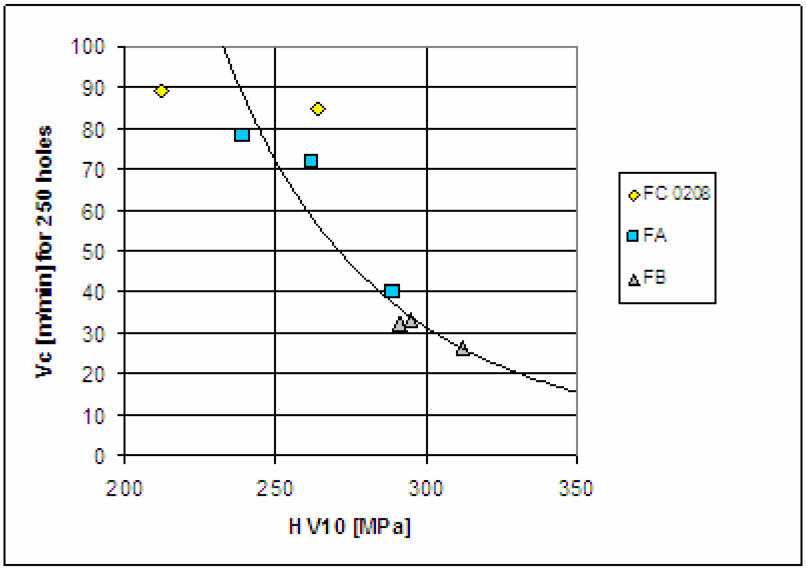

Figure 9. Cutting speed evaluated from Figure 7 as a function of HV10 for each material from Table .

Figure 9 is another presentation of the effect of apparent hardness. Increasing the hardness decreased the cutting speed required to reach 250 holes without tool breakage. At the lower hardness levels, FA was able to achieve similar cutting speeds compared to the reference Fe-Cu-C.

DISCUSSION

Materials suitable for connecting rods must match the demands for mechanical performance and also have acceptable machinability. Mechanical performance is closely related to hardness, i.e. high hardness yields high performance. Hardness has the opposite effect on machinability. High hardness normally means lower machinability. Evaluation of mechanical performance in this study was limited to hardness and CYS. Further tests will be performed on tensile and fatigue test bars as well as on real connecting rods. The reason to limit the investigation to CYS and hardness was twofold. Firstly, there is a strong relation between hardness and fatigue performance as displayed by the Murakami model[6] and between CYS and regular yield stress (isotropic materials) obtained from tensile test. The second reason is that many materials were able to be included in the scanning investigations. Most of the investigated materials show very high mechanical performance based on CYS and hardness data. Of the 11 investigated variations, 7 show higher compressive yield stress than 36MnVS4. All of the materials show higher CYS and HV1 compared to the reference material (Fe + 3.0%Cu + 0.57%C).

Results from the machinability tests on three materials, two newly developed materials FA and FB and with Fe + 3.25%Cu + 0.55%C as reference, show the highest machinability for the reference material. For

FA + 3.25%Cu + 0.55C, 15% lower machinability was achieved compared to the reference material with about the same carbon and Cu addition. The lowest machinability was found for the FB material. The difference in machinability between these three materials was strongly dependent on the different hardness values achieved. This was shown in Figure 9.

All materials included in this investigation are considered as strong candidates for powder forging. A small adjustment must be made to optimize the balance between mechanical performance and machinability. The optimization is a fine tuning process where cooling rate and graphite addition are the important parameters (cooling rate is more or less a given by the setup of the connecting rod powder forging process). Base material and carbon level shall be chosen to get a robust CCT diagram so fine pearlite or dense bainite microstructure is obtained. All material variants included in this presentation are considered to meet this goal.

FUTURE WORK

To complete the evaluation on material FV, machinability studies will be completed. Unfortunately they were not completed in time for publication. A full mechanical property evaluation (tensile properties, impact properties and fatigue properties) will be completed.

CONCLUSIONS

1. The three new materials developed are strong candidates for high performance powder forging applications. Of the 11 variations examined, 7 were able to out perform the 36MnVS4 alloy.

2. Microstructures consisting of predominately pearlite were achieved for materials FA, FB, and FV. The microstructure closest to the reference Fe-Cu-C system was found with material FV.

3. Slightly lower machinability was observed for material FA compared to the reference Fe-Cu-C material system. A balance of performance and machinability will need to be explored in the future.

REFERENCES

[1] M Weber, “Cost effective Finishing of Powder Forged Connecting Rods with the Fracture-Splitting Method”, *SAE Tech paper 910157, 1991*

[2] M A Olaniran and C A Stickels, “Separation of Forged Steel Connecting Rods and Caps by Fracture Splitting”, *SAE International Congress and Exposition, Detroit, Michigan, March 1-5, 1993. , 930033, (1993)*

[3] C K Lee, Y S Ko, S H Kim, H S Park and J D Lim, “Development of High Strength, Fracture Split Steel Connecting Rods”, *SAE 2007 World Congress, Detroit, Michigan, April 16-19, 2007. , 2007-01-1002, (2007)*

[4] S Kato, T Kano, M Hobo, Y Yamada, T Miyazawa and Y Okada, “Development of Microalloyed Steel for Fracture Split Connecting Rod”, *SAE 2007 World Congress, Detroit, Michigan, April 16-19, 2007. , 2007-01-1004, (2007)*

[5] E Ilia, K Tutton, M O’Neill, G Lanni and S Letourneau, “New Improvements in Materials Used to Manufacture Powder Forged Connecting Rods”, *SAE 2007 World Congress, Detroit, Michigan, April 16-19, 2007. , 2007-01-1556, (2007)*

[6] Y Murakami, *Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions,* Elsevier 2002