DYNAMIC PROPERTIES OF LEAN DIFFUSION ALLOY STEEL

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ABSTRACT

Diffusion alloyed steels are known worldwide for their robustness and mechanical property performance. These alloys contain significant amounts of nickel, copper, and molybdenum. However, for heat treated applications, this level of alloying is not necessary for most applications. A newly developed lean diffusion alloy steel, D.AQ, was introduced and shown to have similar static properties to common powder metal (PM) material systems in the heat treated condition. In this paper, the dynamic properties of D.AQ will be compared to common PM heat treat alloy systems using standard test specimens and gears.

INTRODUCTION

One of the advantages of powder metallurgy (PM) is the ability to customize the alloy system by utilizing different powders. The earliest PM material systems consisted of different elemental powders (Fe, Cu, Ni, etc.) being dry blended with graphite and lubricant. While these material systems are still very popular today, they are susceptible to segregation of the alloying elements. Differences in particle shape, size, density and morphology allow the different particles to segregate. Great care must be taken with regards to material handling to minimize the amount of particle segregation that occurs. Often times the alloying elements do not sufficiently alloy during sintering and the resultant properties are not sufficient for high performance components.[1]

One method to eliminate the segregation of alloying elements is to utilize a prealloyed powder. By adding the alloying elements during the melt stage of the powder manufacturing process and then atomizing, the alloying elements are evenly distributed throughout the powder particle. This results in a very uniform microstructure and high performance properties while eliminating the issue of segregation of alloying elements. While segregation is eliminated, the compressibility of the powder is severely impacted. Prealloyed powders typically are not able to reach high densities in single press – single sinter operation without using a special manufacturing technique such as warm compaction.

Diffusion alloyed materials were introduced in order to provide segregation free materials with good compressibility. Diffusion alloying consists of adding fine elemental powders to a compressible base iron. This mix then undergoes a secondary thermal process in which the alloying elements are metallurgically bonded to the base iron. By bonding the alloying elements to the surface of the base iron particle, the chance for segregation is eliminated. The incomplete diffusing of the alloying elements into the iron particle, the compressibility of the iron particle is preserved. Studies have shown that diffusion alloyed materials provide sufficient mechanical strength and fatigue performance to be utilized in high performance applications.[1,2]

The current diffusion alloys available in the market are highly alloyed. Large amounts of nickel, copper and molybdenum have been used to manufacture these alloys. A lean diffusion alloy material was recently introduced to complete the diffusion alloy composition portfolio.[3] This material is intended for heat treated applications where the amount of alloying present in the current FD-0205 and FD-0405 isn't necessary to achieve similar properties. The previous work showed the new alloy could achieve similar mechanical properties compared to the FD-0405 and other prealloyed material systems in the heat treated condition. While tensile properties are important for design purposes, most applications are subjected to cyclical loading which necessitates an understanding of the fatigue performance of a material.

The current work focuses on understanding the complete mechanical performance of the new alloy over a variety of carbon contents. The fatigue performance of the new alloy was also investigated on both test bars and prototype gears. The combination of tensile strength and fatigue performance in the heat treated condition make this alloy interesting for gear applications. The results of these investigations show the lean diffusion alloy to have similar performance levels to more heavily alloyed diffusion alloyed materials.

EXPERIMENTAL PROCEDURE

Powders and Materials

The newly developed diffusion alloy, D.AQ, uses low levels of nickel and molybdenum for alloying. The nickel and molybdenum are diffusion alloyed to a compressible iron particle (ASC100.29) using established diffusion alloying techniques. The chemical composition of the new alloy is shown in Table 1.

Table 1. Nominal Chemical Composition of Alloy (wt%)

Base Iron	Nickel (%Ni)	Molybdenum (% Mo)
D.AQ	0.5	0.5

The effect of carbon content on the mechanical properties was evaluated. Natural graphite (SW-1651, Asbury) and Intralube® E (Höganäs AB) were used in the manufacture of the mixes. Mix compositions are shown in Table 2.

Table 2. Nominal Mix Compositions (wt%)

Mix ID	Base Iron	Graphite	Lubricant
1	D.AQ	0.5	0.6
2	D.AQ	0.6	0.6
3	D.AQ	0.8	0.6
FD-0205	D.AB	0.6	0.6
FD-0405	D.AE	0.6	0.6

Sample Preparation

For Mixes 1 through 3, tensile (MPIF Std. 10) and impact specimens (MPIF Std. 40) were compacted to achieve sintered densities of 6.80, 7.00, 7.10 & 7.25 g/cm^3 on a 60 ton Gasbarre hydraulic compaction press. Warm die compaction (tool temperature 60 °C) was used to compact the specimens for the 7.25 g/cm^3 density level. Plane bending fatigue specimens were compacted from Mix 2 and the FD-0205 to green densities of 7.10 & 7.25 g/cm^3.

In addition to the test specimens, gears were compacted from Mix 2, FD-0205, and FD-0405 to a green density of 7.10 g/cm^3. The gear parameters are shown in Table 3.

Table 3. Gear Parameters

Parameter	Gear Spec.
Outer Diameter (mm)	32
Inner Diameter (mm)	15
Teeth	18
Face width (mm)	10
Module (mm)	1.5875
Pressure angle (°)	20

Sintering

The specimens were sintered on a mesh belt furnace with a conventional cooling rate. The sintering parameters are listed in Table 4.

Table 4. Sintering Parameters

Parameter	Value
Sintering Temperature	1120 °C
Time at Temperature	30 minutes
Atmosphere	90/10 N_2 / H_2
Cooling Rate	0.5 °C/s

Heat Treatment

The specimens were then neutral hardened according the parameters listed in Table 5.

Table 5. Heat Treatment Parameters

Parameter	Value
Type	Batch
Temperature	920°C
Carbon Potential	0.5, 0.6, 0.8%
Soak Time	20 minutes
Atmosphere	Endothermic
Quenching	Oil (60°C)
Tempering	200°C, 1 hour, air

Testing

Carbon content of the as heat treated parts was determined using infrared combustion techniques according to ASTM E1019. The apparent hardness was measured on the impact specimens according to MPIF Standard 43. Sintered density was determined using MPIF Standard 42. Tensile and impact energy was evaluated according to ASTM E8-09 and ASTM E23-07 respectively. Plane bending fatigue was tested on ISO3928 test bars with R= -1 and a run out limit of 2 x 10^6 cycles. Evaluation of the fatigue data was performed according to MPIF Standard 56.

Tooth root bending fatigue was performed on HB gears with stresses evaluated according to ISO 6336 / DIN 3990. A schematic of the testing is shown in Figure 1.

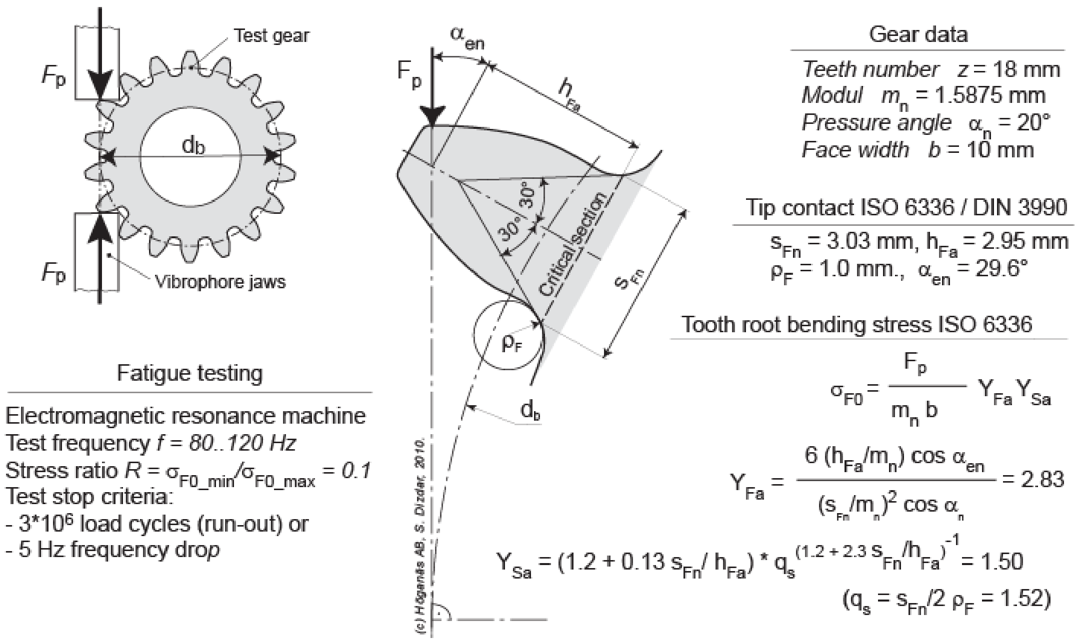

Figure 1. Tooth Root Bending Fatigue Schematic

RESULTS

Microstructure

The microstructure photographs are shown in Figure 2. The pictures shown are from the 7.00 g/cm^3 density level.

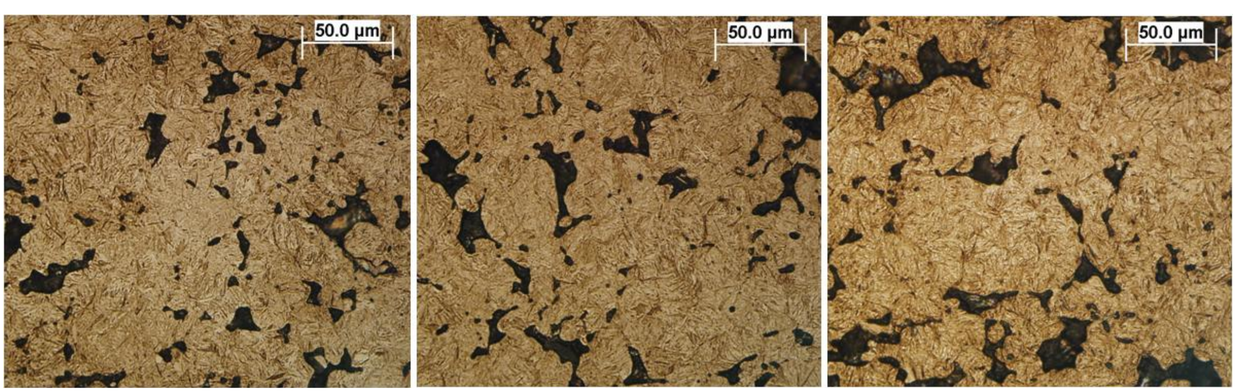

Figure 2. Microstructure Photographs (Left to Right: Mix 1, 2, & 3)

A completely martensitic microstructure was observed for all conditions. One item of note is the lack of large nickel rich austenite. Typical diffusion alloyed materials will still contain large islands of nickel stabilized austenite in the heat treated condition.

The microindentation hardness measurements for the different mixes in the heat treated condition are shown in Table 6. The measurements were performed on the 7.00 g/cm^3 specimens.

Table 6. Micoindentation Hardness Measurement

Mix ID	%C	$HV_{0.1}$
1	0.55	653
2	0.61	692
3	0.76	749

The microindentation hardness measurements were typical of a martensitic microstructure. As expected, increasing the carbon content of the material increased the microindentation hardness. At the highest carbon level, the microindentation hardness was 749 $HV_{0.1}$. This high microindentation hardness will result in lower performance for tensile and impact strength.

Mechanical Properties

The apparent hardness measurements of the impact specimens are shown in Figure 3. As expected, increasing the carbon content and density led to an increase in hardness. Hardness levels greater than 40 HRC were achieved at the highest carbon content level.

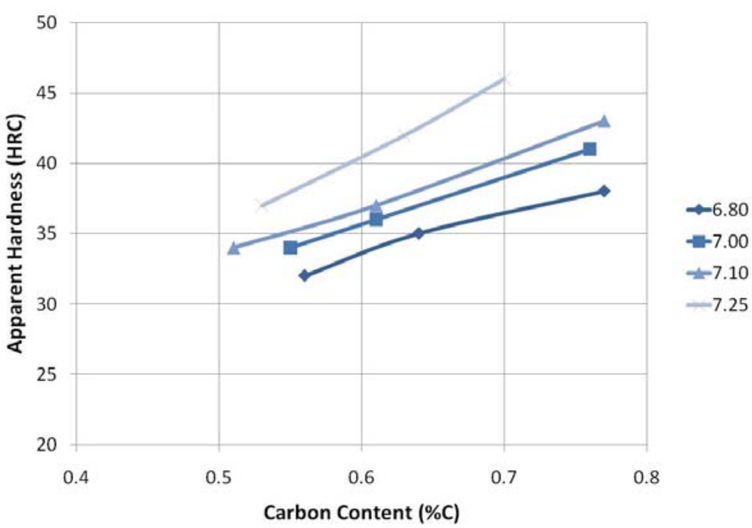

Figure 3. Apparent Hardness of D.AQ as heat treated

Tensile strength of the as heat treated materials are plotted against the as heat treated carbon contents.

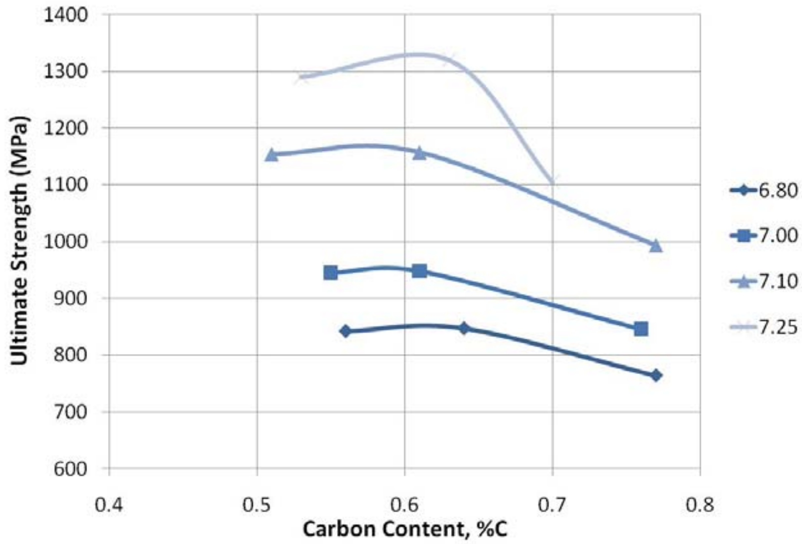

Figure 4. Tensile strength of D.AQ as heat treated

The results of the tensile testing show that maximum strength is achieved at a carbon content of between 0.5% and 0.6%. At the highest density, the tensile strength drops off rapidly once the carbon content starts to approach 0.7%. It is thought that this is a result of the brittleness of the material at this carbon level. The microindentation hardness levels show an extremely hard microstructure.

The results of the impact testing are shown in Figure 5.

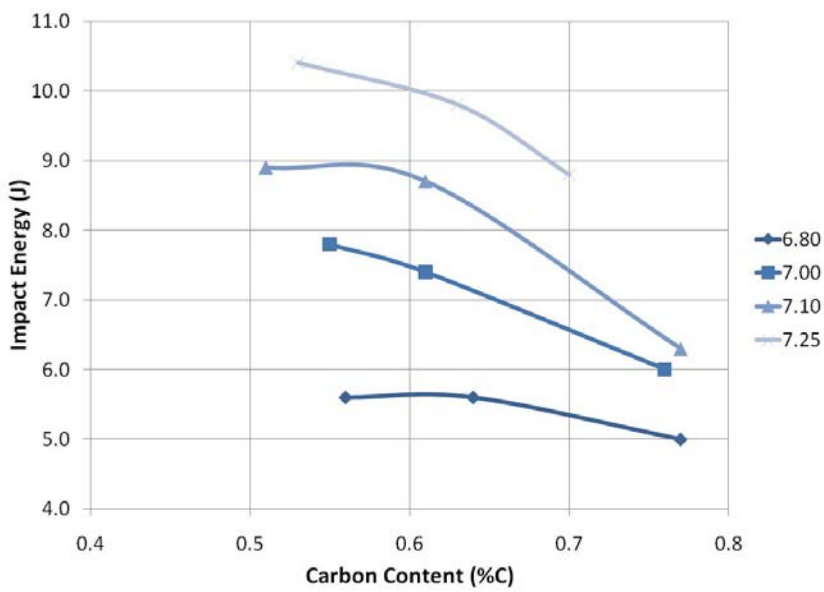

Figure 5. Impact of D.AQ as heat treated

The fatigue strength of Mix 2 in the through hardened condition is presented in Table 7. For reference, test bars from a FD-0205 were processed in the same condition as Mix 2 and were tested. The density of the fatigue specimens is listed.

Table 7. Plane bending fatigue

Material	Density	s50 (MPa)	s (MPa)	s90 (MPa)
Mix 2	7.16	381	16	358
Mix 2	7.29	339	< 10	325
FD-0205	7.13	341	16	319
FD-0205	7.25	356	30	315

Mix 2 showed the same fatigue performance as the FD-0205 in the heat treated condition. The S-N curves for the testing are shown in Figures 6 and 7.

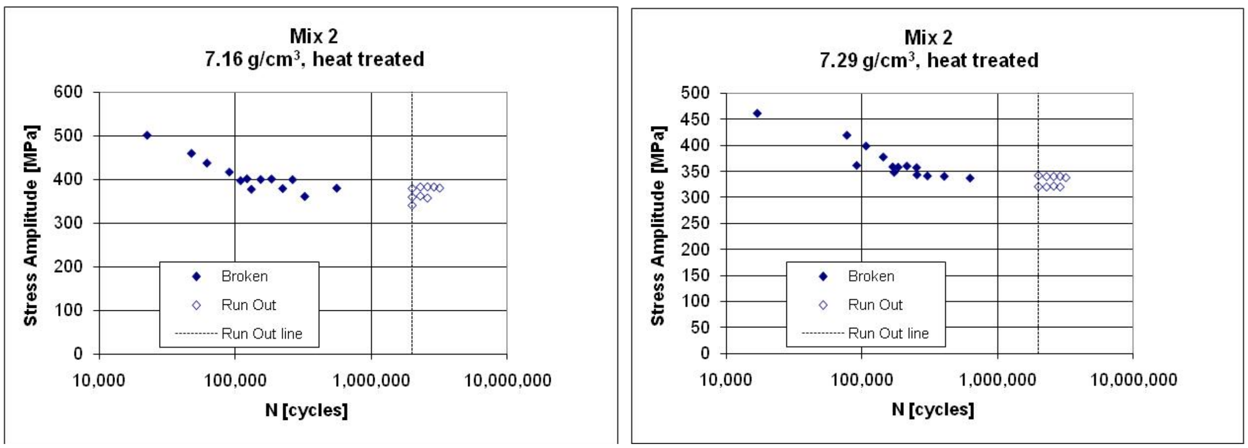

Figure 6. S-N curves for Mix 2

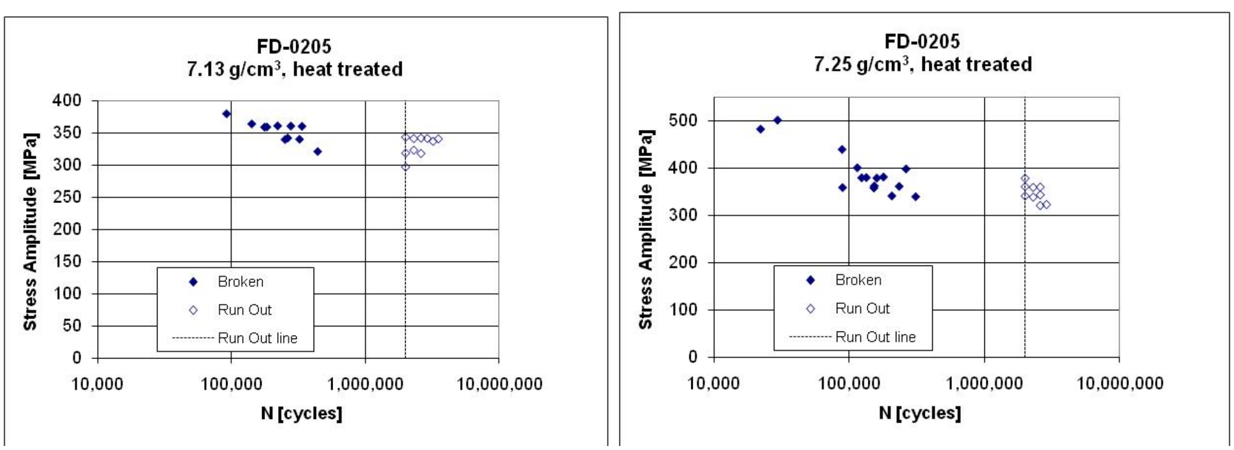

Figure 7. S-N curves for FD-0205

Typical S-N curves were observed for both D.AQ and the FD-0205 material. The D.AQ material showed an anomaly at the highest density level. The fatigue limit at this level was lower than at the lower density. Typically, as density level increases the fatigue limit also increases. At the time of publication, this reason for this has not been determined. It is thought differences in residual stresses could be the root cause. However, the testing shows D.AQ to have similar fatigue performance compared to the FD-0205 material system.

Gear Tooth Root Bending Results

Tooth root bending fatigue tests were performed on the prototype gear described in Table 3. The endurance limit was evaluated in 10 to 12 points using stair-case method by Dixon and Mood.[4] The SN curve slope in the limited fatigue life region was evaluated by testing at two load levels where 10%, 50%, and 90% survival probability was estimated according lognormal statistic distribution. The obtained data is listed in Table 8. The SN curves for each material are shown in Figure 8.

Table 8. Gear Tooth Root Bending Fatigue Results

Mix	σ_{10} MPa	σ_{50} MPa	σ_{90} MPa
D.AQ + 0.6%C	625	590	554
FD-0205	775	681	587
FD-0405	646	575	503

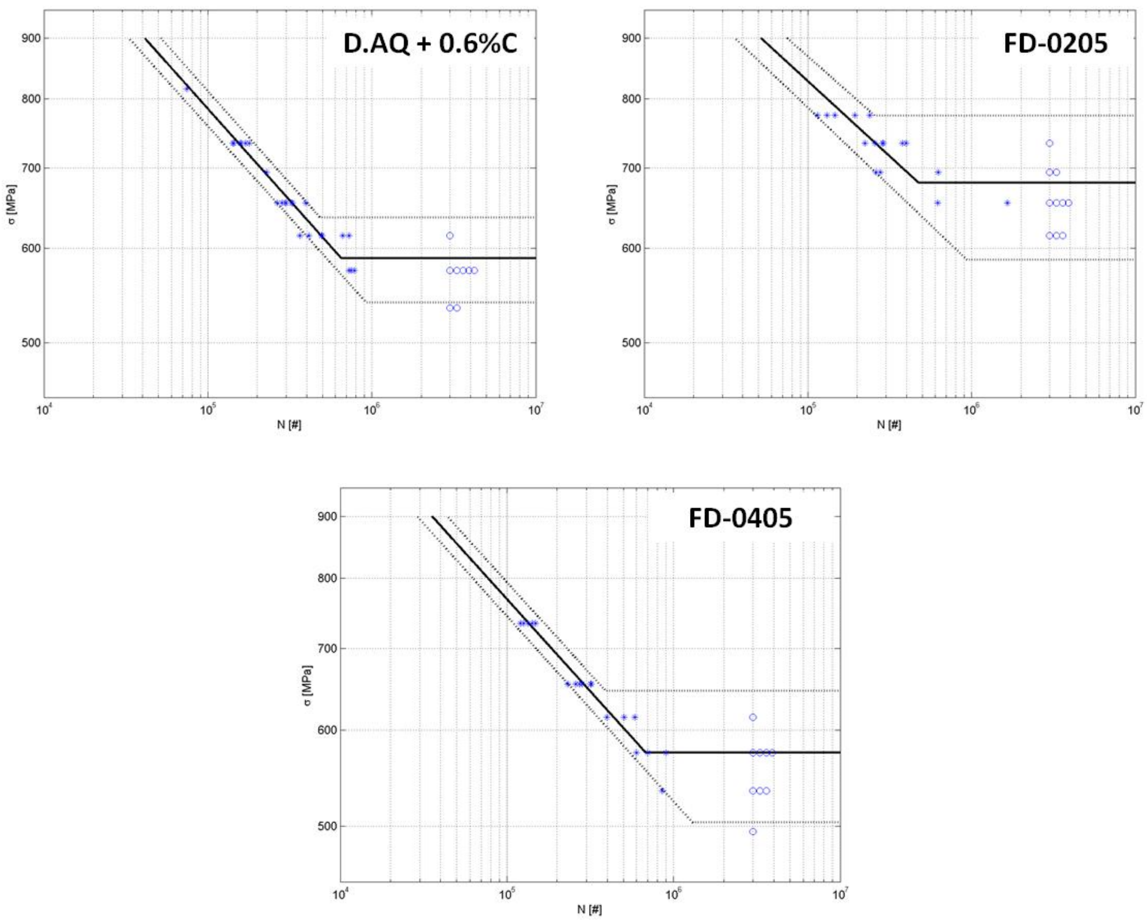

Figure 8. Gear Tooth Bending Fatigue SN Curves for Tested Material Systems

The gear tooth root bending fatigue results show the lean diffusion alloy material to be comparable to more highly alloyed FD-0405 and very close to the FD-0205. Gear tooth root bending fatigue limits of over 550 MPa were achieved using D.AQ.

CONCLUSIONS

The following conclusions can be drawn from this study:

- The optimum carbon content for D.AQ is between 0.5% and 0.6%. At this carbon level the highest tensile strengths were achieved. Tensile strengths of 800 MPa – 1300 MPa were achieved depending on the density level.

- The plane bending fatigue testing showed D.AQ to be similar to the more highly alloyed FD-0205 material system in the heat treated condition. A plane bending fatigue limit of 358 MPa was achieved at a density of 7.16 g/cm^3.

- The tooth root bending fatigue limit of D.AQ was slightly lower than the FD-0205 material system (554 MPa vs. 587 MPa). The new alloy however was found to have a higher tooth root bending fatigue limit compared to the FD-0405 material system (554 MPa vs. 503 MPa).

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FUTURE WORK

This work focused on using D.AQ in the through hardened condition. Based on the fatigue results, the case carburization of this material may be interesting to take advantage of the alloying to have a high surface hardness and ductile core. Fatigue and gear testing in the area is currently under development.

REFERENCES

1. H. Sanderow and T. Prucher, “Mechanical Properties of Diffusion Alloyed Steels: Effect of Material and Processing Variable”, *Advances in Powder Metallurgy and Particulate Materials,* compiled by C. Lall and A. Neupaver, Metal Powder Industries Federation, Princeton, NJ, 1994, Vol. 7, pp. 341 – 354.
2. U. Engström, B. Johansson, et al, “Properties of Diffusion Bonded Alloys Processed to High Densities”, *Advances in Powder Metallurgy and Particulate Materials,* compiled by M. Phillips and J. Porter, Metal Powder Industries Federation, Princeton, NJ, 1995, Part 10, pp. 77 – 95.
3. R. Warzel III, R. Frykholm, et al, “Lean Diffusion Alloyed Steel for Heat Treat Application”, *Advances in Powder Metallurgy and Particulate Materials*, compiled by M. Bulger and B. Stebick, Metal Powder Industries Federation, Princeton, NJ, 2010, Part. 7, pp. 30 – 43.
4. J. Dixon and A.M. Mood, “A Method for Obtaining and Analyzing Sensitive Data”, *Journal of the American Statistical Association,* 1943, pp. 109 – 126.