COMPARISON OF COST EFFECTIVE Cr-Ni STEEL WITH COMMON HIGH PERFORMANCE POWDER METAL (PM) STEELS

Alex Klekovkin and Roland T. Warzel III
North American Höganäs
Hollsopple, PA 15935

Sven Bengtsson and Senad Dizdar
Höganäs, AB
Hoganas, Sweden

ABSTRACT

In order to achieve high performance, the powder metal (PM) industry has relied upon alloys containing high amounts of nickel and molybdenum. Recent volatility in the price of metals has spurred the development of leaner alloys. A newly developed chromium – nickel steel has been shown to provide exceptional mechanical properties. In this paper, the properties achievable with the newly developed steel will be compared against common PM material systems. Static and dynamic properties will be compared using both test bars and components.

INTRODUCTION

As the powder metal (PM) market expands, new material systems will be required to meet the requirements of more demanding applications. Past practices have focused on increasing the alloying content of a material system to increase its performance.[1] While this method works, increasing pressure in metals prices has made these high performance alloys less attractive.[2] With this in mind, recent alloy development has focused on materials with lean alloy content.[3]

The excellent heat treated properties of a new developed prealloyed steel – Astaloy^{TM} CMN have been presented in recent years.[4,5] The properties reported have shown the possibility to use the new alloy in highly loaded / stressed applications. The alloying content still relies on the traditional alloying elements of molybdenum and nickel although at much lower levels. The ability to lean out the traditional elements is achieved by using chromium. Chromium has high hardenability and a much lower raw material cost compared to nickel and molybdenum.[6,7] The alloy combination provides a cost effective alloy with sufficient hardenability to achieve the desired static and dynamic properties for high performance applications.

The purpose of this paper is to demonstrate the static and dynamic properties achievable with Astaloy^{TM} CMN. These properties are compared against those of other common PM material systems.

EXPERIMENTAL PROCEDURE

Materials

Three commercially available base irons were chosen to compare against Astaloy CMN. The chemistry of the base irons is shown in Table 1. All of the base irons investigated were water atomized. Both Astaloy CMN and Astaloy 85Mo are pre-alloyed base irons while D.AE is a diffusion alloyed base iron.

Table 1: Chemical Composition of Base Irons Evaluated (wt %)

Base Iron	Fe	Cr	Mo	Ni	Mn	Cu
Astaloy CMN	Balance	0.50	0.10	0.50	0.2	-
Astaloy 85 Mo	Balance	-	0.85	-	-	-
ASC100.29	Balance	-	-	-	-	-
D.AE	Balance	-	0.50	4.0	-	1.50

The base irons were mixed with natural graphite (Graphite SW-1651, Asbury), nickel (Type 123, Inco) and lubricant (Kenolube, Höganäs AB) to manufacture the material systems shown in Table 2.

Table 2: Material Compositions Investigated

Material ID	Base Iron	Mix composition			
		MPIF	Graphite	Ni	Kenolube
A	Astaloy CMN	-	0.25%	–	0.6%
B	Astaloy 85Mo	FL-4400	0.25%	–	0.6%
C	ASC	FN-0200	0.25%	2%	0.6%
D	D.AE	FD-0400	0.25%	–	0.6%

Sample preparation

The test specimens were prepared from each mix according to MPIF Standards: Standard 41 – Transverse Rupture Strength (TRS); Standard 10 – Tensile Strength (TS) and Standard 40 – Charpy Impact Energy (IE).[8] Conventional compaction was used in order to obtain a green density of 7.1 g/cm^3.

In addition to test bars, gears were compacted for case carburization and tooth bending fatigue. The gear (Figure 1) parameters are shown in Table 3. Gears from Material A and Material B were warm die compacted to a green density of 7.3 g/cm^3 using 0.5% Intralube® E (Höganäs AB) as the lubricant.

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

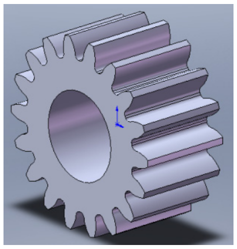


Figure 1. Gear for case-carburization.

Sintering

The test specimens and gears were sintered in a nitrogen-hydrogen atmosphere with normal cooling rate on a mesh belt furnace. The sintering parameters are listed in Table 4.

Table 4: Sintering Conditions

Furnace type	Mesh belt
Temperature	1121 °C (2050 °F)
Atmosphere	90%N_2 / 10%H_2
Time at temperature	30 min
Cooling rate	0.5 °C/s (1.0 °F/s)

Heat Treatment

Heat treatment of all test specimens and gears was performed at Pennsylvania Industrial Heat Treaters (St. Mary's, Pennsylvania) based on parameters described in Table 5. After CQT the gears were subjected to a gentle tumbling operation to remove any burrs.

Table 5: Heat Treating Parameters

Parameters	**Test bars**	**Gears**
	Case hardening	**Case hardening**
Type	Batch	Batch
Temperature	899 °C (1650 °F)	899 °C (1650 °F)
Carbon potential	0.8 %C	0.8 %C
Soak time	1 min	6 min
Atmosphere	Endothermic gas	
Quenching	Oil 60 °C (140 °F)	
Tempering	177 °C (350 °F) for 1 hour	

Testing

Carbon and oxygen contents were determined using infrared combustion techniques according to ASTM E1019.[9] Dimensional change was tested on TRS bars after heat treatment according to MPIF standard 44.[8] Apparent hardness, transverse rupture strength, tensile strength and impact energy were evaluated as heat treated per MPIF standards 10, 43, 44 and 40.[8] Determination of effective case depth was performed according to MPIF standard 52.[8] Tooth root bending fatigue testing was performed according to ISO 6336/DIN3990.[10]

Figure 2 shows a schematic of the prototype spur gear, testing details and calculation of tooth root bending stress.

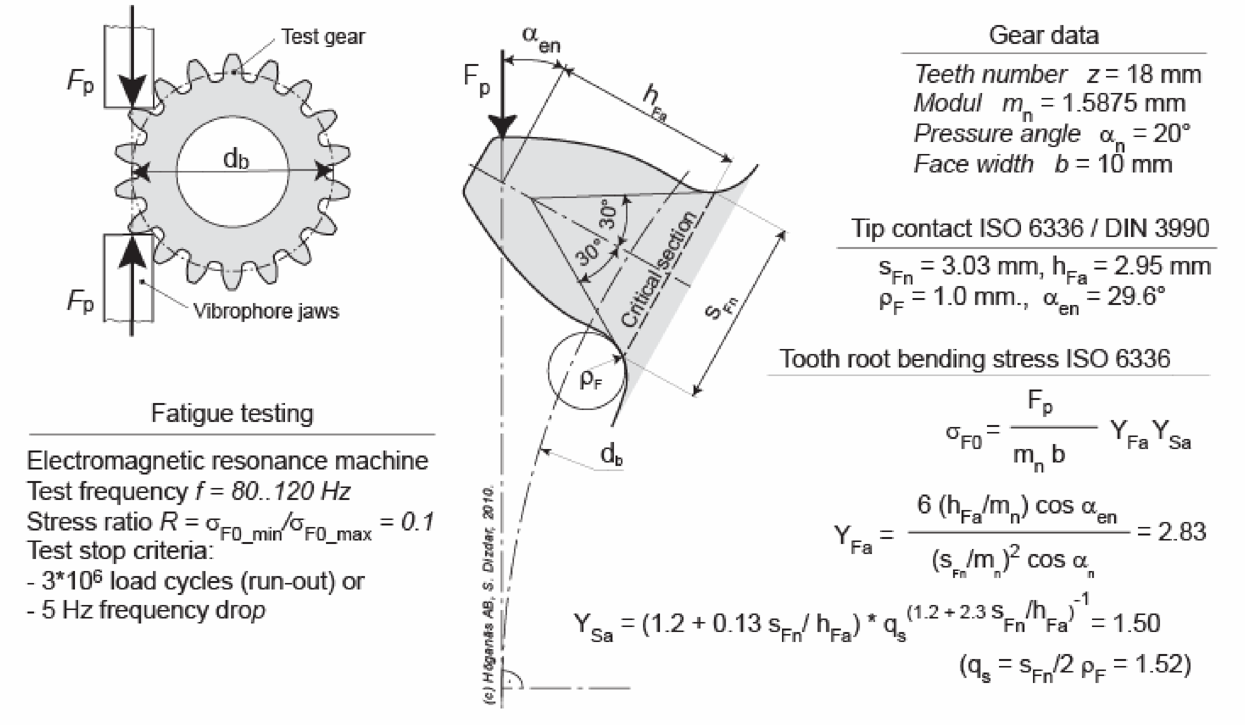


Figure 2. Gear for case-carburization.

Metallography

Metallographic investigations were carried out on the as heat treated specimens and gears. The polishing procedures and equipment are listed in Table 6. Struers (Copenhagen, Denmark) equipment and consumables were utilized in the preparation of the specimens. The etchants used for each material are listed in Table 7.

Table 6: Heat Treated Metallographic Steps/ Equipment

Step	Equipment	Wheel / Pad	Media
Cutting	Discotom-5	60A25 Cutoff Wheel	Water Coolant
Mounting	LaboPress-3	N/A	N/A
Grinding	Abraplan	Aluminum Oxide Stone	Water Coolant
Fine Grinding	RotoForce-4 / RotoPol-22	MD Allegro Pad	9 µm Diamond Dosing
Polishing 3 µm	RotoForce-4 / RotoPol-22	MD MOL Pad	3 µm Diamond Dosing
Polishing 1 µm	RotoForce-4 / RotoPol-22	MD NAP Pad	1 µm Diamond Dosing

Table 7: Etchant Selection

Material	Etchant
A	1% Nital / Picral
B	1% Nital
C	1% Nital / Picral
D	2% Picral

RESULTS AND DISCUSSION

Carbon and Oxygen

Carbon (includes case and core), oxygen and nitrogen contents after heat-treatment are shown in Table 8.

Table 8: Carbon and Oxygen after Heat-Treatment

Materials	C, %	O_2, %	N_2, %
A	0.26	0.07	0.01
B	0.25	0.04	0.01
C	0.23	0.04	0.01
D	0.24	0.03	0.01

The oxygen contents in all cases are typical for heat treated PM alloys.

Apparent Hardness and Impact Energy

Figure 3 shows the apparent hardness of TRS bars and unnotched impact energy for all materials after heat treatment. The apparent hardness was similar for all specimens.

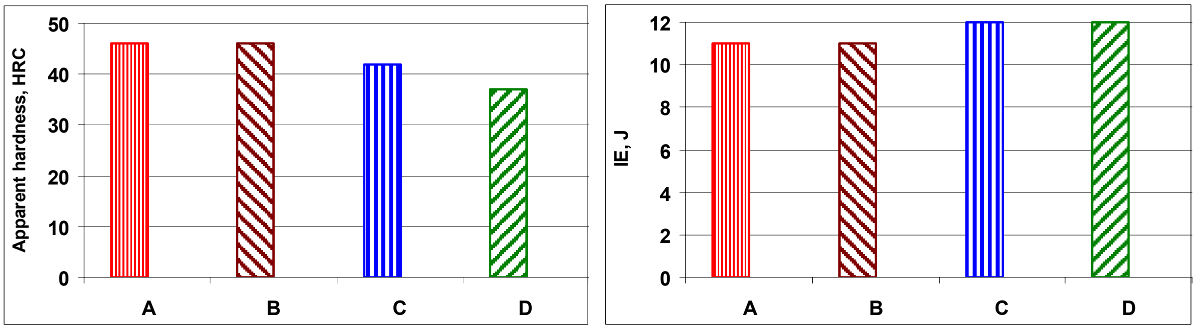


Figure 3. Hardness and impact energy of materials A, B, C and D in the heat treated condition.

After case carburization the highest apparent hardness value observed for Materials A and B. This is expected due to the alloying elements being pre-alloyed and the lack of nickel rich "soft spots". These nickel rich spots, however, contribute to the higher impact performance observed in Materials C and D.

Transverse Rupture and Tensile Strength

Figure 4 shows the transverse rupture strengths and tensile strengths of heat treated materials.

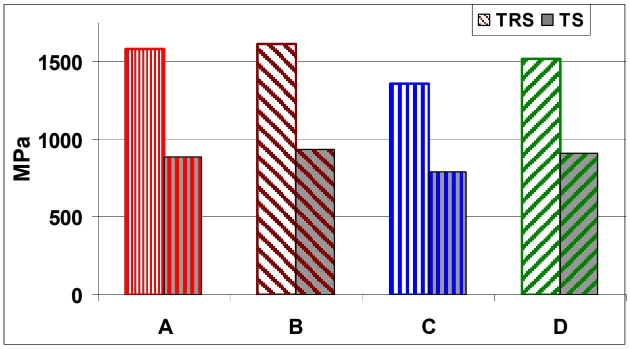


Figure 4. Transverse rupture strengths and tensile strengths of heat treated materials A, B, C and D.

The pre-alloyed materials show the highest tensile and transverse rupture strength.

Microstructures

An unetched microstructure of Material A after heat treatment is shown in Figure 5. This microstructure is typical for the other materials.

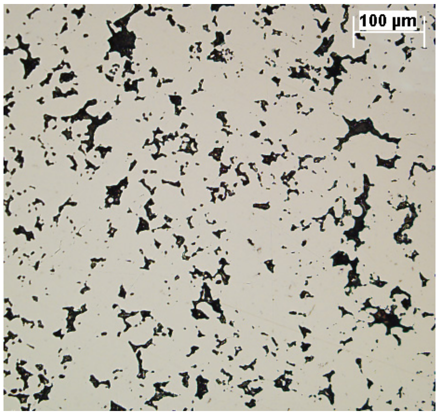
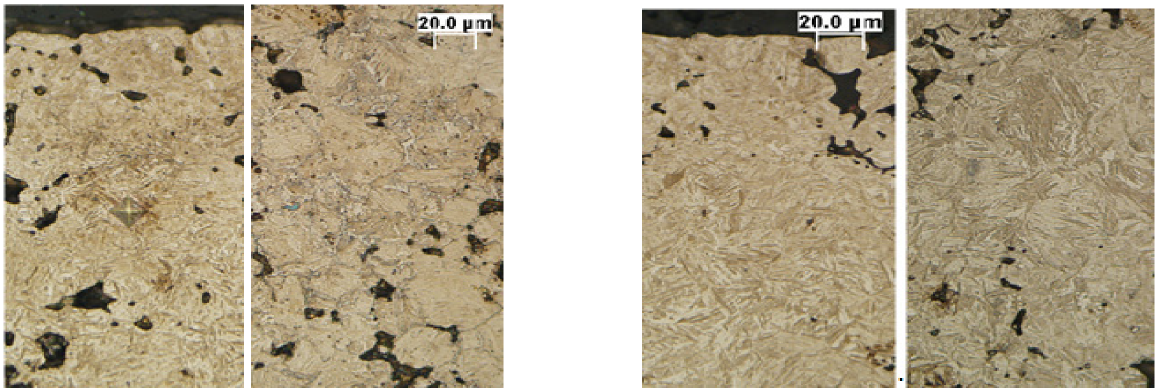
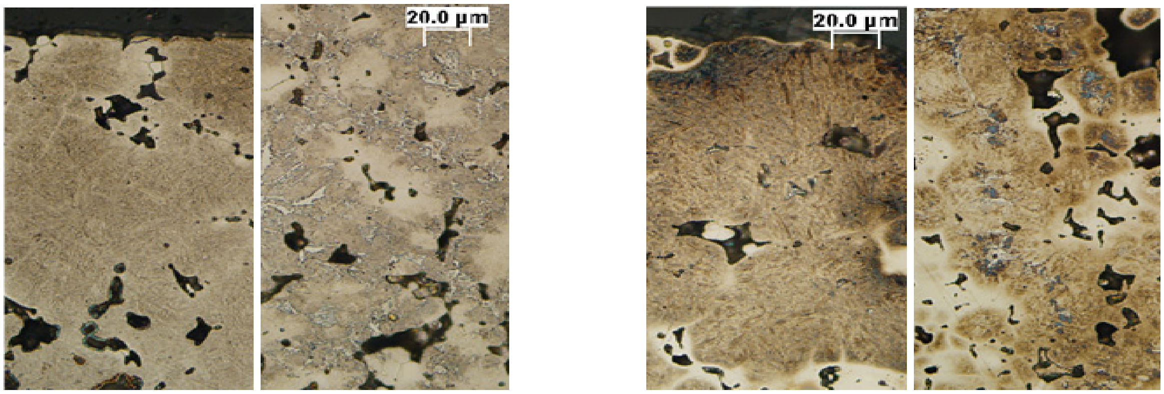


Figure 5. Unetched microstructure of Material A (similar for Materials B, C and D).

The heat-treated etched microstructures of Materials A, B, C and D at the surfaces and core are presented in Figure 6. At the surface of Material A, plate martensite was generated due to high carbon content while the core was mostly pearlite. Material B obtained a martensitic microstructure at the surface and low carbon martensite in core.


Material A

Material B


Material C

Material D

Figure 6. Etched heat-treated microstructures, case and core (same magnification).

Material C obtained a martensitic microstructure with some nickel-rich austenite at the surface and ferrite-pearlite with nickel-rich austenite in core. A martensitic microstructure with some nickel-rich austenite was developed at surface of material D while the core consisted of martensite, pearlite, austenite and some lower bainite.

CASE CARBURIZATION OF GEARS

Gears usually require a hard surface and a tough core.[11] These features are commonly achieved by case hardening operations. A gear case carburization study was done comparing Astaloy CMN to FL-4400, a common PM gear material.

Apparent Hardness

The apparent hardness achieved in the surface of the heat treated gears is shown Figure 7. Similar hardness values to the test specimens were achieve for the gears.

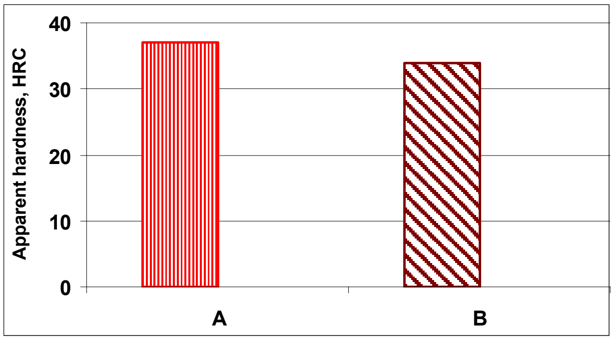


Figure 7. Apparent hardness of gears made from Materials A and B.

Microindentation Hardness

The microindentation hardness profile measured perpendicular from the surface and inwards of fillet radius is shown in Figure 8.

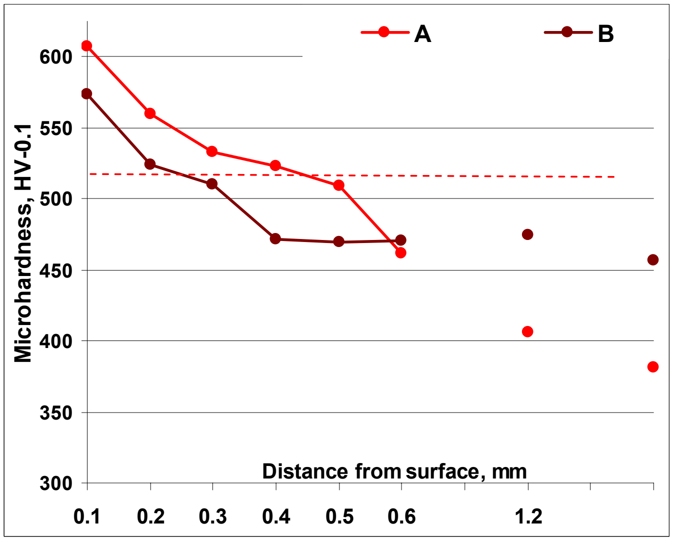


Figure 8. Microindentation hardness of case carburized gears**.**

Effective case depth (the distance from the surface) to 50 HRC (equal to 515 $HV_{0.1}$) is required if no different hardness level is specified.[6] In case of Material A the effective case depth reached 0.45 mm while Material B obtained lower case depth of 0.25 – 0.35 mm. This is due to higher hardenability of Material A (Astaloy CMN), which plays major role at high density.[5] The highest microindentation hardness of 610 $HV_{0.1}$ also was achieved at the surface of Material A.

Microstructure

Figure 9 shows heat-treated microstructures of the gear teeth at the surface and core.

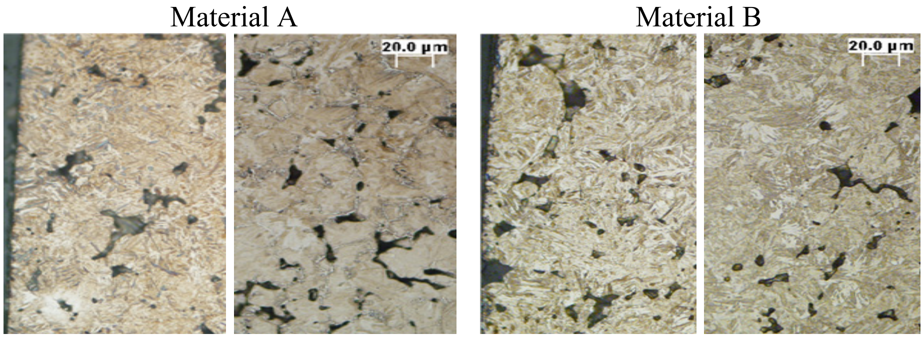


Figure 9. Gears heat-treated microstructures, teeth case and core.

At the tooth surface of Material A, plate martensite was generated while the core obtained a mix of low carbon martensite, dense pearlite and some lower bainite. Material B obtained a martensitic microstructure at the surface and low carbon martensite in core.

Gear Bending Fatigue

Figure 10 shows the results of the prototype gear tooth root bending testing as SN curves with 50% survival probability.

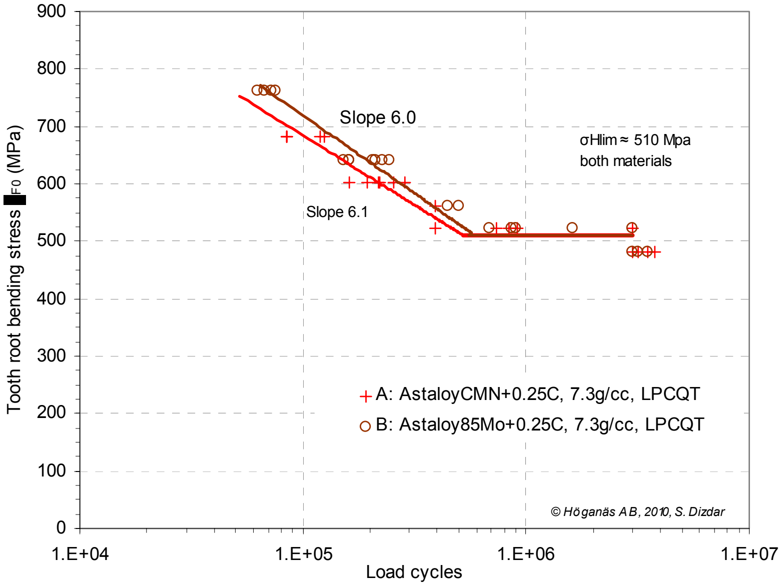


Figure 10. SN Curves, 50% survival probability limit.

The endurance limit was evaluated in 10 to 12 points by using stair-case method by Dixon and Mood.[12] The SN curve slope in the limited fatigue life region was evaluated by testing at two load levels where 50% survival probability was estimated according lognormal statistic distribution. As seen, SN curves for materials A and B overlap each other – they have the same endurance limit and its scatter. The difference in slope is very small, and the scatter is as expected. Obtained data are listed in Table 9.

Table 9: Results of Gear Tooth Bending Testing

Code	Material A	Material B
Endurance limit σ_{Hlim} ($P_{0.50}$) in MPa	510	510
Endurance limit scatter $P_{0.10}/P_{0.90}$	1.11	1.11
S–N curve slope	6.1	6.0
Limited fatigue life stress / scatter $P_{0.10}/P_{0.90}$	762 /1.27 642 / 1.77	682 /1.65 602/ 1.81

CONCLUSIONS

- Astaloy CMN, a lean Cr-Ni alloy, is suitable to conventional heat treatment and shows excellent hardenability. The strength and hardness achieved by the new alloy are similar to or slightly better than other common high performance PM material systems.

- Astaloy CMN achieved a tooth root bending fatigue limit (50% probability of survival) of 510 MPa at a density of 7.3 g/cm^3. The fatigue limit was identical to the FL-4400 material system.

- The ability to generate a hard surface and tough core combined with the apparent hardness, strength and fatigue properties make Astaloy CMN suitable for PM gears and other highly loaded PM applications.

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