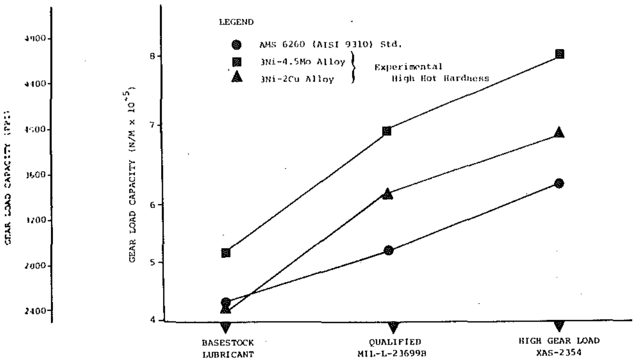

Fig. 2 Gear load capacities of combinations of standard and advanced materials and lubricants

(*b*) A qualified MIL-L-23699B Lubricant—one qualified lubricant was selected based on a survey of the currently available MIL-L-23699 lubricants in the Navy inventory.

(*c*) An XAS 2354 Lubricant—this is an advanced high temperature/high gear load lubricant for aircraft propulsion systems developed for the Navy experimental specification XAS 2354.

Discussion and Analysis of Results

The results of the test series are presented in Table 3. Using the statistical methods described in [6], an Analysis of Variance (ANOVA) was performed on this data in order to determine the effects of gear material, lubricant, and gear material/lubricant interactions on LCC. All three effects (lubricant, material and interaction) were found to be significant at the 5 percent level of significance. The data of Table 3 show these effects graphically in Fig. 2. The main effects of both the lubricant and gear material are evident showing that:

(*a*) the 3Ni-4.5Mo alloy steel is superior to both 3Ni-2Cu alloy steel and AMS 6260 steels, regardless of the lubricant used.

(*b*) XAS 2354 lubricant is superior to MIL-L-23699B lubricant which in turn is superior to the basestock lubricant.

The best performing combination may therefore be achieved with the use of the 3Ni-4.5Mo alloy steel in combination with the XAS 2354 lubricant. The statistical analysis also identified a lubricant/metal interaction. The analysis further indicated that the interaction effect, although statistically significant, was not nearly as strong as the main effects. The interaction effect can be visually identified in Figure 2 by observing that although the 3Ni-2Cu alloy steel is no better than the AMS 6260 steel, with the basestock lubricant it interacts favorably with the additives of the MIL-L-23699B and XAS 2354 lubricants to give performance superior to the AMS 6260.

The data of Table 3 are presented in a different form in Table 4 in order to show percentage change in load carrying capacity using the MIL-L-23699B lubricant/AMS 6260 gear steel combination as a baseline. This is of interest since the data indicate improvements that may be reasonably expected over the currently used lubricants (MIL-L-23699B) and gear material (AMS 6260) by the use of advanced lubricants (XAS 2354) and gear alloy (3Ni-4.5Mo). The most notable features in Table 4 are:

Table 4 Relative lubricant/material load capacity with respect to a MIL-L-23699B/AMS 6260 combination

	AISI/SAE 9310 (AMS 6260)	3Ni-4.5Mo Alloy	3Ni-2Cu Alloy
HERCOLUBE C BASESTOCK			
ABSOLUTE CHANGE IN RATING N/M	-76618	3940	-92598
(PPI)	(-437)	(22)	(-528)
Percent Change	-15	1	-18
MIL-L-23699B			
ABSOLUTE CHANGE IN RATING N/M	Baseline	178892	105514
(PPI)		(1021)	(602)
Percent Change	Baseline	35	21
XAS-2354			
ABSOLUTE CHANGE IN RATING N/M	132532	285806	183226
(PPI)	(755)	(1632)	(1046)
Percent Change	26	56	36

(*a*) An increase of 35 percent in load carrying capacity may be realized with the use of the 3Ni-4.5Mo alloy steel and current lubricant technology (i.e. MIL-L-23699B).

(*b*) An increase of 26 percent in load carrying capacity may be realized with the use of an XAS 2354 lubricant and current technology gear steel (AMS 6260).

(*c*) A change to XAS 2354 lubricant in combination with the 3Ni-4.5Mo alloy steel results in an improvement of 56 percent over currently used lubricants and gear materials.

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DISCUSSION

P. J. Fopiano[1]

The reported work is of considerable importance in the development of advanced high performance gearing for aircraft. The synergistic effect of material/lubricant on the load carrying capacity as demonstrated by the results is very significant and needs to be more widely recognized and exploited to the fullest extent if full advantage is to be taken of advanced gear materials. The Army is currently interested in the development of high temperature gear steels for which the material/lubricant interactions can be expected to assume importance (even critical importance) in the successful operation of these gears.

Scuffing is a very poorly understood phenomenon and therefore it may be frustrating but perhaps not surprising that Nitralloy N shows virtually no improvement while M-50 indicates considerable improvement in scuffing resistance over AMS 6260. Metallurgically, of course, M-50 attains its high temperature capability by the formation of stable alloy carbides while Nitralloy N attains its high temperature capability by the formation of stable alloy nitrides. The core of Nitralloy N, however, would have little resistance to softening above about 300 F and therefore could have contributed to the poor load carrying capability (scuffing resistance) of Nitralloy N. Or al-

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[1] Department of the Army.

ternatively, do the authors view this as another example of material/lubricant interactions which as yet are not well understood?

AMS 6260 is not considered a high hot hardness steel. CARTECH EX 14 was originally developed as a higher hardenability modification of AMS 6260. Based on increased additions of silicon and molybdenum CARTECH-EX 14 should have a higher resistance to tempering and hot hardness than AMS 6260.

It would be useful if the authors referred to specific alloys CBS 600, CARTECH X-53, etc. even if there is no comparable AMS, SAE, AISI designation.

A. Lemanski[2]

The authors have conducted Ryder gear tests to evaluate the relative gear tooth surface load carrying capacity of two experimental steels and a base line production gear steel (AISI 9310) lubricated with three different turbine engine/helicopter gear box synthetic lubricants.

Several years ago we conducted similar tests on a disk machine using the same type of lubricant and similar experimental steels including AISI 9310 as the base line. It is interesting to note that we also discovered a lubricant/metal interaction.

On behalf of gear designers, it is suggested that the authors add detailed heat treatment and carburizing information for all three steels. Many questions can be raised regarding the processing features. Such as preoxidation, the carburizing cycle/temperature, deep freeze, etc. The case hardness of the 9310 gears was Rc 58 (Ra 80). This low hardness which is not typical may adversely effect the test results; also, the heat treatment is questionable. In Table 1 the case depth is not specified as total or effective. How did the authors determine material surface quality? Was Nital Etch used to evaluate a grind burn condition? Was surface finish measured? In actual practice, these variables significantly effect the surface load capacity of gears.

The authors are to be congratulated for investigating the lubricant/material interactions of advanced candidate gear steels and lubricant formulations to increase our knowledge in this important area of technology.

Author's Closure

The authors wish to thank the discussors for their comments and for their interest in this work.

Dr. Fopiano raises the question regarding the superior performance of an M50 steel to a Nitralloy N steel (reference [3]). It is difficult to answer this question because the authors have never evaluated these materials. Moreover, the literature is very skimpy concerning the Load Carrying Capacity (LCC) of these two materials. However, reference [3] does indicate a highly probable lubricant/material interaction effect but does not discuss the effects of microstructure or other metallurgical properties on LCC.

Mr. Lemanski poses some pertinent questions. They will be answered in the order in which they were asked. Table 5 is a listing of the typical heat treatments used for each of the test gears. This AISI 9310 heat treatment is fairly common while the heat treatment procedures used for the 3Ni-4.5 Mo alloy and the 3Ni-2 Cu have not been completely optimized for gearing. A point was also raised regarding the hardness of the case R_C 58 (R_A 80) listed in Table 1. The actual case hardness of the test gears is R_C 61 which was inadvertently converted to a 30-N Superficial scale instead of the R_A scale. There was not a significant difference in the case hardness of these materials to have an effect on the LCC. The case depth listed in Table 1 is the effective case depth after grinding. The surfaces of the test gears were subjected to a nital etch for grind burn inspection. No grind burns are allowed on the contacting surfaces of the gears. The surface roughness measured was 0.51–0.64 um RMS (20–25 um RMS) which is in the specification range for these test gears. We agree that all of these factors may have a significant effect on LCC and that they should be documented with respect to each of their effects on LCC.

Table 5 Typical heat treatment for the test gears

	AISI 9310 (AMS 6260)			3 Ni–4.5 Mo Alloy			3 Ni–2 Cu Alloy		
	Temperature		Time	Temperature		Time	Temperature		Time
Process	°K	°F	Hr.	°K	°F	Hr.	°K	°F	Hr.
Preoxidation	—	—	—	1226	1750	0.5	—	—	—
Carburization	1172	1650	8	1226	1750	2.5	1200	1700	3
Furnace Cool	—	—	—	—	—	—	1103	1525	—
Air Cool to Room Temp.									
Hardening	1117	1550	2.5	1367	2000	0.167	1103	1525	0.5
Quench (Oil)	—	—	—	811	1000	—	—	—	—
Air Cool to Room Temp.									
Cold Treatment	200	−100	3	200	−100	2	200	−100	1
Temper	450	350	1	811	1000	2	422	300	1
				811	1000	2			
				811	1000	2			

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[2] Sikorsky Aircraft.