Austempered Ductile Iron:
Technology Base Required for an Emerging Technology

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This paper addresses Austempered Ductile Iron (ADI) as an emerging technology and defines its challenge by describing the state-of-the-art of incumbent materials. The writing is more philosophical in nature than technical and is presented to establish a perspective. Incumbent materials are those materials which are solidly entrenched as favorites for given applications. Materials resulting from new emerging technologies must be more attractive than incumbents and other potential competitive materials. Materials technology is dynamic; incumbent materials are always in jeopardy from potential replacements. Improvements in processing, performance and cost are in perpetual demand. They have one strong advantage, however, and that is that they are proven and there is an existing data base with which practicing engineers are familiar. Our litigation prone society causes the engineering community to be very conservative. I recently saw the following as a title for an article in a popular trade magazine: "Pass the Aspirin, We're Changing Materials". That statement gives a reasonably accurate description of the environment in which new materials find themselves.

For numerous reasons, though, alternate materials technology continues to be an attractive place to put development dollars. Materials technology can have a very beneficial impact on the competitive position of a firm. It can impact on engineering performance, product development times, productivity, and costs including gratis and capital goods costs.

Why are we so high on Austempered Ductile Iron technology? Because of important favorable attributes, refer to Table 1, it has the potential of giving birth to a new series of engineering materials which will challenge existing ductile iron and cast steel applications, and, more importantly, critical applications which have been dominated by forged steel as well. Fig. 1[1] is presented with two purposes in mind: one, to show the tonnage of the domestic alloy steel market and, two, to show the variations in generic alloy steel applications along a time line.

TABLE I

- GOOD ENGINEERING PERFORMANCE (i.e., fatigue & toughness)
- ATTRACTIVE COSTS (cost improvements of 30% plus reported in some cases)
- 10% LIGHTER WEIGHT THAN STEEL
- IMPROVED NOISE AND VIBRATION DAMPENING
- IMPROVED WEAR AND SCUFFING RESISTANCE
- INCREASED FLEXIBILITY IN DESIGNING FOR OPTIMUM SHAPE

The latest tonnage figure available to the writer was 10,000,000 tons which was for 1979. I'm sure there was a decrease in the recent recession years, but certainly this is a potentially lucrative market. The total current shipments of ductile iron are only 2.0 million. ADI is the most promising cast material for use in critical machine elements to emerge for some time. Although it won't replace all steel applications, I believe that a decade from now when we look back, we'll all be surprised at the inroads ADI has made if the technology is adequately nourished.

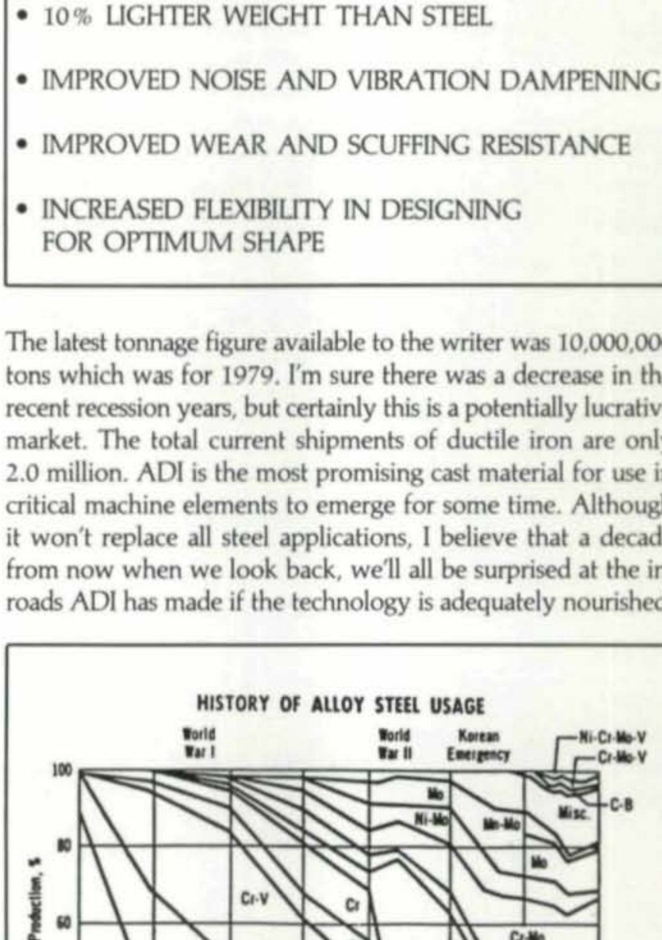

Fig. 1—Through the years since 1900, the pattern of alloy steel usage has changed greatly. The dotted line indicates alloy steel production.

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Its proponents can't, however, become over-confident as forged steel technology is not lying dormant. The literature is beginning to reveal significant new developments such as warm precision forging, superplastic steels and injection molded powdered metals. So ADI must beat out the other competitors as well as incumbent materials. ADI, though, has many additional unexplored possibilities such as near net shape castings finished by rolling or grinding, induction austempering, and reduction in numbers of parts by combining into a single casting and so on.

DESIGN TECHNOLOGY

The existence of a mature technology base was mentioned earlier as a plus for the incumbent materials. These demonstrate both some potential applications and some of the failure type which designers and metallurgists work together to prevent. The prime design criteria is fatigue. In these figures, axial, bending, torsional, contact plus traction, contact plus environmental assist and thermal stress fatigue are demonstrated. Some applications may require unusual toughness and wear properties (lubricated and unlubricated).

Designers of machine elements have considerable information available to them concerning the performance characteristics of heat treated and carburized type steels. In the following discussion, the intent is to present a "thumbnail" sketch of some important performance data available concerning steel. In specialized applications, such as gears and bearings, special performance information is required. This will be discussed subsequently. First, as was stated previously, usually machine elements are designed to a fatigue performance criteria. Two important tools are the Allowable Stress Range (ASR) Diagram and the Stress-Number of Cycles to Failure (SN) Diagram.[3] Fig. 2 shows the former and Fig. 3 the latter. They are related as shown in Figs. 3a and 3b. The ASR diagram, actually a strength diagram, gives a variety of useful information. It can thoroughly describe the fatigue capacity of a material under a multiplicity of load types and manners (contact fatigue excepted). Using fatigue ratios for ADI taken from Fig. 4[4], a

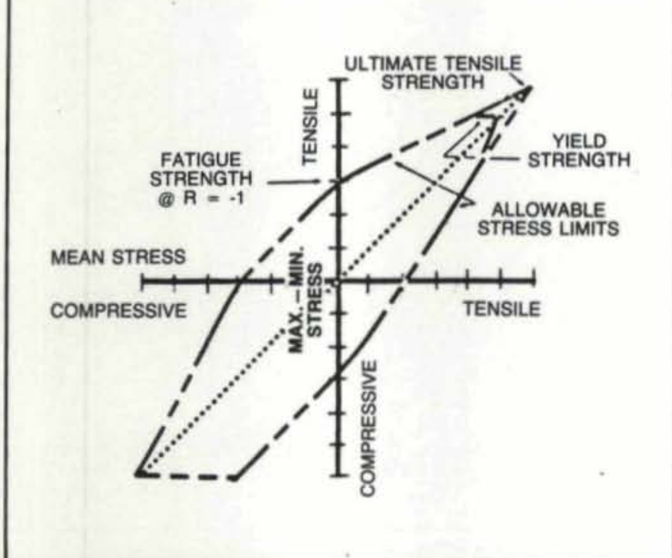

Fig. 2—Typical allowable stress diagram construction.

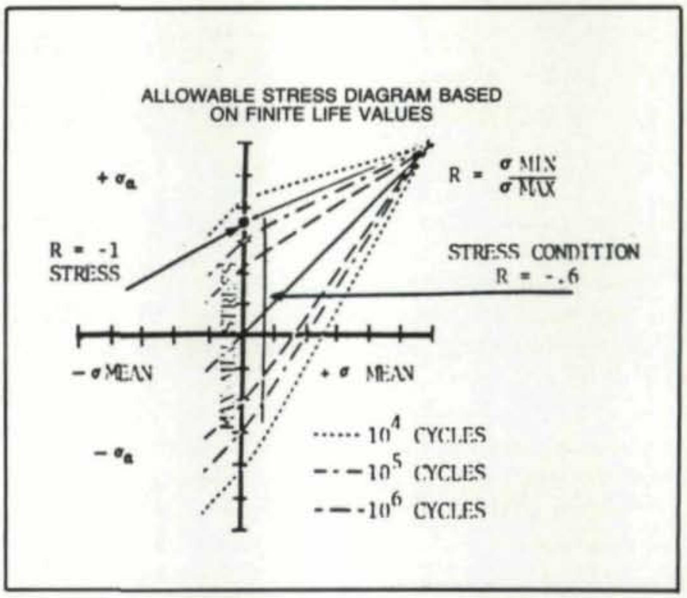

Fig. 3a—Finite Life ASR Diagram
Shows R = −1 equivalent stress for R = 0.6 loading.

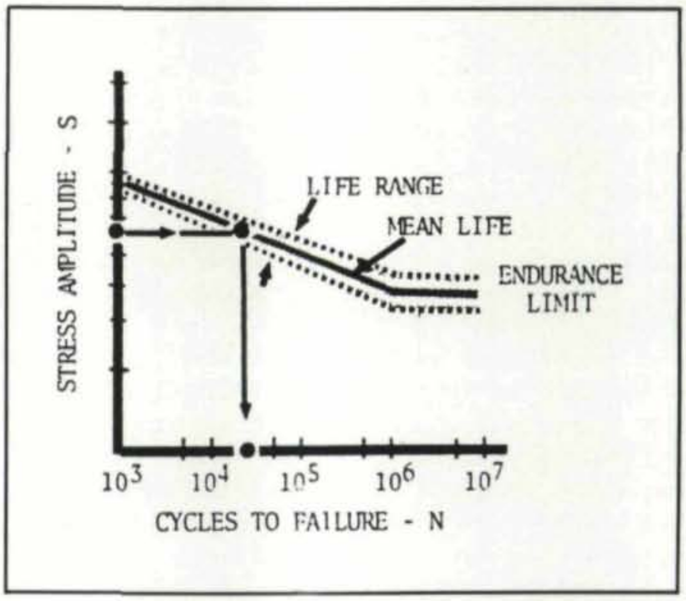

Fig. 3b—S-N Diagram
Shows life prediction for R = 0.6 loading using R = −1 equivalent stress.

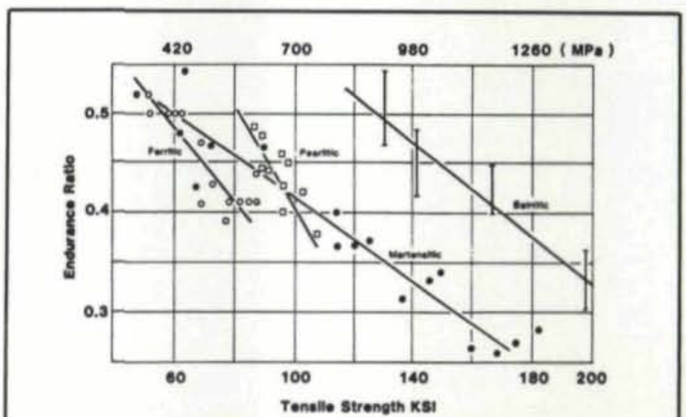

Fig. 4—The endurance ratios for nodular iron as influenced by its tensile strength and matrix microstructure. Endurance ratio for the bainitic irons defined at 2 x 10⁶ cycles; for all other irons the ratio was calculated at 10⁷ cycles.

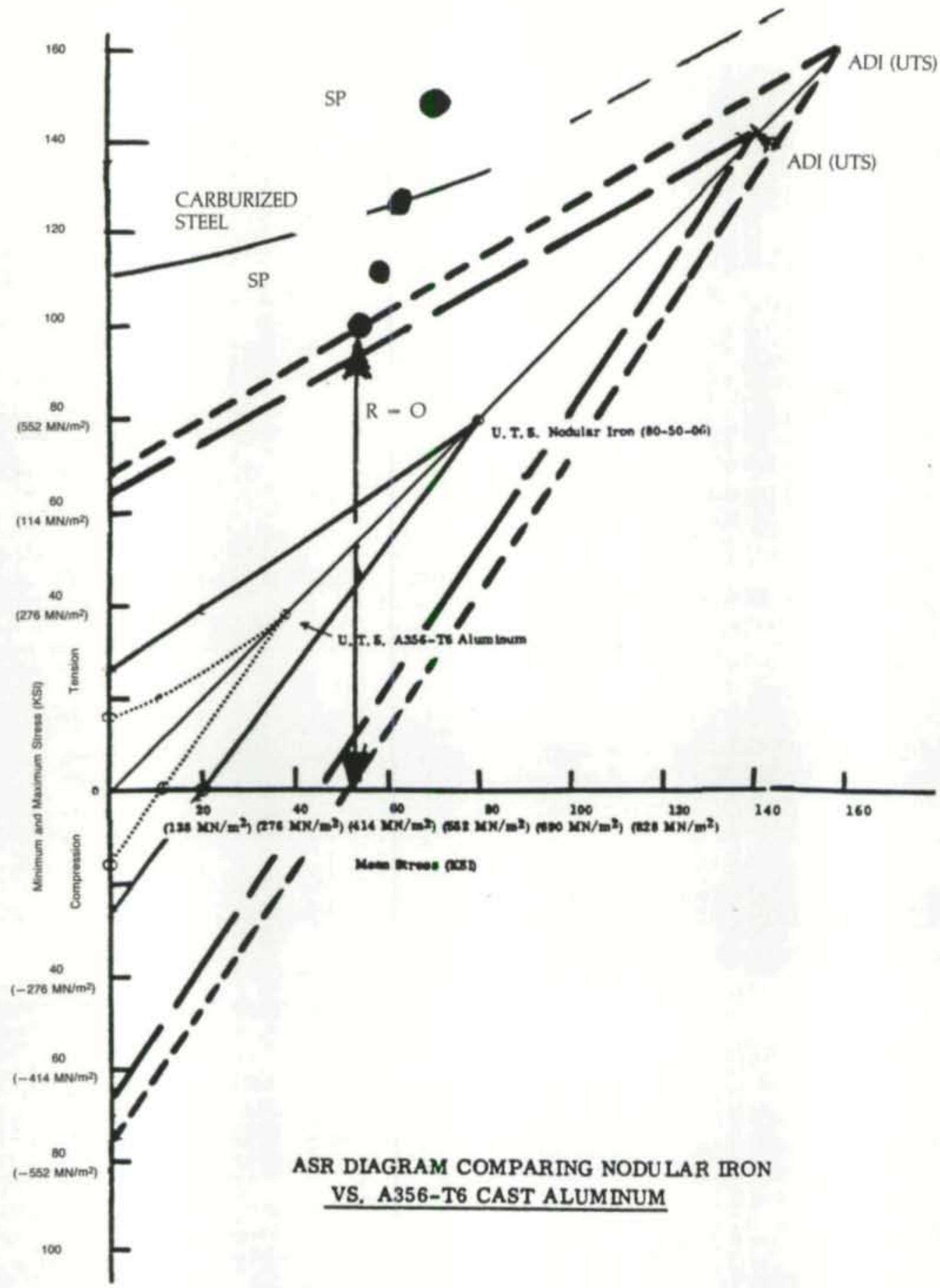

Fig. 5

comparison of some ASR information is shown in Fig. 5. This is not quite accurate, since the comparison is at $2x10^6$ cycles for the ADI and $1x10^6$ cycles for all others. Since the reverse bending (R=-1) endurance limit for the 356-T6 and the 80-50-06 NI is for one million cycles, the 10 million cycle envelope would be even smaller. Obviously, ADI at 140 ksi and 160 ksi tensile strength has some attractive load carrying capabilities. To put it in perspective, however, I have shown some dots for undirectional bending, R=O type loading, so one can consider applications such as gear tooth bending which is close to R=O. The dot for ADI/160 ksi occurs at 100 ksi (R=0). Shot peening, assuming 25 percent increase in R=-1 limit, translates to the next dot up, so the R=0 load limit in the shot peened condition would be about 110 ksi. The upper two dots are for carburized steel. The dot corresponding to an R=0 strength of about 125 ksi is for the unpeened condition, whereas the one at 150 ksi is for the peened condition. These are all constructed diagrams, thus do not represent actual data. Real data is urgently needed. One can develop a perspective though and conjecture about possibilities. Shot peening or rolling to improve bending fatigue properties is apparently going to be a necessity in many applications. This is one of the challenges. We need to know quantitatively what to expect and the best procedures for processing. The data shown in Fig. 6 may be conservative, as it

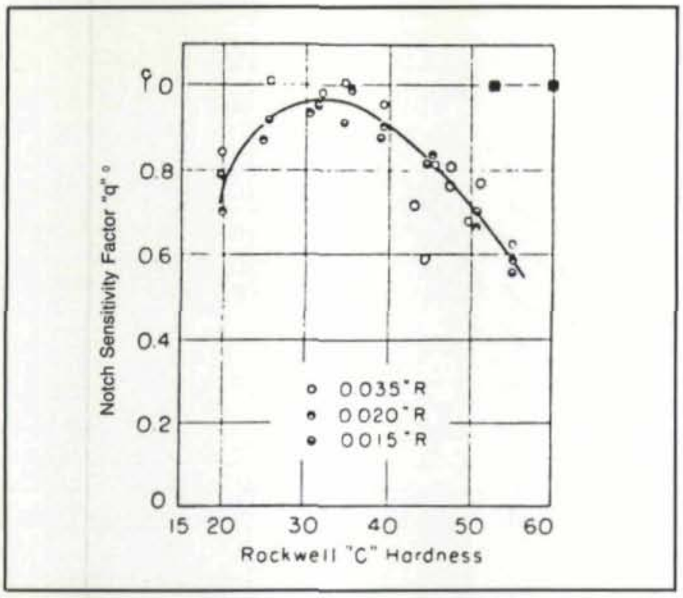

Fig. 6—Variation of notch sensitvity factor "q" with hardness.

has been assumed that peening will increase the EL by only about 25 percent. Previous data reported[5] has indicated improvements by as much as 65 percent, possibly because of the favorable work hardening of austenite.

Contact fatigue properties look very promising, but the literature is quite terse in this respect. Enough is known, however, to recognize the potential; but here is another challenge: we need data! ADI is not a single material, but consists of many possible grades with wide ranges of possible properties.

Fatigue notch sensitivity factors (q) and fatigue notch reduction factors (K_f) are also needed. q is related to K_f (fatigue reduction factor) and K_t (theoretical stress concentration factor) as follows:

$$q = \frac{K_f - 1}{K_t - 1}$$

The relationship of q and strength/hardness is shown in Fig. 6[6] for heat treated steel. This type of information on ADI is not yet available, but is badly needed.

It is not within the scope of this writing to discuss toughness as a design criteria, but it is certainly important, especially in applications where significant yielding can be expected such as roll-over protective structures.

GEAR DATA REQUIREMENTS

Machine elements such as gears are normally designed to bending fatigue and contact (pitting) fatigue criteria. Figs. 7 and 8* show the design allowables for carburized steel as shown in AGMA standards. Comparable data, in which the designer can have confidence, is required for ADI.

* "Extracted from AGMA Standard Design Guide for Vehicle Spur and Helical Gears, AGMA 170.01, with the permission of the publisher, the American Gear Manufacturers Association, 1330 Massachusetts Avenue, NW, Washington, D.C. 20005."

In regard to toughness, carburized steel has K_{Ic} values in the high carbon case region varying from 15-22 ksi in. There are

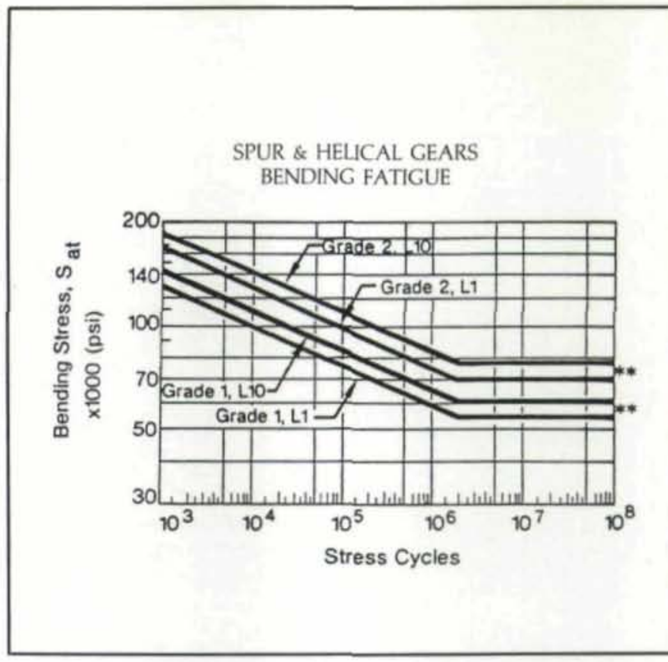

Fig. 7—Alloy steels case carburized to Rc 58-63 case hardness, Rc 30-42 core hardness.

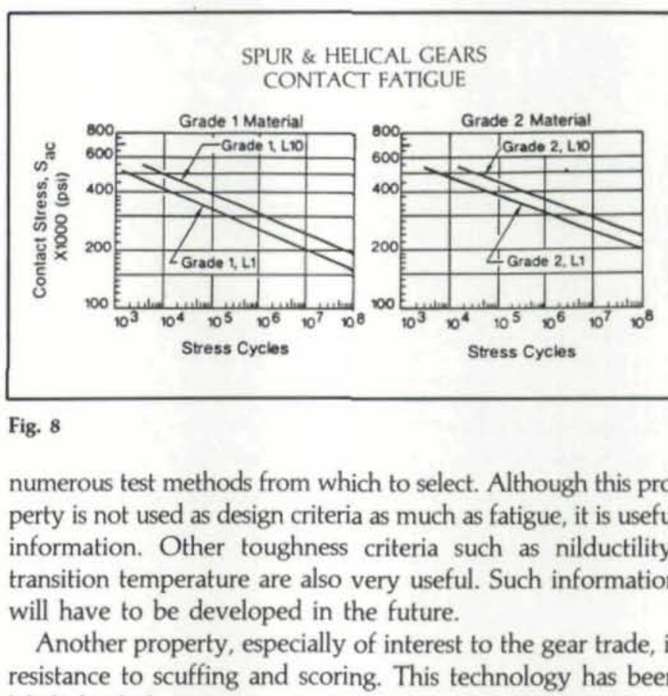

Fig. 8

numerous test methods from which to select. Although this property is not used as design criteria as much as fatigue, it is useful information. Other toughness criteria such as nilductility-transition temperature are also very useful. Such information will have to be developed in the future.

Another property, especially of interest to the gear trade, is resistance to scuffing and scoring. This technology has been labeled tribology.

Scuffing and scoring properties of materials per se have not been systematically categorized. A recent publication by Terauchi[7] is a good review of the subject. The technology might best be understood by looking at a few excerpts from his paper. The safety factor against the danger of scoring can be defined by:

$$Sf = \frac{Oa}{O}$$

where O is the instantaneous surface temperature at the point of contact on the active profile and Oa is the allowable maximum temperature to prevent scoring. The following equation is given for O:

$$O = Oo + 157 \times 10^{-4}\, u\, K_R\, E_A$$

where Oo is the surface temperature just prior to mesh and

TABLE II

INFLUENTIAL FACTORS ON SCORING RESISTANCE OF GEARS

Influential factors on 0	*Operating conditions* Dynamic load, Over load, Speed variation, Impact load, etc.	*Geometric variable of gears* Module, Pressure angle, Face width, Helix angle, Amount of addendum modification. Profile modification, etc.
		Accuracy of gears Tooth profile error, Spacing error, Pitch error, Lead error, Surface roughness, etc.
		Basic amount of gear operation Nominal peripheral velocity, Nominal carrying load
Influential factors on 0_a	*Characteristics of working tooth faces* Metallurgical structure, Hardness, Property against wear, Thermal property, etc.	
	Characteristics of lubricants Viscosity, Kind and composition of lubricants, Additives (Thermal property, Adsorption and reactivity to tooth material), etc.	
	Lubricating methods Splash lubrication and/or jet lubrication, Oil volume, Oil supplying rate, Oil supplying position, etc.	

u is the coefficient of friction. E_n contains factors relating to loading, material thermal coefficients, tooth load sharing and relative velocities. K_r is related to surface roughness after "run-in". Table II shows the factors influencing the scoring resistance of gears. Fig. 9 shows the calculated temperature rise along the involute of a gear active profile. Note that at the pitch line, where there is no relative sliding, there is no significant temperature rise. Fig. 10 shows the relationship between hardness and critical scoring temperature for several steels.

The technological aspects of lubricated contact are fairly well understood, and there is basic agreement on the elastohydrodynamic-critical temperature concept when nonreactive lubricants are involved. The literature is extensive. [8] [9] [10] [11] [12] Most, however, deal with the lubricants, surface finish, dynamics or coatings, not the metallurgy of the contacting materials. Also, much of the work relates to systems with zero or low slide/roll ratios, such as bearings. The contacting surfaces of gears are subject to rather high slide/roll ratios.

Traditionally non-reactive oils have been simpler to study than reactive oils.[13] Scoring is dependent on a number of independent variables. At some speeds where elastohydrodynamic lubrication prevails, performance is determined by lubricant properties as influenced by load and speed. The coefficient of friction is basically independent of surface roughness or the frictional properties of the contacting surfaces. Performance is not dependent on the boundary lubrication properties of the lubricant. When appreciable asperity interaction occurs, the situation changes. Surface roughness and the metallurgy of the contacting surfaces become important and the lubricant reactivity plays a role. The interactions become complex. Wear and temperature effects make a contribution and instability occurs. It will be interesting to see where ADI fits in the scheme of things in a quatitative way. The presence of free graphite and strong, plastic austenite may enhance this property significantly.

The other possible plus for ADI is its potential to improve noise and vibration damping capability. Quatitative information is needed to help assess this potential benefit.

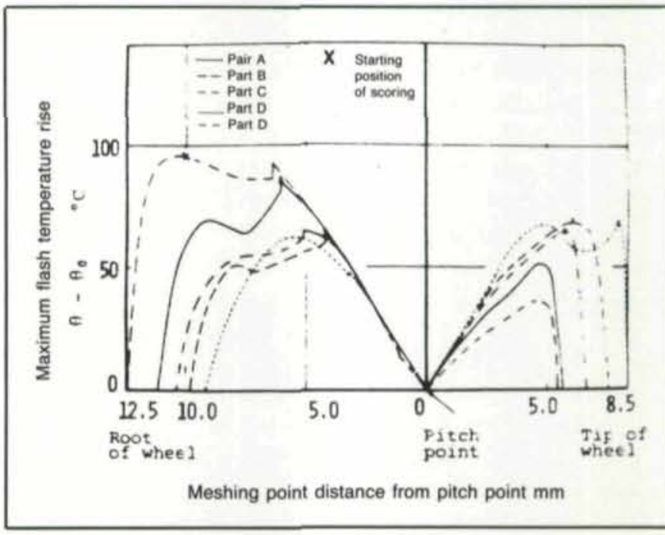

Fig. 9—Calculated variation in surface temperature rise along the line of action (load sharing included).

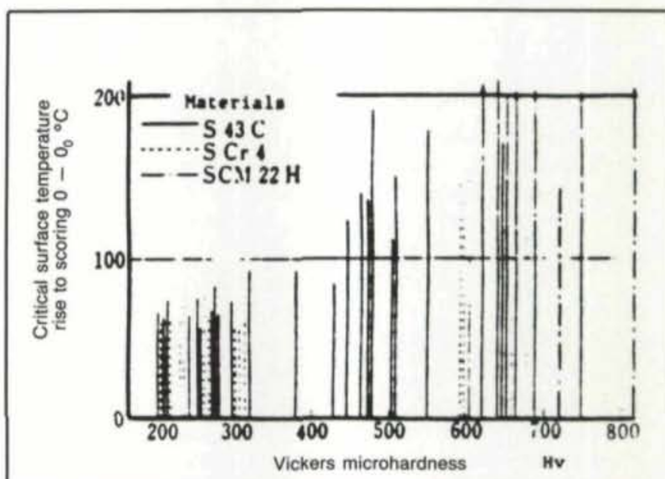

Fig. 10.—Relation between hardness and critical surface temperature rise to scoring of disks.

Concluding Statement

This has been a terse scan of some of the technologies that are important to the design of machine elements. It is intended to help define some of the needs related to ADI, so that engineers are in a better position to take advantage of it, in both new designs, and as a substitute material in existing designs. The challenge then has many aspects, but two important ones are: on target generation of necessary data and timely and competent use of it by the user community. Processing needs such as influence of alloy on hardenability, machinability data and quality assurance procedures, although very important, have not been discussed.

As a concluding thought, I'd like to reflect on a quote from Harry McQuaid, who said "I was once told that the ideal design is one that is just good enough; that anything better than good enough was wasting someones money; and that anything not good enough means you wouldn't have a job very long."

That is a very succinct and on target statement. It has two technical elements: one, components must perform and two, their costs must be optimized. The implications of this are profound. This implies that we must have comprehensive technical knowledge concerning what the performance criteria are in terms of loads, their frequency and variations, the states of stress they induce, environmental conditions, and so on. In addition, we must quantitatively understand properties of materials of construction in terms of fatigue and fracture resistance, and the influence of the myriad environments components they are exposed to, and thirdly, we must have comprehensive knowledge concerning producing the complex shapes required. This includes costs and sensitivity to capital equipment requirements. This is a call for dedication and competency. There are numerous instances where these elements have been displaced by lack of appreciation for technology and corner cutting by U.S. industry. The third element of the statement has to do with job security. McQuaid's prediction of job loss has occurred on a massive scale. Certainly a large percent of U.S. component tonnage is now produced abroad.

ADI is on a threshold. We must learn all we can about it as quickly as possible, to help it gain its proper position as an engineering material, and thus, enjoy its benefits. We need to be careful, however, and find successful applications so as not to jeopardize ADI by developing a track record of failures.

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CIRCLE E-5 ON READER REPLY CARD

CORRECTION: Two formulas were shown incorrectly in the Back to Basics article, Vol. 1, No. 1, page 41. They should be corrected as follows:

$$\text{arc}\,\theta = \text{invo}\,\phi = \tan\phi - \text{arc}\,\phi$$

and

$$r = \frac{rb}{\cos\phi}$$