Metallurgical Aspects to be Considered in Gear and Shaft Design

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Introduction

In his *Handbook of Gear Design* (Ref. 1), Dudley states (or understates): "The best gear people around the world are now coming to realize that metallurgical quality is just as important as geometric quality." Geometric accuracy without metallurgical integrity in any highly stressed gear or shaft would only result in wasted effort for all concerned—the gear designer, the manufacturer, and the customer—as the component's life cycle would be prematurely cut short. A carburized automotive gear or shaft with the wrong surface hardness, case depth or core hardness may not even complete its basic warranty period before failing totally at considerable expense and loss of prestige for the producer and the customer. The unexpected early failure of a large industrial gear or shaft in a coal mine or mill could result in lost production and income while the machine is down since replacement components may not be readily available. Fortunately, this scenario is not common. Most reputable gear and shaft manufacturers around the world would never neglect the metallurgical quality of their products.

Additionally, there exists today a wide range of sophisticated and reliable control equipment available to the gear industry to ensure that all of the metallurgical processes in gear making are adequately quality assured.

New Opportunities for Manufacturers

In the automotive industry, customers have always demanded lighter, cheaper and quieter gears that carry higher loads at increasing speeds. It is only through an increased knowledge and understanding of the metallurgical aspects of gear and shaft design that these demands can be satisfied.

For many years, industrial gear manufacturers have followed the larger automotive gear companies in introducing processes such as gas carburizing for their small to medium sized gears. Surface hardening techniques such as flame hardening and contour induction hardening are frequently used to improve the endurance or load carrying ability, allowing reduced weight and cost. Gears and shafts manufactured for mining machines, for example, have been surface hardened using techniques that include gas carburizing, nitriding, induction hardening and shot peening. In all of these cases, customer demands can be fully met by an intimate knowledge of the metallurgical changes occurring before, during and after manufacturing. This includes material selection, machining, heat treatment processing, shot peening, grinding, chemical treatment and subsequent lubrication.

Design Engineer's Role

The design engineer has overall responsibility of the engineering specifications of new gears and shafts used to transmit torque, change rotational speeds or drive machinery. This responsibility includes calculating the geometric or dimensional specifications and ensuring that the loads can be transmitted smoothly and safely without breakage or seizure. The designer makes use of various gear standards, handbooks, and computer software to aid in this process. He will utilize tables and charts in these references to obtain the load carrying properties of various materials or, more likely, to compare the surface load and bending endurance limits of the available materials. The most commonly tabulated metallurgical property shown in these tables and graphs is Brinell hardness, which is directly related to ultimate tensile strength, as are all indentation hardness tests (Ref. 2).

These charts apply to normalized or hardened and tempered steel gears up to a maximum of about 400 Brinell hardness. Metallurgical factors such as sur-

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> — *DARLE W. DUDLEY*

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face microstructure, grain size and steel cleanliness can have a major influence on gear and shaft endurance limits, but they are typically ignored. Such factors are not easily expressed numerically and are difficult for the design engineer to use directly in his calculations. It is probable that the designer may consult tables giving the full mechanical and physical properties of specific materials and rate them on performance in areas such as impact strength, ductility, fatigue life, or surface load and bending endurance limits if these figures are available. In reality, it is implied that the vast majority of vital metallurgical factors must be correctly dealt with by the material supplier or process provider, who must ensure that metallurgical integrity and the optimum balance between strength and toughness properties are achieved in the final product.

Materials Engineer's Role

In larger gear and shaft companies, it is the responsibility of the materials engineer to ensure the metallurgical integrity of the final product. This includes selecting the correct materials and thermal processing, as well as quality assurance of all the vital production processes that could change the properties of the final gear or shaft. Many metallic and nonmetallic materials have been successfully used to manufacture gears (Ref. 6). A wide variety of steels, cast irons, nonferrous alloys, phenolic resins, thermoplastics and sintered irons are available, but by far the greatest number of highly stressed gears and shafts are made from steels because of their high strength to weight ratio and relatively low cost. Additionally, ferrous materials gain their wide acceptance from the fact that their structural properties can be modified by heat treatment, and their surface chemistry can be changed by diffusing carbon or nitrogen into their surfaces. It has been estimated, for example, that steels account for about ninety percent of all gears and shafts produced in Australia. There are also a wide range of surface hardening options to select from, so specialist knowledge and material test equipment is required. It is in this area that most materials engineers receive their training.

Mechanical and materials engineers work together in their differing roles to arrive at the correct design and manufacturing route to make better and cheaper gears and shafts that will not fail prematurely.

Materials and Process Selection

In general, the design engineer will consult with the materials engineer to discuss all of the available options before selecting the final materials and heat treatment processes that satisfy the design requirements for a particular gear or shaft as well as fulfill the economic requirements of the business in an increasingly competitive environment. In Australia there are a limited number of steels and process options available (Ref. 6), so the right decision at the design stage is essential. For example, an automotive transmission shaft may be made from a low carbon alloy steel and carburized and quenched, or it could be satisfactorily made from a cheaper plain carbon steel and induction hardened. The final decision will depend on the configuration and type of gear or shaft being considered as well as the location, magnitude and duration of stresses that are likely to be present. Also vital are the capability, reliability and cost of the metallurgical processes available at the time.

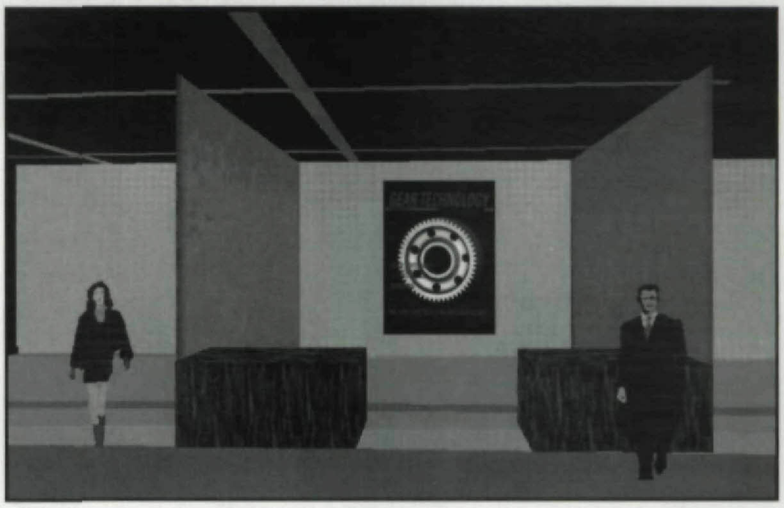
At this stage, the materials engineer must consider metallurgical problems such as distortion during heat treatment processing, the likely impact and fatigue loads that may be encountered during service, and the added costs related to ensuring metallurgical quality. The two engineers must be able to apply theory and experience to the particular application in question so as to arrive at the desired result—a precision product at a competitive price to satisfy the customer.

Considerable experience and knowledge of existing successful designs is normally required. Discussion of the precise application needs and requirements may reveal that special problems exist with lubrication or overheating. Impact loads are normally impossible to estimate accurately and some metallurgical factors may not be known precisely. For the most highly loaded gears and shafts, this uncertainty may affect the final factor of safety in the design calculations. The gear design standards may mention certain metallurgical factors to be considered, but they may not give precise answers regarding what can be tolerated. Finally, confusion may exist between the different standards regarding how they should be applied.

These problems are of major concern to smaller gear companies that cannot afford an in-house materials engineer and do not possess in-house heat treatment facilities.

Gear Tooth Loading

Any discussion of the metallurgical aspects of gear design must begin by looking at basic gear tooth loading. Regardless of the gear type, whether spur, bevel, helical, hypoid or worm, in highly loaded mechanical gear trains, the



forces acting on the mating gear teeth when they engage to transmit power will produce high surface contact stresses on the loaded flanks of the mating teeth and high bending stresses at or near the root of those teeth. Differences exist in the magnitude and depth of the shear stress as well as in the thrust direction and amount of sliding that occurs in the different gear types, but these differences will not be considered at this point.

Surface stresses. Surface fatigue is a frequent cause of gear failure. Although wear and scoring can be related to poor lubrication or surface roughness, pitting fatigue and subsequent breakage can be related to metallurgical factors.

The surface and near surface stresses developed between two steel surfaces under load have been studied by the 19th century German engineer Hertz, who developed formulae to aid in rating pitting resistance. However, these Hertzian equations are correct only for static loads on isotropic homogeneous materials. Because of the complex stress patterns existing in modern gears, where sliding and rolling take place above and below the pitch line, more recently developed relationships are available. However, these too are of limited value as the effect of lubricants was not considered (Ref. 4).

Initial wear or "wearing in" may be normal, and unless cracks develop in the tooth surface, it will generally not lead to pitting. However, pitting fatigue is progressive and leads to the destruction of the tooth profile.

A combination of rolling and sliding takes place both above and below the pitch line. The sliding motion plus the coefficient of friction tends to cause additional surface and subsurface stresses. Compressive stresses are present just ahead of the contact zone in the direction of sliding. Just behind this zone, there are tensile stresses. Beneath the contact zone are shear stresses. The depth of the point of maximum shear stress is about one third the width of the contact band. For any given load, the magnitude of these stresses is dependent on the length of the contact band and the action of the lubricant present.

As already mentioned, gear design tables and standards make use of the strong relationship that exists between indentation hardness, ultimate tensile strength, the surface stress factor (Sc) and the bending stress factor (Sb) for static loads. But as the majority of gears and shafts fail by fatigue at loads well below the ultimate tensile strength, then such tables are only useful in determining the steel's behavior under static loads. They are of little help in predicting the material's behavior under cyclical loading. It is at this point that the influence of residual stresses on fatigue must be discussed.

It has been well documented that processes introducing residual tensile stresses into the surface of a cyclically loaded specimen decrease its fatigue life. Processes that introduce residual compressive stresses into the surface of a

specimen increase its fatigue life (Ref. 3). Because indentation hardness does not indicate the sign or magnitude of residual stresses existing at or below the surface, load tables based on hardness are of little help in designing fatigue resistant, highly loaded gears and shafts. It has also been well documented that the presence of surface abnormalities in the microstructure, or inclusions in the base material, can initiate fatigue cracks that eventually lead to failure. In addition, cracks can initiate at the surface of high hardness gears and shafts if high impact loads are present. Therefore, in order to know more about improving the fatigue life of gears and shafts, and so be able to build lighter and cheaper gears and shafts that give longer service, we must concentrate on knowing more about:

1. processes that introduce high residual compressive stresses into the surfaces of gears and shafts where fatigue failure is likely,
2. the metallurgical factors controlling impact toughness,
3. the factors affecting the cleanliness of the steel.

Residual Compressive Stresses. High surface contact loads can produce unfavorable tensile stresses in the tooth surface. These stresses eventually produce cracks that lead to failure of the surface by pitting and breakage. The introduction of residual compressive stresses into the tooth surface opposes the tensile stresses and prevents the initiation of fatigue cracks. It is well documented that manufacturing processes such as carburizing, carbonitriding, nitriding, induction hardening and shot peening considerably increase the residual compressive stress level at the surface of ferrous components. Also, thermal, mechanical and chemical processes can be used together as in the case of automotive planetary gears which are carburized, acid treated and shot peened with hardened steel shot. (This process produces the most fatigue resistant gears that the author is aware of.) It is extremely important that all such processes be precisely controlled if maximum residual compressive stress levels are to be consistently achieved.

Thermal Processing of Gears and Shafts

Carburizing. Case hardening processes have been known to impart high residual compressive stresses at the surface of a gear or shaft. It is these beneficial internal stresses that give the gear or shaft the improved endurance properties that allow the components to carry higher loads without failing.

Carburizing has been used for many years to case harden gears and shafts to improve wear resistance and load carrying ability. The process has come a long way from the early years of pack and salt bath hardening to modern controlled atmosphere furnaces that use sophisticated gas measuring devices and computers. The process, when correctly carried out, produces very high residual compressive stresses at the surface and underlying cased region. This results in improved surface endurance and wear resis-

tance, as well as improved bending fatigue life and impact resistance. The metallurgical requirements (in the tooth contact zone) to achieve these benefits can be stated briefly below as:

1. surface carbon level to achieve the eutectoid composition for the particular steel used:
2. absence of excessive retained austenite after quenching:
3. absence of cementite networks (carbides) at or near the contact face:
4. absence of sub-surface oxides:
5. absence of intermediate transformation products. 100% martensite or mixtures of martensite and lower bainite being the aim (no pearlitic or upper bainitic skins):
6. fine grain size throughout the case.

The above requirements can only be achieved by precise control over

1. furnace temperature and carbon potential of the furnace atmosphere at the desired level:
2. use of the optimum quenchant and quench conditions (oil type, agitation, and oil temperature):
3. fine grain steel of the correct hardenability to ensure the gear or shaft meets the requirements for surface hardness, effective case depth, and core hardness:
4. optimum heat treatment cycle to produce the required case depth (carbon gradient) and microstructure.

The above requirements become difficult to achieve if the carburizing furnace load contains gears or shafts made from carburizing steels of different composition, or the furnace is overloaded to the extent of reducing either gas circulation or subsequent quench oil circulation. For example, a plain carbon manganese carburizing steel such as YK1320H will require a higher carbon potential than a high nickel carburizing steel such as X3312H.

Residual surface stresses must now be considered in relation to the commonly available gear heat treatment operations. By far the greatest quantity of highly stressed gears are carburized. These gears are made from low carbon, low alloy steels which, in and of themselves, lack surface durability. However, after raising the surface carbon of these gears to about 0.8–0.9% carbon, they exhibit the most desirable combination of surface endurance, bending endurance and toughness. Extremely precise control of all variables is required during carburizing and subsequent quenching to achieve the highest quality, lowest distortion gears.

Whether the gear designer requests direct quenching or reheat quenching after carburizing will depend on the known applications of the gears. Direct quenching has been used for many years with automotive gears where extremely fine grained, automotive quality steels are specified. However, the reheat method for more precise gears such as turbine gears has been said to produce better metallurgical structures and more assurance that the gears can run satisfactorily for a much higher number of cycles.

Induction hardening. Induction hardening has long been used to harden plain carbon automotive axle shafts. Surface hardening shafts using induction techniques also develops residual compressive stresses at the surface and in the hardened zone (Ref. 7). The exact pattern of these stresses depends on the process conditions and the composition of the material being hardened.

Apart from delaying the initiation of fatigue cracking in service, these residual compressive stresses are known to delay the process of stress corrosion cracking. Gears can also be induction hardened using different inductors and fixtures. The method best suited to large gears, where the profile and root area can be hardened without embrittling the tip of the tooth, involves using an inductor shaped to fit between the teeth. Modern techniques use dual frequencies in order to achieve the deeper case depths required by larger gears. Shafts are induction hardened using a scanning-type machine, which progressively moves the shaft through the inductor, heating and then quenching a small moving zone. The depth of the induced currents that heat the steel shaft or gear are related to the frequency of the induction hardening unit. Case depths for small shafts require higher frequencies (RF), while larger shafts require low frequencies (AF).

Automotive axle shafts are hardened using motor alternator units with a frequency between 3 and 10 Khz. The resulting hardened depth, measured to 40 HRC, is approximately 2.5 mm. Smaller solid state units operating at radio frequency 450KHz can harden small shafts within seconds to a depth of 0.7 mm.

Mechanical Processing

Shot Peening. The automotive industry uses dynamometers, driven by either electric motors or gasoline engines, to carry out precise life tests on finished transmission assemblies. These tests have proven that carburized automotive gears and shafts can achieve significantly improved fatigue life after peening with hardened steel shot, precisely carried out. The shot peening process is expensive but has allowed automotive companies to upgrade the ratings of automatic and manual transmissions without the need to make expensive dimensional changes to their gear trains. The peening operation induces beneficial residual compressive stresses in the flank and root area of the teeth under strictly controlled conditions. Compressive stress prevents or limits failure in gearing due to fatigue failures at the fillet and pitting failure at the pitch line.

Rolling. In some applications, work hardening of a component surface by rolling can induce residual compressive surface stresses and improve the surface finish, but care must be taken not to produce fine surface cracks that may initiate fatigue.

Common Failure Modes of Gears and Shafts

Fatigue Considerations. In regard to surface stresses, the limiting load for wear depends upon the surface endurance limits of the material, which in turn depends on geometric as well as metallurgical factors. Surface endurance limit values appear to be related consistently to a Brinell hardness number up to approximately 400 Brinell hardness (Ref. 2). When the Brinell hardness is over 400, the steel does not

TABLE 1
Spur and helical Gears (Ref. 2)

Brinell Hardness HB	Surface Endurance Limit (psi)
200	70,000
300	110,000
400	150,00

TABLE 2—For steels over 400HB (Ref. 2)

Brinell Hardness	Surface endurance limit (psi)			
HB	1 X 10^6	2 X 10^6	5 X 10^6	10^7
450	188000	170000	147000	132000
500	210000	190000	165000	148000
550	233000	210000	182000	163000
600	255000	230000	200000	179000

When the Brinell hardness is over 400

appear to have a definite endurance limit. Values for the surface endurance limit for steels over 400 Brinell are given in the table above.

The focus up until now has been on uniform loading, but in reality many gear systems experience fluctuating loads ranging from moderate to heavy shock. The sensitivity of the gear or shaft material to notches or sharp corners is a major consideration. In addition, most gears and shafts fail by fatigue at loads well below their yield strength. Although Tables 1 and 2 above are comparatively useful to design engineers in calculating load carrying capacity, they do not impart any information about the toughness or impact properties of the material, nor can they shed any light on the materials' fatigue strength. The often quoted "rule of thumb" that the fatigue strength is about 50% of the yield strength is probably very conservative. More information about the metallurgical factors that influence toughness and fatigue life is needed so that the engineer can confidently reduce the weight and hence the cost of a drive system. Research work to date points clearly at factors such as steel cleanliness, alloy combinations present, heat treatment condition, grain size and grain flow and the nature of micro-constituents present at or near the surface. Of critical importance is the steelmaking practice and the processing route used to make the components. Two steels with the same Brinell hardness could vary dramatically in impact and fatigue properties, particularly in the presence of small stress concentrators such as machine tool marks or subsurface defects.

Impact Properties

The selection of the correct material and heat treatment process for steel must be considered to be a compromise between strength and ductility. Although through hardened gears with a surface hardness over 400 Brinell can give excellent wear properties, they may lack the toughness for many applications. Tempering will reduce the hardness and wear resistance but will increase the toughness. The balance between strength and toughness, developed after quenching and tempering, is a critical consideration for the materials engineer.

The only processes where both strength and toughness increase together are those involving grain refinement. This is achieved by making micro-alloy additions to steel and thermo mechanical processing. Heat treatment processes involving the diffusion of carbon, or carbon and nitrogen combinations, into the surface of a low or medium carbon steel can result in the production of wear resistant gears and shafts that are also tough. The resulting high hardness is at the surface of the case where it can improve wear and fatigue strength, while the core is softer and more ductile, giving high toughness properties. The core, however, must not be too soft as the case needs adequate support to prevent case crushing (Ref. 4).

Importance of Flow Lines

The impact properties of steel castings, plates, and forgings are not uniform in all directions, but are related to the flow line direction. Charpy tests indicate that the impact strength across the flow lines can be up to 50% lower than tests where the test piece is parallel with the flow lines. Since any inclusions and microsegregation will follow these flow lines, they must not be parallel with the base of the gear teeth in highly stressed gears (Ref. 4).

Importance of Composition

During the eighties, research was completed on the impact properties of alloy steels with higher molybdenum content using instrumented Charpy testers. Although the early results indicated that molybdenum steels were tougher than nickel steels, it was later shown that certain combinations of the two alloys gave the best results. The instrumented Charpy tests gave the researchers valuable information regarding the initiation of the propagation of cracking that could not be obtained otherwise.

Conclusions

Many workers have generated a wealth of metallurgical knowledge and information about the surface fatigue resistance and impact resistance of various materials. There is also considerable information about the metallurgical factors affecting those thermal and mechanical processes used to improve the life of highly stressed gears and shafts. Much of this information is available for the designer to consider and apply in order to achieve metallurgical and geometric quality and meet customer demands for precision gears and shafts at minimum costs. ○

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This paper was first presented at the Gear and Shaft Technology seminar organized by the Institute of Materials Engineering Australasia.

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