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What is the difference between metals and ceramics-from the standpoint of industrial scientist.

K.Funatani

Nihon Parkerizing Co.,Ltd
Nihonbashi 2-1-15, Chuou-ku, Tokyo, 103, Japan

Abstract

The excellent properties of advanced ceramic materials could give the more superior performance to miscelaneous industrial products by effective use of results attained by advancement of basic science and applied research work in processing, microstructure and defect control related with strength and fracture mechanism.

Break through from the ordinary reputation on ceramic materials as hard but extra-ordinary brittle, unreliable and expensive compared with metals, the difference and similarity of those materials should be discussed in more details.

Adding to extensive scientific research and development works at every country, as a results of lot of industrial development efforts in fabrication technology in Japan performed the mass market use of the ceramics components on domestic vehicles. The quality, reliability and product cost of those components are now reaching near the level of metalic and polymeric materials.

From the standpoint of industrial engineering, the importance of micro defect cont-rol, strength and toughness in relation with hardness and atomic bonding energy gove rning elastic and plastic deformation behaviors arediscussed in this paper.

1. INTRODUCTION

Based on long scientific R & D results and via extensive efforts in processing technology development made by Japanese ceramic manufacturers largely supported by the challenging attitudes of automotive industry have enabled the mass production of more than one dozen ceramic structural components on vehicles.

Ceramic processing as two steps gas pressure sintering method and nano-scale microstructure control concept have made alarge contributions to materialize the production of highly desified sintered products with satisfactory strength and reliability. And industrial efforts concentrated into the accumulation of bitter experiences and improvements to establish exact know how for consistent fabrication technologies made a greate contribution to realize the mass production of quality products.

On the other hand, the strength of Silicon Nitride the most popular automotive ceramic material has been improved day by day renewing the strength record, and reached the high level of more than 1,600 MPa flexural strength recently. Minimization of micro-flaw and control of silicon nitride crystal and size are the key of the strength.

Although the economical recession is disturbing the expansion of ceramics applications, the characteristics of the materials are contributable in many faces for solving miscellanious upcoming energy and ecological problems.

Considering the future possibility of increased use of the materials and fundamental concept of industrial materials engineering, it seems quite useful to assess the strength and toughness of the ceramics comparing with competitive metalic materials.

2. STRENGTH AND TOUGHNESS OF METALS AND STEELS

2.1. Strength and toughness of iron and metals.

During the long history of improvement of metals, strengthening of metals are mostly concentrated to depress and controle the plastic deformation resulting from the movement of dislocations. Strengthening of soft iron are performed by input of interstitial atoms as Carbon and Nitrogen, forming or precipitation of compounds as carbides, nitride and intermetalic compounds, to depress the dislocation movement and slip, resulting higher hardness and strength as shown in figure 1.

Other method to improve strength is change of crystal phase from pure soft alpha to over saturated and distorted crystal as martensitic structure via

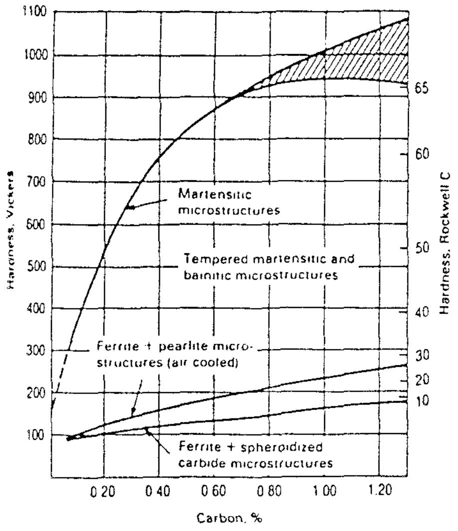

Fig.1. Hardness as a function of carbon content for various microstructures in steels(1).
Reprinted from:Metals Handbook 2nd Edt. 1985, Heat treating 28.9.

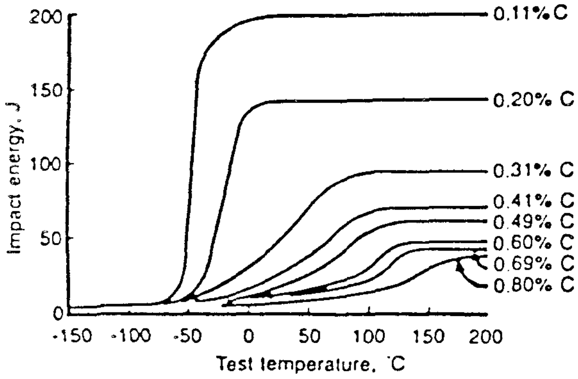

Fig.2. Change in impact strength with carbon and perlite content in normalized steels(2).
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carbon and nitrogen addition and phase transformation phenomena.
The hardness is almost directly co-related with higher proportional limit, stiffness and strength, depressed plastic deformation resulting in decrease of toughness or absorbed energy in fracture test as shown in figure 2.

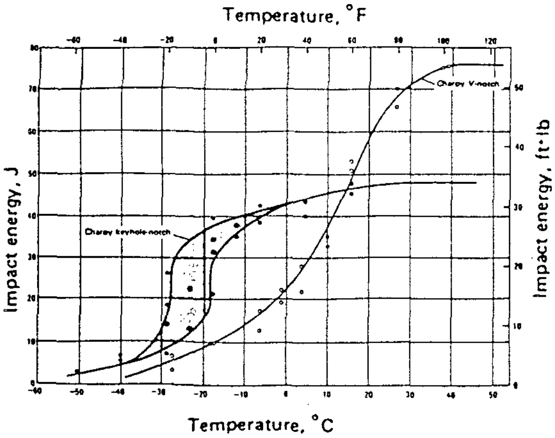

Fig.3. Transition behavior of low carbon steels(3).
Reprinted from:Metals Handbook 2nd Edt. 1985, Carbon and Aloy steels 4.84.

Toughness of materials especially of many steels are greately affected by testing temperature and show sharp drop under lowered test temperature as shown in figure 3 even with low carbon steels. The mobility of disloation and slip are affected by temeprature and are depressed quite extensively at lower temperature.

2.2. Strength and toughness of hardened steels

Contrary to the soft pure metals, most of metalic materials used for industrial products are hardened to sustain designed stress. Carbide tools and carburized and hardened steels used in high stress applications have high hardness and low toughness which fracture surface do not show pattern of deformation under impact or fatigue failures. The fracture pattern and energy absorbing properties are not so different from that of ceramics.

Toughness and brittleness are a little different concerning with plastic and elastic deformability and are very important when we consider the industrial applications. Tough material should not only be not brittle but also should possess good strength, and not yield nor crack at low stress. Any material cann't withstand to designed stress and easy to starts crack is difficult to use for most of industrial applications even it can absorb large energy. The toughness value measured by precracked test pieces can not directly useable for designing highly stressed component. High static and fatigue strength are proportinal to some extent and are very important to design durable components taking operational stress amplitude into account even the impact strength is rather low. In hard materials it should be noticed that crack propagation speed are faster compared with soft materials and could not anticipate crack heeling or suspended crack under highly stressed condition.

Therefore, the most important matter in long life component design is to prevent from crack initiation.

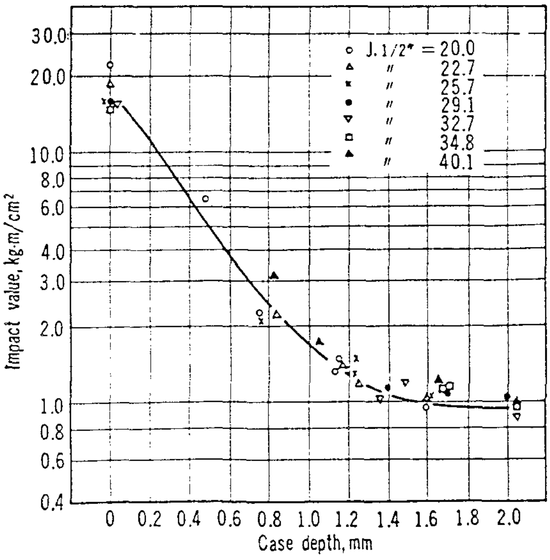

Fig.4. Change in Charpy impact strength with different carburizing case depth.

Automotive gearing materials used for transmission and chassis components are carburized and hardened for excellent wear and fatigue live. Those hardened materials have very low shock value and their fractography of carburized and hardened steel is similer to that of ceramics and are very flat and smooth, which is quite different from that of soft or quench and tempered materials. As shown in figure 4 increased case depth has large effect and sharply lower their impact strength(4).

As the carburized case increases the impact strength drops remarkably and becomes almost constant at thicker than 1.2 mm case depth where impact value becomes constant about 1.0 kg-m /cm^2.

They do not reveal deformation and quite difficult to decide the cause of fracture. However, by the observation of micro-fractography by SEM or high resolution Electron Microscope (HREM) we can identify the starting position and fracture history and same approach can be applied to ceramics(5).

Investigation of the change of peak load and absorbed energy to make crack and to propagate it in the load strain-time impact curve of the carbudized and hardened steels, it was made clear that even though the total energy of high hardness core test piece is smaller, but its maximum load is higher, as shown in figure 5. Tendency completely reverse to the crack forming energy of the total and crack propagation energy were made clear that contrary to the larger total absorbed energy, maximum load and energy to initiate crack of softer core test piece are lower than that of hard core pieces(5). This results indicate that the energy to initiate crack and to propagate crack is not always proportional. According to this investigation results, strength design of a gear having time dependent failure was improved and succeeded to eliminate failure trouble completely by giving higher core strength and resulting lower total energy. Toughness measured by precracked test piece methods dosen't proportionally related with true crack initiating properties and missleading at some conditions.

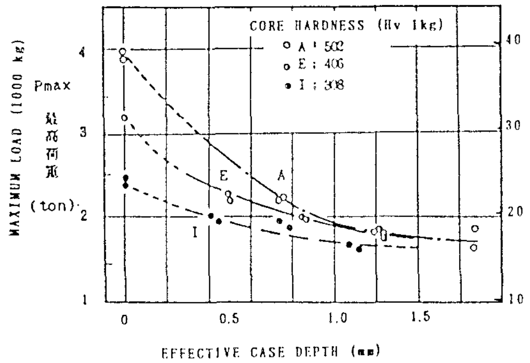

Fig.5. Change of peak load in Charpy impact test of carburized hardened test pieces with different core hardness(5).

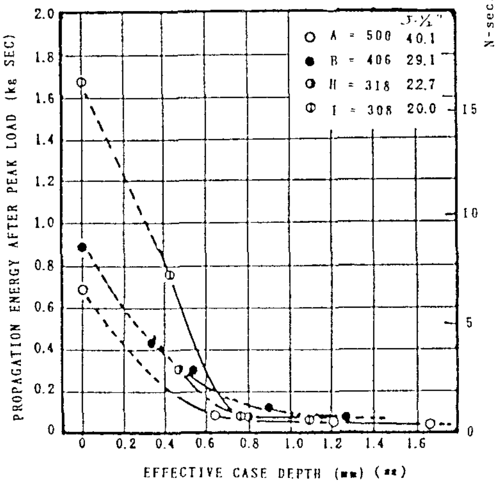

Fig.6. Change of absorbed energy in Charpy impact test of carburized hardened test pieces with different core hardness(5).

Brittle fracture phenomena, of metalic materials especially at lower than transition temperature is similar to that of room temprature toughness of ceramics, but their temperature zone are quite apart because of the difference of atomic bonding energy. Those relation are concerned with types of crystal and bonding energy and governed by thermodynamics.

3. STRENGTH AND TOUGHNESS OF CERAMICS

Despite the well said effect of defects and flaw within ceramics materials, research and investigation in this area up to recent years are quite unsatisfactory caused by traditional research methods depended to much on the non-destructive inspection methods, and partly related with methods of microstructure observations. Both of those reason disturbed direct observation of defects size and distributions. Ceramics research routs from traditional ceramics products with low density porous structure also seemed to cause those results. Not only the strength and toughness of ceramics products but also that of powder metallurgy products have quite similer experiences with defects distribution like the relation between steel strength and toughness with inclusions. Figure 7 shows the relation between density and impact strength of forged iron power metallurgy preforms. Greate increase of impact strength are attainable by almost theoretical density compact suggesting the importance of minor defects even in the case of sintered and forged iron having very good deformabilities(6).
The problematic of brittleness of very hard ceramics materials in early years are seened to be caused by poor density resulted from poor raw powder quality and unsatisfactoly forming and sintering processes.

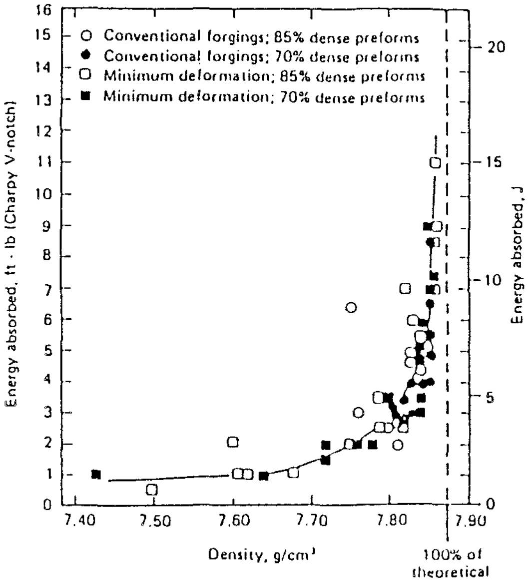

Fig.7. Charpy V-notch strength of P/M forgings as a function of density.
Reprinted from:Metals Handbook,2nd Edt. Ferrous powder Metallurgy,25.5.

3.1. A challenge to high strength silicon nitride.

Different from NDT evaluation methods use of optical microscope is quite useful to evaluate residual surface micro flaws. The effects of powder and processing variables are co-related with

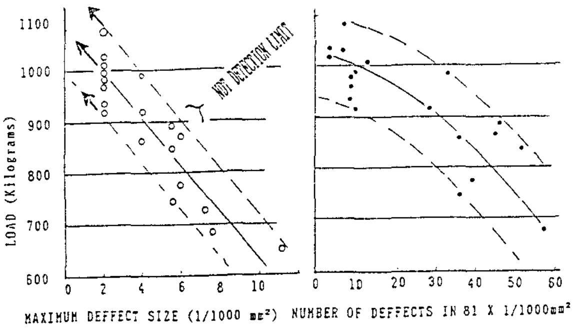

Fig.8. Flexural strength of sintered Silicon Nitride as a function of size and amount of small defects(7).

defects data obtained via optical observation down to micron order and shown in Figure 8. Revealing the size and amount of small defects have large influence on the strength of sintered body.

Adding to the improvement of minimizing the size and amount of defect observation method a series of research in the investigation in crystal phase and microstructure control resulted in recording high strength value of more than 1600 MPa. The high performnce sintered body give many improved physical properties including toughness value and enabled to get high K_{IC} 6.2 value and Charpy Impact value of 15 N/mm^2, nearly to that of carburized and hardened steels as shown in figure 8 and 9.

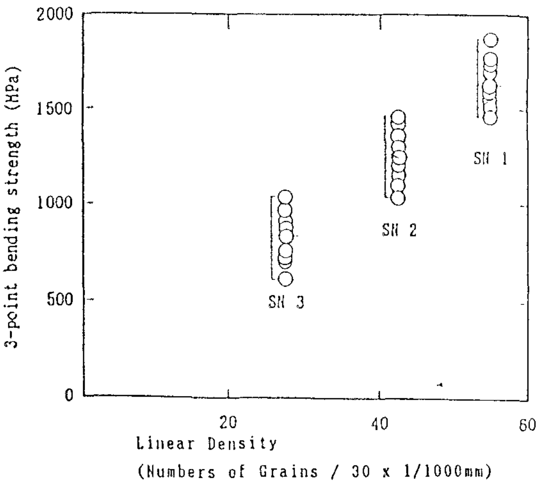

Fig.9. Effects of crystal size on the flexural strength of sintered silicon nitride(8).

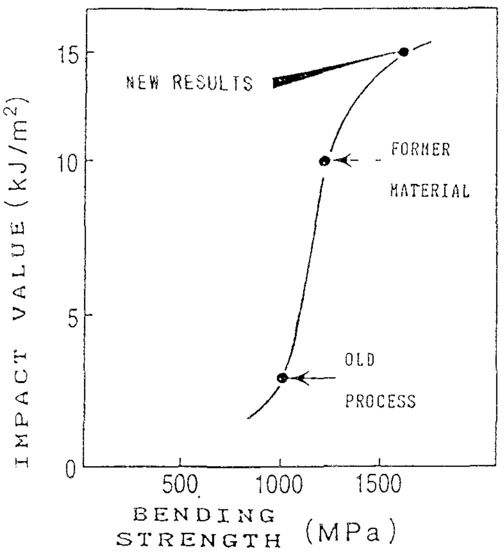

Fig.10. Progress of improvement Charpy impact strength of sintered silicon nitride(8).

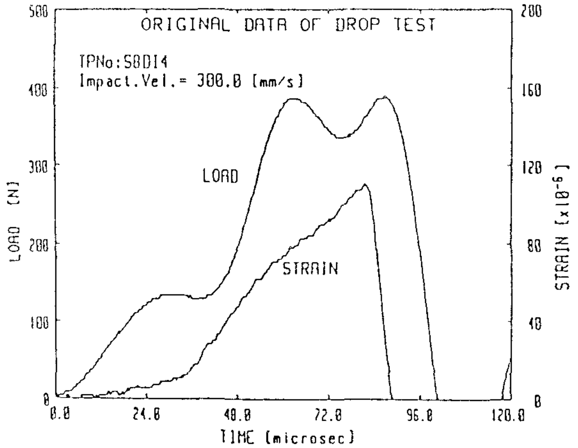

Fig.11. Typical load and strain-time curve of ceamics(9).

3.2. Toughness and Resilience

In both of flexural, fracture toughness or drop test of carburized and hardenend steels and hard ceramic, test piece formes crack and propagates rapidly at the peak load without showing any proportional limit of two percent elongation (Fig. 11). The same is also observed in bending and impact test of carburized and hardened steels. High hardness and strength are mostly accompanied with high stiffness and youngs moduls enable to store very large energy before crack formation and instantanious fracture.

Tough does not only means hard to crack but also means a property with good strength and not to yield at low stress. There is no wonder that toughness is important but it is wonderous whether the materialas does not have high strength and rather easy to crack but absorbs a lot of energy could get fair position as a useful materials usable for mechanical design and engineering.

As mentioned before on carburized and hardnened steels energy necessary to form crack is not always proportional to energy for propagation. the toughness value tested by precracked specimen based on a important assumption should be more carefully handled in strength and life design of industrial products. Especially with high stress component design it should extends satisfactory properties not to break nor yield, nor crack at the designed stress amplitude and life. Crack propagation speed of hard materials is much faster than that of soft materials and could not anticipate crack heeling nor suspended crack under high stress condition. Therefore, the most important matter in engineering design of high strength hard materials is how to prevent from cracking via investigation of operating stress level and amplitude and optimisation of material selection and their strength.

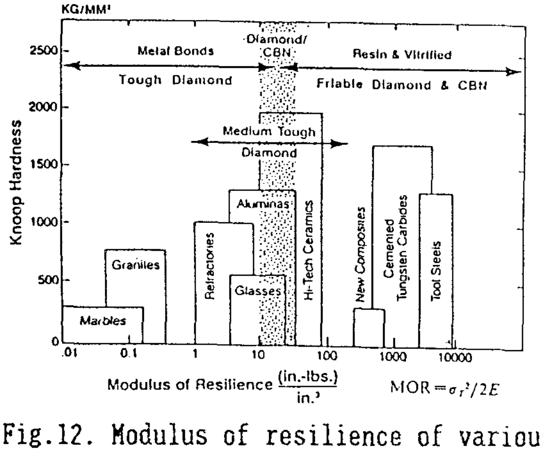

Fig.12. Modulus of resilience of various materials(10).
Reprinted from:C.F.Gardiner,Cera.Blet., V.67, N.6,1007, 1988.

High hardness and strength property accompanies low impact strength in most of the case in relation with elastic and plastic deformability resulting from its crystal type and binding mode. Whether the properties of ceramics and metals are completely different or not should be eveluated by Modulus of Resilience where natural gem, synthetic ceramics and hard carbide tools are comparable in one measure as shown in figure 12. And by the further research and development in ceramic science and processing technologies their properties may much improved and also the gap between metals and ceramics will be reduced in the future.

4. SUMMARY

1. Differences between pure and soft metals and ceramics are very large, but metalic materials and steel used for industrial machine and equipments hardened to give designed strength. Increase of strength reduce the ductility down to show brittle fracture depending on the test condition and its strength.
2. Hardened metalic materials such as carburized and hardened work exhibits very low impact strength and fractures without showing any deformation similar to ceramics.
3. Crack initiate at the peak load in hard and high strength materials and propagate very quick thereafter. Energy to form crack seems to be increased by material strength improvement and is not always proportinal to the energy to propagate.

4. Minimization of micron size defects and nano size microstructure control accompanied with control ofcrystal phase and size via advanced ceramic processing enabled fabrication of silicon nitride with morethan 1600 MPa flexural strength and 15 N/mm^2 Charpy strength.

5. Although the hardness and stiffness of ceramics materials is much higher than hardened metals their mechanical behavior exhibits many similarities and it seemed better to co-relate their properties with the measure of Modulus of resilience.

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