Globalization's Effect Upon Gear Steel Quality
Background on development of high-speed, automatic hardness tester

Aizoh Kubo

Introduction
Globalization continues driving the world economy — with deterioration of gear steel quality as one of its ramifications.

In this presentation, examples of gear failure are shown and gear material problems are introduced.

For example — it is difficult today for companies to confirm the real quality of purchased gear steels because their gear engineers are not metallurgists and therefore do not have the time — nor money — for that inspection. To address the quality issue regarding purchased steel, we have developed a new tester for measuring thousand-points hardness — automatically — and in quick order. Examples of quality evaluation of some steels with this tester are introduced here.

As a gearing troubleshooter, I feel that the probability of material problems causing gear failure have increased since globalization of the world economy. The deterioration of gear steel quality is the rational result of globalization because purchasing departments of machine companies typically look for the cheapest choice among the same mill-certified steels around the world. The usual question from the purchasing department regarding gear material is, "Why do we pay so much money for the same steel? There is much cheaper steel of the same kind in the world."

Gear steel prices enter the market today amid fierce competition between industrialized countries and other emerging players. Similar to gear engineers not being metallurgists, purchasing agents are typically not mechanical engineers. Nor, for that matter, is a company's top management, who severely cut production costs. As opposed to obtaining available steel of top quality, the nominal-quality steel is received by the standardized steel name and bearing a mill test report (mill inspection certificate). In today's competitive atmosphere "expensive" — but high-quality — steel can barely make it to market. There are also some cases where steel quality somehow changes for the worse after the purchasing contract was signed. The reliable checking of steel quality requires solid metallurgical knowledge, time, and money, rendering users' prompt checking of gear steel quality difficult. In Japan we have created a new-concept apparatus for quality evaluation of gear steels, for which some information is here introduced. I also intend with this presentation to help people understand that good quality costs money is why "it takes money to make money" — a universal fact.

High-Strength Gear Steel
In machine design textbooks the definite values of strength and endurance limits are always written for steel material to be used as machine parts, which imparts incorrect information to the green machine designer, i.e. — that the steel material is "homogeneous." An so there is nothing gained by informing them that steel is *heterogeneous* and thus contains a considerable amount of inclusions and foreign objects.

Figure 1 is an example of typical gear steel — a big naval bevel gear made from 18CrNiMo67 steel that incurred some mild scuffing, and the matrix material on the surface is slightly removed while inclusions appear on the tooth flank. Today, high-strength steel for gear manufacture is designed to disturb the movement of dislocation inside the steel matrix by distributing solid solution

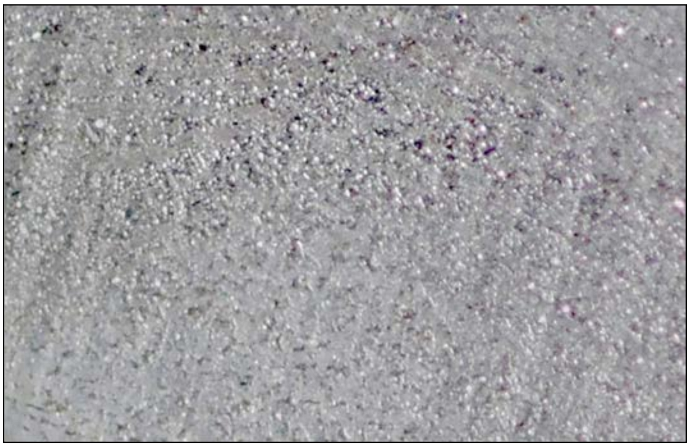

Figure 1 Inclusions that appear on the gear tooth.

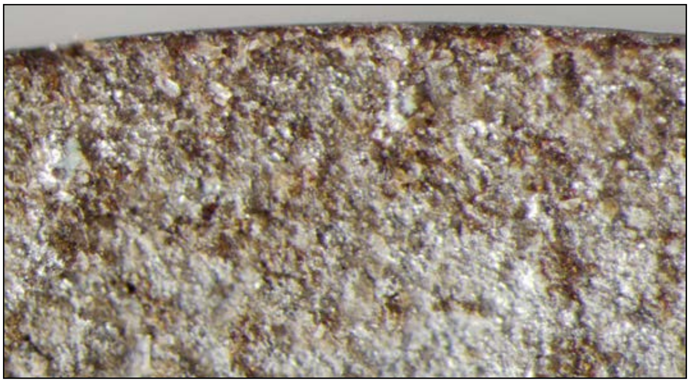

Figure 2 Fracture section of case hardened CrMo steel bar specimen, after endurance test.

This paper waqs first presented at the 2017 VDI Conference on Gears, Munich.

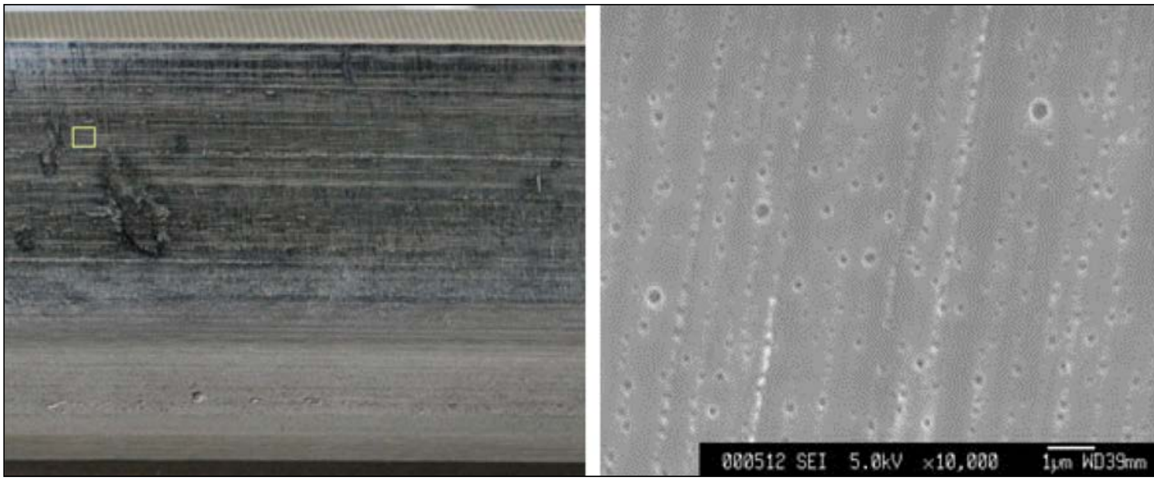

Figure 3 **Tooth flank after long heavy usage (left) and the observed SEM picture.**

and/or precipitating articles properly into the matrix. It is as if gear steel were a mixture of small stones in mud; thus it is never homogeneous, and stones in mud carry the load and resist wear.

Figure 2 shows another example — a fractured surface of a case-hardened steel specimen made from JIS SCN420H after bending-rotating endurance testing. You can see many black balls; those are precipitating particles to carry load. One common problem is that those particles are barely detected by conventional testing methods of steel quality before endurance testing.

Figure 3 (left) shows a failed tooth flank of a case-hardened, ground helical gear made from JIS SCM835 steel after long, heavy usage. (In Fig. 3, right) is the SEM picture of a still-healthy part of that tooth flank shown with rectangle frame in (Fig. 3, left). The SEM picture was made with replica and the dark spots are surely particles in the steel matrix. It is very strange that those particles align in lines of sliding direction between contacting tooth flanks. There are only two probable reasons for this: 1) the particles align by the plastic deformation of the steel matrix through strong frictional force due to slipping tooth flank contact; or 2) they were created during the gear operation by strong frictional heating. This shows that those hard particles in the matrix of high-strength gear steel carry considerable stress.

Production of Gear Blank

Today, most steel is produced via electric heating converter. Melted steel material is processed with continuous casting into a bloom bar. The sampling for elements-check for the mill certificate of this steel is usually taken from the melted steel in the upper stage of the production. During cooling, steel congeals and crystalizes. Crystal formation proceeds differently from part to part of the bloom material. Impurities in the melted steel gather more thickly at the center of the cross-section.

Figure 4 shows a macro-etched cross-section of a steel bloom obtained by cutting the bloom just after its congealed state in continuous casting production. There are many impurities, voids, etc. in the central part of the bloom. The steel bar that we usually use for gear production is made from such a bloom via the press-rolling process, which means that the steel texture remains almost the same as that of Figure 4. When the amount of discarded steel reduces to help offset economical steel production cost, some amount of agents for refining — like Al, Si etc. — remain in final-state steel bar available on the market. Figure 5 shows a cross-section of a CrMo steel blank of 800 mm

Figure 4 **Cross-section of steel bloom just after congealed state in CC production.**

Figure 5 **Macro-etched figure of a cross-section of CrMo steel bar of 800 mm diameter.**

diameter for gears. Around the center of the blank, segregated impurity and voids are distributed in circular fashion. Each part of the segregation has considerable length in the axial direction of the blank. Figure 6 shows a macro-etched figure of rectangular CrMo steel slab of 500 mm side length. The left edge is the surface of the rectangle slab, and ca.⅛ from the right edge is the center of the slab. It is clear that the state of crystallization and impurity distribution at both the periphery and center of the slab are different. Surely the strength or the durability of the material is considerably different at the peripheral or middle of the cross-section and at the central part. But the gear designer calculates the load-carrying capacity of gears using the same value for the material strength that is typically indicated by the specification of the steel.

The gear blank of an internal gear has more serious problems because the gear blank takes ring form, which means that the internal gear teeth are made at the central part of the original steel slab, where much segregation, etc., exists. Figure 7 (left) shows a cross-section of a blank piece for a large internal gear; this figure is digitally treated to increase the contrast. The upper side of (Fig. 7) corresponds to the central part of the slab, i.e. — the part to be toothed. To ring form the gear blank the central part of the original slab is punched to create a hole from both front and reverse sides. You can see the state of plastic flow of the material: the twisted figure of segregation curves. The internal gear made from this gear blank operated for several years before suffering from a strange surface failure (Fig. 7, right). This gear was not case-hardened; it was a so-called "soft" gear. But the cracks observed on the tooth flank look very brittle. The run of cracks corresponds to the plastic deformation flow curves inside the gear blank, along which the material contains much segregation. Surely the cause of this surface failure has a strong correlation with the steel quality.

Figure 8 (left) shows the fracture surface of a case-hardened SCM420H steel bar specimen; a test was conducted (Ref. 1). In the cross-section a great deal of hard-to-explain segregation is observed. The test piece was cut at 2 mm; a partial specimen from this fractured section was polished and nital-etched; the (Fig. 8, right) figure shows the result. The figure appears here in the same angular position as the (Fig. 8, left) figure. In observing this etched surface it is difficult to determine that this specimen contains such a robust segregation

Figure 6 Macro-etched figure of 500 mm rectangular CrMo steel slab made by rolling.

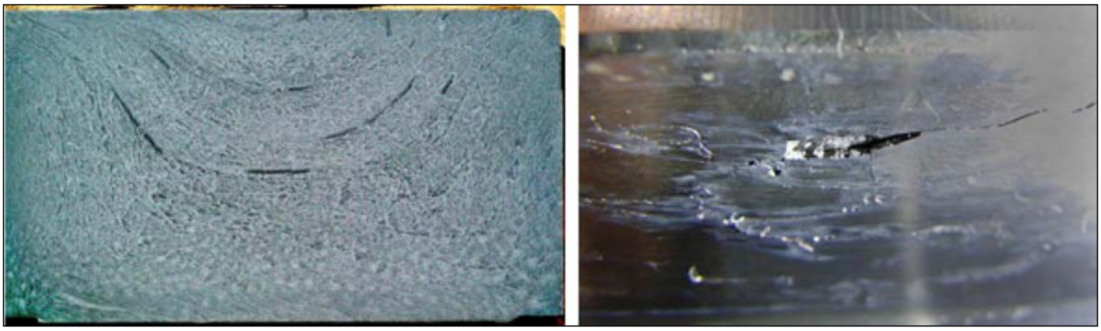

Figure 7 Plastic flow and segregation remained in the cross-section of a blank for big internal gear. **Induced tooth flank failure.**

Figure 8 Segregation found in fatigue fracture surface and the polished and etched figure.

Figure 9 **Cluster forming of impurity particles in gear steel.**

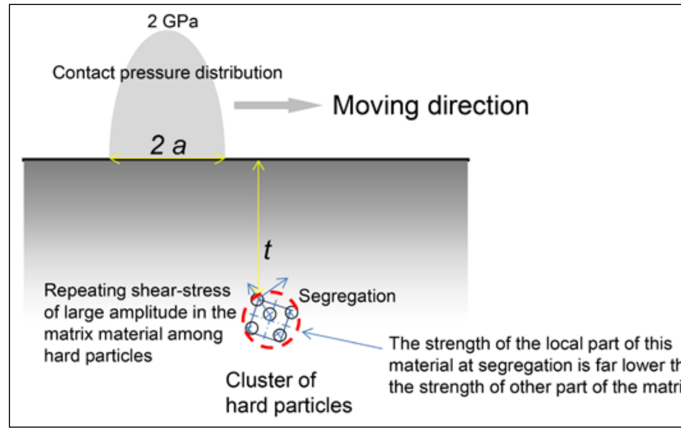

Figure 10 **Possible micro crack initiation in a cluster of inclusion.**

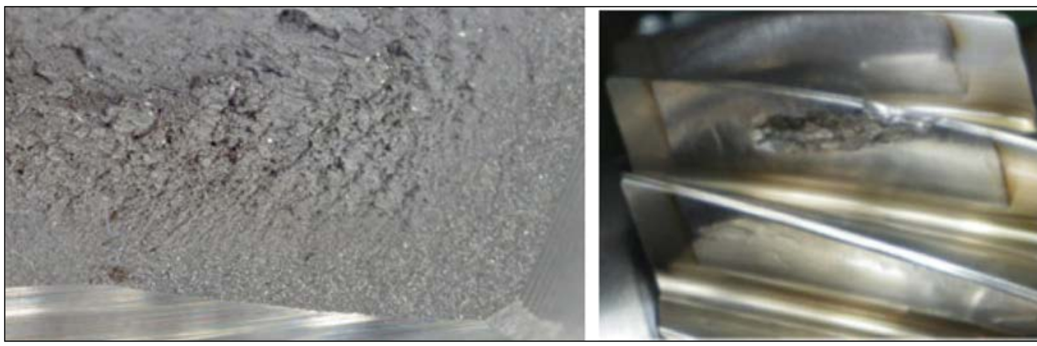

Figure 11 **Cluster of impurity particles just under the tooth flank. Sudden spalling of tooth flank.**

in material texture. This is a very serious problem in that qualified mechanical engineers could not determine steel quality via accepted etching methods.

Material-Induced Gear Failure

As previously mentioned, the steel material is *designed* as homogeneous — but is actually heterogeneous and contains a considerable amount of inclusions. Foreign objects — small, hard particles in the steel matrix — work in part to strengthen the material. To do so the foreign objects must be small and distributed uniformly within the material. In actual steel material, however, it is not easy to realize such a homogeneous state.

Figure 9 shows an example of an undesirable state of existence of impurities in steel matrix, i.e. — they gather and form a cluster. Also in this material some thin layers of MnS exist (Fig. 9, lower right). You can see the oblique ridges of material in the fractured section. When a cluster of hard particles exists in the material, just beneath the surface, and the surface is loaded with heavy contact, the state of shearing stress induced between the particles in the cluster differs from that of homogeneous material. The shearing stress between hard particles in the cluster becomes higher than normally induced stress value (Fig. 10), and micro-crack can initiate there rather easily. Such micro-cracks are thought to be a trigger for the development of *macro*-crack, which leads to the fracture of, for example, gear teeth. Figure 11 (left) shows a fractured surface of gear tooth broken in the endurance test. In (Fig. 11, lower left) a cluster of impurity particles is found just under the tooth flank. A helical gear was made from the same material, of the same lot, and an endurance test was conducted under the maximum contact pressure of 2.3 GPa. Until 3×10^7 loading cycles, all tooth flanks showed no sign of failure initiation. At 3.7×10^7 loading cycles, there appeared suddenly a big and deep spalling of tooth flank. On the bottom of the crack cavity a cluster of foreign objects was observed. Other tooth flanks of this gear are all OK and look quite healthy. There is no sign of surface failure (Fig. 11, right).

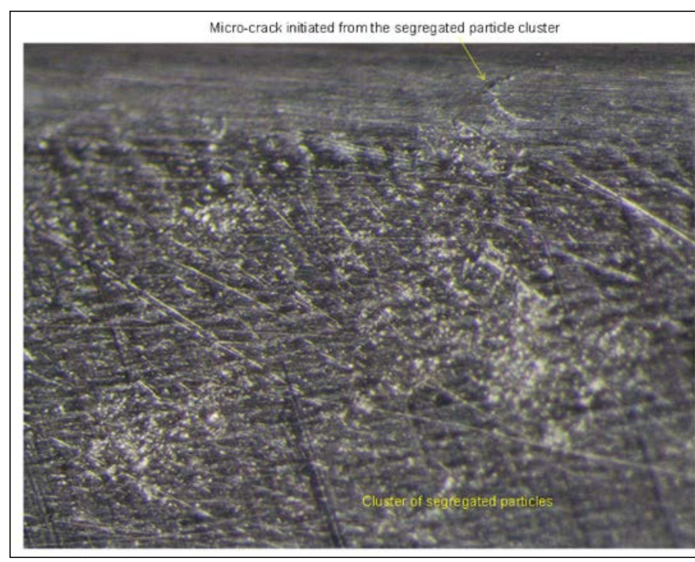

Figure 12 **Cluster of impurity particles appeared on tooth flank from which a fatigue crack initiated.**

On another tooth flank of the same gear, a cluster of impurity particles was found on the surface of the tooth flank (Fig. 12); a fatigue micro-crack initiated from that impurity cluster.

Summing up the above — the existence of impurity clusters can be a cause of serious tooth flank failure that can lead to tooth breakage. To evaluate gear steel quality, we should pay much more attention to checking for the existence of impurity clusters.

Detailed Measurement of Steel Hardness

We know of course that the hardness of steel is synonymous with strength. We usually use hardness measurement to evaluate heat treatment to find whether the process is carried out properly or not. At measurement when light loading is used, the scattering of measured data becomes extensive. To obtain a stable result, rather larger loading is typically used. When considering the nature of steel texture — consisting of crystals and some inclusions — it is heterogeneous. Then the scattering of measured hardness values must have some meaning, when the measurement is carried out accurately. To address this issue a high-speed, automatic hardness tester has been developed as a joint project of JGMA (Japan Gear Manufacturers Association) and RIAS (Research Institute for Applied Sciences), with the financial support of the Japanese Ministry for Economy, Technology and Industry. In Figure 13 we see a test piece for the measurement. The material is annealed carbon steel JIS SK4, and the surface is mirror-like-polished with a roughness of Rz = 0.07 μm. The surface to be measured cannot reflect light into camera; the lighting is peripheral and the surface looks black. The entire surface looks uniform and the steel quality looks perfect. The dotted horizontal band in the diagonal position of the specimen is the trace of 1,200 points of Hv measurement. With 50g loading and each 3 seconds steady loading time, the measurement took 86 minutes (Fig. 14). In the region near the center of the specimen, an abnormal situation is clearly observed that must be material-related, but its indication has never been found.

To determine the cause of this measured result of probable material problems, the specimen was aggressively macro-nital-etched. The roughness of the etched surface becomes Rz = ca. 4 μm. Near the center of the specimen a dim, circle-like figure appears. This position corresponds well with the state of hardness distribution in Figure 17. This indicates the probable existence of segregation in this bar steel material. The large number of hardness tests with rather smaller loading appears to be a good method for identifying material quality problems.

Figure 15 shows a measured hardness of a case-hardened, big bevel wheel tooth at 600 points. It is clearly observed from the rather wide scattering band of hardness in the right part of the figure that the texture of the core is constructed with different kinds of steel crystals. But in the hardened case the scattering band becomes narrow,

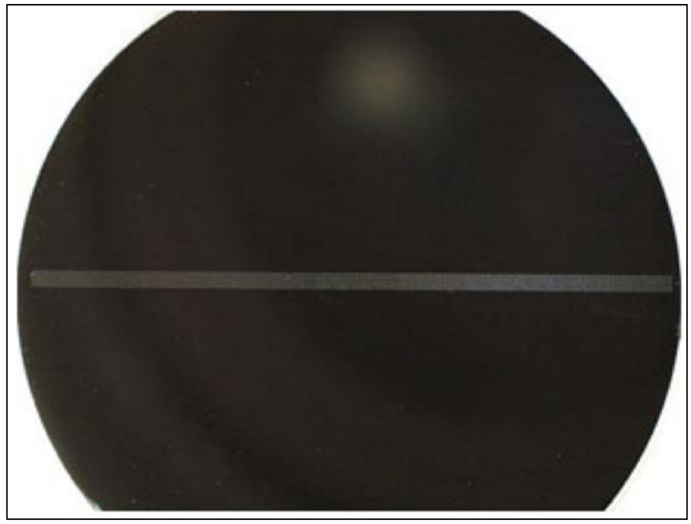

Figure 13 Specimen for hardness measurement.

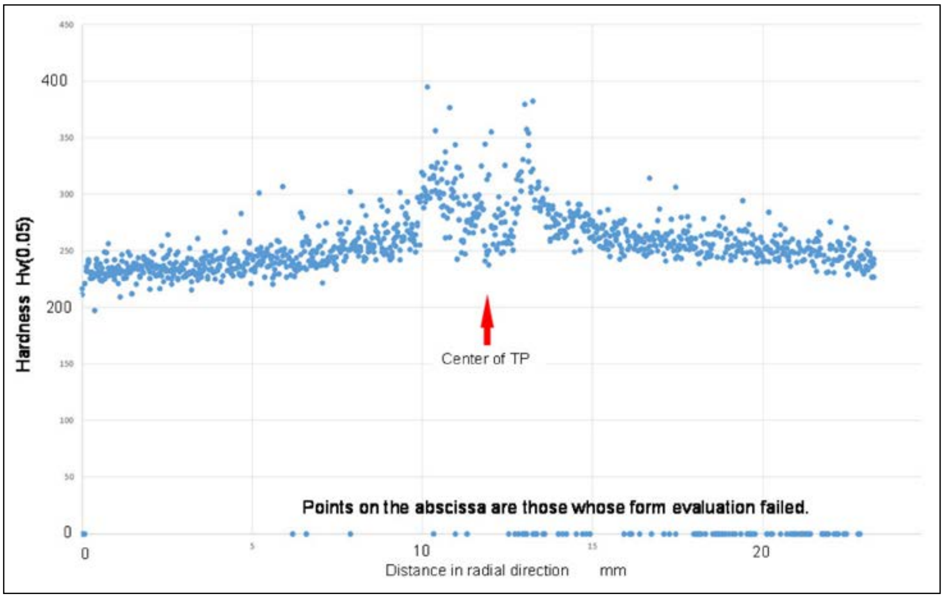

Figure 14 Measured Vickers' hardness value distribution.

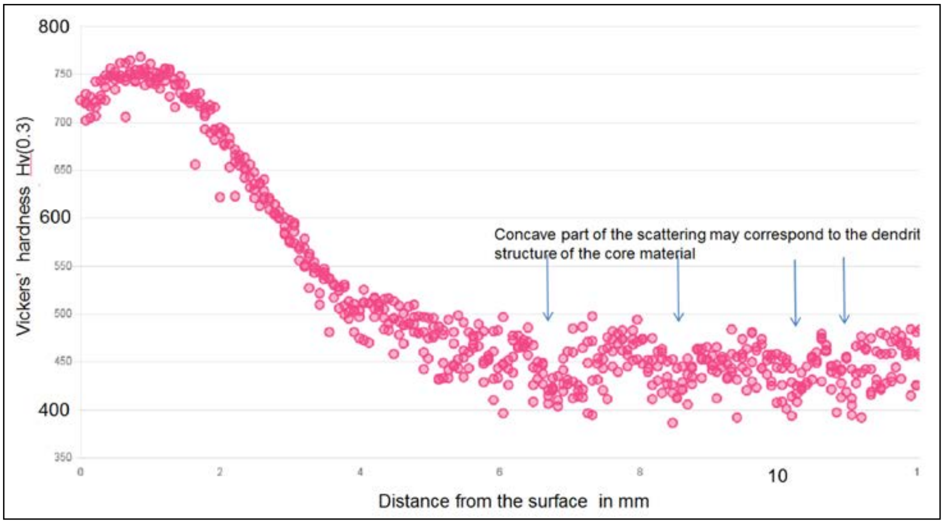

Figure 15 Case hardness of carburized gear tooth.

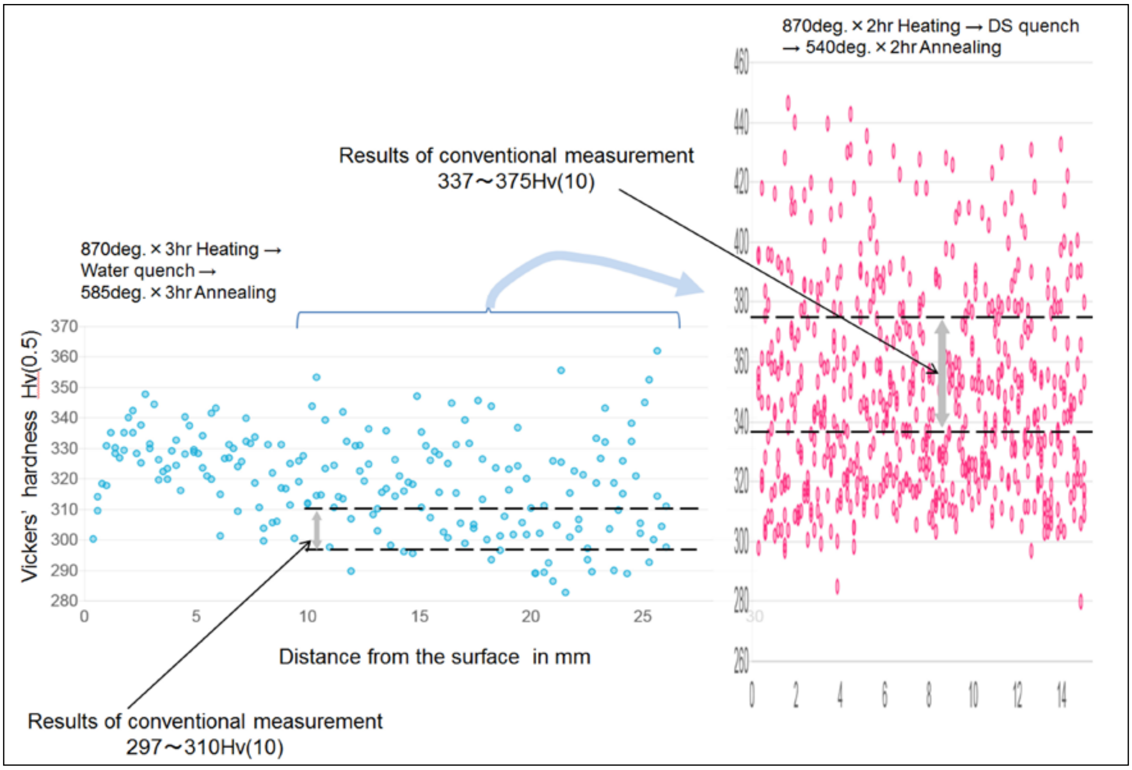

Figure 16 Difference of hardness as function of the loading value at measurement.

indicating that the kind of constructing crystals is focused. Near the tooth flank surface the hardness drops — perhaps due to the escape of carbon.

Figure 16 shows the hardness of JIS SCM435 steel after two different quench and tempering processes; both test pieces were made from the corresponding position of the same steel block. The hardness was measured with the conventional method using constant load 10kg. The hardness of the 2-hour-processed specimen is Hv337-375, and that of the 3-hour-processed is Hv297-310, where the kind of cooling media was different. The test surface was then hand-lapped carefully for smoothness and the hardness was measured with 500g loading at many points over the same part of the specimen. It clearly shows that the hardness measured with light loading has wide scattering. We can see that this wide scattering band of hardness values is compressed to narrow band, when large loading is incorporated; very local high hardness values cannot be measured and vanish. It is important to find the high-hardness inclusion and its state of distribution in the matrix because local hard material in the texture could induce very local initiation of micro-crack in the neighboring, soft part of the texture.

Such important information concerning steel quality is lost when we incorporate large loading at hardness measurement. It is perhaps better to measure the hardness at as many points as possible using rather light loading, and to evaluate the scattering distribution of the hardness. Such a method can produce a lot of information about steel quality, in comparison with the evaluation based on a rather small sample size of hardness values under heavy loading. Incorporation of heavy loading at hardness measurement means that the operator puts a high-cut mechanical filter on that measurement.

Conclusions

With globalization of the world's economic structure, gear steel quality can no longer be guaranteed using last-century testing methods. The result is "garbage in — garbage out."

Segregation, impurities, etc. remain in the material and do not disperse well in the material; they often gather together and cluster; and the crystal structure of the material becomes lamellar. All of which impacts steel quality.

Hardness tests using heavy loading elicit high-cut-filtered information, including regarding material quality.

Hardness testing at many points using rather light loading and evaluating the bandwidth of the scattering distribution of measured data produces critical information about the steel quality. It is a proven method for identifying inferior-quality steel.

References:

1. Kubo, A., S. Matsumoto, M. Nakamura et al. "Contact Bending Fatigue Test of Gear Material Against Failure Due to Tribo-Cause to Fatal Subsurface Crack Propagation," *Proc. Int'l VDI Conference on Gears*, Oct. 2013.

Prof.hc.Dr.-Ing. Aizoh Kubo earned his degrees, including his 1971 Ph.D. (research on the dynamics of high-speed gearing), from Kyoto University. He subsequently served as guest researcher at the University of Stutgart (1972) and at FZG, T.U. Muenchen (1973). Kubo's professional/academic career began (1971–1979) as a research associate at the Kyoto Institute of Technology, followed by fifteen years (1979–1994) as associate professor at Kyoto University's precision mechanics department. From 1994–2007 he was a full professor in the university's department of mechanical engineering. Since 2007, Kubo began Gear Technologies Company (owner and president), was general manager of the Research Institute for Applied Sciences EV, and since 2009 has been president of Alchemica Co. Ltd.