Application of a Unique Anti-Wear Technology — Ion-Sulfurized Lubricating Gradient Material

By Gordon Wang, Yifei Zhang, Xinhui Zhang, and Hua Liu

Ion-sulfurized lubricating gradient material (LGM) is a state-of-the-art technology conferring excellent anti-friction and wear-resistant characteristics on metallic parts, including gears, splines, and bearings. In this article, the engineering characteristics of LGM technology are introduced and exemplary applications are presented.

HISTORY OF ION-SULFURIZED LUBRICATING GRADIENT MATERIAL (LGM) TECHNOLOGY
In modern industry, large fraction of machinery components, including gears, splines, and bearings, continually fall out of service because of wear and wear-related damages, along with which there is tremendous loss in raw materials, labor, and energy. Besides wear damages, friction consumes huge power share and decreases power transferring efficiency. Lubricating oil and grease can fail at a variety of conditions, which sometimes cause severe accidents [1]. Therefore, sound friction-reduction and wear-resistant technology is beneficial to economy, environment and safety.

With such background, in 1980s, physicist Zhang Yifei developed the low-temperature physiochemical ion-sulfurization technology. In a vacuum environment, ionized sulfur diffuses into the metal, and a solid-lubricating case with composition gradient of sulfur is formed. Thus this technology is called ion-sulfurized lubricating gradient material (LGM) technology, or LGM technology, and the ion-sulfurization process is called LGM process. The LGM configuration is indicated in Figure 1, and the microscopic picture in cross section is shown in Figure 2. During the implementation and industrialization of this technology, substantial engineering advantages have drawn a constantly increasing attention.

CHARACTERISTICS OF LGM
Extraordinary tribological characteristics
The sulfides formed in LGM process possess hexagonal lattice structure and extreme lattice anisotropy, which contributes to low friction coefficient [2]. Owing to such characteristics, LGM technology increases power-transferring efficient and reduces friction heat. It also retards asperity welding and adhesive wear with insufficient or non-uniform lubricant, especially under high speed rolling and sliding condition.

There are various surface processing mythologies that target acquiring advanced tribological properties on metallic parts, including physical or chemical depositing/bonding/spraying, and chemical diffusion process, like carburization and nitriding [3, 4]. LGM technology distinguished itself by forming a micro-porous friction-reduction layer.

Due to its micro porous feature (Figure 3), the LGM layer provides myriads of micro-reservoirs for lubricant agent and ensures hydrodynamic lubrication. Efficient lubrication alleviates seizure and galling and prevents premature failure. Furthermore, regular lubricants might fail under certain circumstances, such as chemical decay, emulsion instability, and foaming. Thus, solid lubrication effect of LGM layer functions as backup protection under unexpected lubricant deterioration.

It is well recognized that high contact load in gears causes extreme-pressure malfunction in lubricant [5]. The LGM layer, however, mitigates shear stress in lubricant and compensates for the insufficient extreme-pressure additives.

Another noticeable engineering benefit of LGM is that it reduces run-in time, as it smoothes the part’s surface via merging contact asperities.
The LGM processed article maintains a solid lubricating and wear-resistant surface, either at elevated-temperature or in radiating environment. Ion-sulfurized LGM in steel is able to maintain its lubricating property at a temperature even higher than phase transformation temperature of steel, while conventional lubricating grease only works up to 300ºC (specific formula may survive a higher temperature), and molybdenum disulfides survive 315ºC under non-vacuum environment [2].

LGM technology is being utilized in steel molds/dies in forming aluminum parts, due to the chemically inert characteristics of the sulfide layer. Figure 4 indicates that less damage was induced from service of LGM processed tools.

In regular dies, the chilling effect from the mold-releasing agents sets on hot fatigue cracks on surface. However, the sulfide layer allows for less amount of mold-release agent to be used, which inhibits the occurrence of this kind of cracks (Figure 5). LGM process is also being applied in steel hot milling industry. The service life of LGM processed rolls, made of either alloy or cast iron, can increase by 50% ~ 100%.

**Nondestructive inspection effect**

With LGM processing, the sharp geometric non-continuities on parts turn more readily visible via color contrast, which is the effect of sulfur plasma interacting with geometric edges. Such advantage can be specified to delineate surface cracks induced by heat treatment, forging, welding, hydrogen embrittlement, and grinding or hard turning. Therefore, open defects can be identified visually, as in conventional dye-penetration or magnetic-powder inspection. This approach helps avoid assembling flawed parts into machines or automobiles and reduces latent maintenance cost. One exemplary defect is shown in Figure 5.

**Friction/wear test**

Friction and wear test was designed in a manner that severe wear condition of bearing ball was simulated - the sliding of ball against steel ring. There was a remarkable reduction in friction coefficient and wear marks on LGM processed bearing rollers. Although this test was conducted on ball/ring pair for simplicity and expedition, analogous contributions of LGM can be observed in gears.

**No distortion in LGM process**

LGM is formed at temperatures as low as 80ºC ~ 200ºC, which is lower than the tempering temperature for most carbon and alloy steels. Thus, the microstructures of the substrate are not impaired. The process inflicts no geometric distortion, and the dimension variation is below 0.0005 mm. There is no need for finish grinding under most circumstances.

**An environment-friendly technology**

LGM is called a green technology, as very little hazardous emission and waste is released during the treatment. LGM extends part’s service life and renders low-cost metals gain excellent tribological properties, which reduces cost in raw materials. As the friction coefficient plummets, power and fuel consumption drops noticeably. Therefore, this technology is strategically advantageous since energy in one key-drive gear for the economy. With wear damage reduced, extra profit is garnered by reducing maintenance time and cost.

**TEST MACHINE, INTERFACE, AND SAMPLES**

A universal vertical friction and wear test machine was used in friction/wear test. The indicative test setup is shown in Figure 6. In each relatively sliding pair, there are two parts, φ 6.35 mm bearing ball, and φ 54 mm steel ring. Friction/wear data of LGM processed pair was compared with regularly heat treated/carburized pair.

The following list contains the primary test conditions:

- Steel bearing ball (surface roughness Ra=0.8μm: Fixed in disc clamp with one side sliding on the steel ring (surface roughness Ra=1.6 μm)
- Force: 50N
- Temperature: Room temperature
- Shaft rotating rate: 100 RPM in run-in, 800 RPM as working rate
- Time-span: 1 minute run-in at 100 RPM, and 21 minutes run at 800 RPM
Lubricant: #32 lubricating oil (viscosity 27~33 mm²/S at 40°C)

**SPECIMENS PREPARATION**

Two wear couples of bearing ball and steel ring were used, one pair was conventionally heat treated, and the other was LGM processed after conventional heat treatment.

I. Regularly processed parts
   - φ 6.35 mm bearing ball: AISI 52100, heat treated (quenched and tempered).
   - φ 54 mm steel ring: AISI 4118, carburized.

   Heat treatment for AISI 52100 bearing ball:
   Austenitize -> oil quench -> cryogenic treat -> temper to hardness HRC62-64.

   Heat treatment for AISI 4118 ring:
   Carburize - > double quench -> temper
   Case depth: 1.1-1.2mm, hardness HRC 54-56.

II. LGM processed parts
   - φ 6.35 mm bearing ball: AISI 52100, heat treated (quenched and tempered), and LGM processed.
   - φ 54 mm steel ring: AISI 4118, carburized, quenched and tempered, and LGM processed.

**WEAR INSPECTION**

Macro wear-marks were inspected with SLR camera, and micro wear marks were characterized with optical metallography.

**TEST RESULTS**

Tests indicate that on LGM processed parts, friction coefficient decreased by 30%, wear mark area dropped by 80%. Figures 7 and 8 demonstrate the friction coefficient data on regular wear couple composed of heat treated ball and carburized ring.

While Figures 9 and 10 show the friction coefficient on LGM processed test parts, it can be observed that LGM drastically reduces friction coefficient and force, and the peak values, which is highly correlated with improved run-in efficiency and reduced wear damages. Figures 7 and 9 indicate that LGM decreases heat build-up rate. Figures 11 through 14 present the comparison of wear marks on LGM processed parts with regularly heat treated and carburized parts. The wear mark morphology in the former is much less ridged.

**APPLICATION OF LGM IN GEARS AND BEYOND**

Conventional bulk heat treatments and surface treatments, including but not limited to quenching/tempering, carburizing, nitriding and other thermochemical processes, having being used to gain

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Test data on nitrided part</th>
<th>Test data on nitrided and LGM processed part</th>
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<tbody>
<tr>
<td>Load, N</td>
<td>Stress, MPa</td>
<td>Friction torque, Nm</td>
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<tr>
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<td>250</td>
</tr>
<tr>
<td>1500</td>
<td>7.5</td>
<td>320</td>
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<td>2000</td>
<td>10</td>
<td>450</td>
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NOTES: The data may vary per specific test condition.

Table 1. Indicative friction test comparison on nitrided part and nitrided/LGM processed part, under same lubricating condition (#32 lubricating oil, with viscosity of 27~33 mm²/S at 40°C)

- Lubricant: #32 lubricating oil (viscosity 27~33 mm²/S at 40°C)

Figure 4. Surface characteristics of tool steel mold conveying high-pressure liquid aluminum to cast mode (left, conventionally processed, used for 9599 cycles, right, LGM processed, used for 40322 cycles)

Figure 5. Surface defect identification in LGM processed bearing roller used in windmill power generator

Figure 6. Indicative configuration of friction and wear test machine.
friction and wear resistance [3]. Following heat treatment, and carburization or nitriding, which forms a microstructure with hardness, rigidity, and contact and flexural strength several times higher than brass, the gears/bearings can be further LGM processed, which greatly extends and upgrades the tribological property by superimposing a self-lubricating layer. Table 1 shows the benefit of LGM in friction coefficient with respect of nitriding process. The low-interaction LGM layer prohibits adhesive wear, which was considered as the most universal and least preventive form of wear [4]. The solid-lubricating effect also attenuates shear stress in the contact surface. Furthermore, the LGM technology improves marvelously the fatigue property, as to be described below. Because of those highlights, the substitution of LGM processed steel bears for counterparts made of copper alloys turns strategically valuable, and overcomes such drawbacks as low contact and flexure strength, hardness, toughness and rigidity. Furthermore, because of high strength and toughness of steels, the load-transferring unit can be more compact and precise. The high cost of copper also favors this tentative approach.

Table 1 indicates that in LGM processed parts, friction coefficient drops by 10~24%, compared to parts that were nitrided only. Friction temperature drops by 2~8% as well. Even without lubricant additive, parts with LGM are superior to regular counterparts in friction characteristics.

Ion-sulfurized LGM contributes greatly to fatigue resistance, primarily due to the dominating or consummating contribution(s) as detailed below:

- The run-in process in gears with LGM is rapid and efficient, thus reduces surface roughness, and alleviates localized stress raiser, which prevents the onset of microscopic fissures.
- It reduces shear stress and friction torque in part’s surface.
- It maintains a contiguous unbroken lubricant, which prohibits mechanical pitting effect caused by the bombarding force imposed by lubricant agency [5].
- It slows down the generation of working hardened layer in substrate.
The improvement in fatigue property in LGM processed gears is demonstrated in Figure 15. In engineering application, it shall be marked that the fatigue characteristic is a consummating effect of multiple factors. Gear design, dimension tolerance, and load configuration are no less critical than surface conditions.

In one world-class automobile enterprise, new-generation 10- to 12-speed transmission gearbox is used, and ten gears/splined parts were LGM processed. Picture of some LGM processed automotive parts is shown in Figure 16. The wear resistance, thermal stability, fatigue and assembly reliability were upgraded to a new level, even with heavy load, high rotating rate and harsh impact from gear switching. The transmission system with LGM processed gears passed the three yearlong 200,000 kilometer tests under various driving conditions. Typical test results in gears are listed in Table 2.

Due to its solid lubricating effect, LGM suits rolling and sliding units with limited addition of oil/grease lubricants, or under the condition of degrading lubricants. As tested in sun gears made of Nb-Ni alloy in aero engine, it yields reliable lubrication under no addition of lubricants and with a wide temperature range of -50ºC ~ 800ºC.

In one type of gas engine, multiple components, such as gears, piston rings, cylinders, crankshafts, camshafts, tappets,
valves and the rocker-arm shafts, were LGM processed. Only twenty three hours of run-in process stabilized the friction power, while the regular engine without LGM parts needed a run-in span of seventy four hours. In addition, the average frictional power-loss dropped by 4.7% for the engine with LGM parts, and up to 7% under high rotating rate. In a diesel engine used in one brand of 10,000-ton cargo ship, seizure and galling took place in full load and super-speed run-in stage. In order to counteract such premature damage, eighteen key rolling and sliding articles were processed with LGM technology, including roller pins and bushing cylinders (Figure 17). As a result, the run-in passing ratio was enhanced from 20% to 100%.

As previously mentioned, exemplary applications of LGM technology in machinery and automotive industries were introduced. It needs to be noted that the test and engineering data may be different under particular situation and environment. In order to have a full-angle characteristic picture of this technology, part and its bulk material quality factors, such as basic design, dimension tolerance, fitting reliability, material strength, plasticity, toughness, and microstructure, must be thoroughly considered. In engineering evaluation, sound experimental configuration and analytical methodology need to be laid out to derive or present objective results [6].

CONCLUSIONS
In general, ion-sulfurized lubricating gradient material (LGM) entails great tribological advantages for its use in gears and other rolling and sliding articles. Thesolid lubricating effect and lubricant accommodating capability reduce friction coefficient, prevent adhesion, scuffing and galling, and shorten run-in time for gears and bearings used in vehicles and machines. LGM in steel can survive elevated service temperature. In addition, the LGM technology brings on great fatigue resistance in components. The dimension tolerance and substrate properties are well maintained during LGM process. It is a green technology as very little hazardous waste is generated. As application of LGM in automotive and machinery units grows, its engineering benefits will be further manifested.

REFERENCES

ABOUT THE AUTHORS: Gordon Wang is running Sam Metallurgical and Materials Solutions, LLC. He got his bachelor and PhD degrees in materials engineering. Having worked in the field of metallurgical characterization and processing for twenty years, and launched a series of innovative technologies into mass production, he is devoting his efforts to researching, developing and introducing cutting-edge technologies on moving/rotating components, such as gears and bearings. Currently he is collaborating with Shanghai Pioneering Surface Material Co., Ltd, and implementing a state-of-the-art anti-wear surface treatment — Ion-sulfurized Lubricating Gradient Material (LGM) technology — in gears, bearings and splined shafts used in automotive and machinery industries. Yifei Zhang, Xinhui Zhang, and Hua Liu, Shanghai Pioneering Surface Material Co. Ltd.