

## **The Tribological and Fatigue Properties of Steel modified by Hybrid Surface Modification combining Super Rapid Induction Heating & Quenching and DLC coating**

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### **Summary**

In order to achieve power transmission parts like a compact gearwheel which indicates high performance properties, hybrid surface modification was performed by combining Super Rapid Induction Heating & Quenching(SRIQ) which creates high fatigue strength and Diamond Like Carbon (DLC) coating which are well known for their high hardness, low friction and excellent wear resistance. And, in order to prevent the base material from decreasing its fatigue strength, DLC was coated by using Unbalanced Magnetron Sputtering (UBMS) method which can coat at low temperature. Rotational bending fatigue tests and friction-wear tests were carried out. It was clear that it is possible to keep high fatigue strength and to create excellent tribological properties at specimen surface by performed hybrid surface modification.

### **Introduction**

In recent years, qualities of mechanical properties and strengths which were demanded for compact gearwheel have been elevated year by year. In order to solve these demands, for example, Induction heating & quenching(IHQ) method which can create the hardened layer near the surface was modified for gearwheels[1-3]. Recently, among the IHQ methods, Super Rapid Induction Heating & Quenching (SRIQ) method which can perform quenching in a short period of time by controlling the high output power of the induction heating communicator with a high degree of accuracy was developed. SRIQ has a lot of advantages; it is possible to create higher compressive residual stress, to prevent from deformation of substrate, to perform contour quenching whether the gearwheel was smaller[4-7].

In general mechanical parts like gearwheels transmit motive energy by contacting each other automatically. So, it is prospective that the stress of root of tooth and the noise involved in mechanical contact get lower by improved the tribological properties at contact area. However, for the materials modified SRIQ, such experimental approaches were not carried out, and the effectiveness is not clear yet. So in this study, we had an interest in Diamond Like Carbon(DLC) coating which are well known for their excellent tribological properties[8-10].

However, there are some reports which are concerned that coated materials like DLC indicate low fatigue strength compared with substrate only due to high heating

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history during the coating process[11-12]. Especially, in the case of the materials modified quenching like SRIQ, the effect of heating history after quenching is very sensitive. So, in this study, in order to maintain the strength which was created by SRIQ and to acquire adhesion strength between the coating layer and the substrate enough for practical uses, original laminate DLC coating was suggested. Furthermore in general, in the case of quenching process like SRIQ, low-temperature tempering process which can improve the toughness was carried out. However, in this paper, we tried to prevent from increase of process by incorporating the heating history during the DLC coating process into tempering process.

So the aim of this paper is to achieve the high functional materials which indicate high fatigue strength and excellent tribological properties by combing the SRIQ and DLC coating.

### **Specimens & Experimental method**

A material (substrate) used in this study was a medium carbon steel(AISI1045) with carbon content of 0.45%. After performing thermal refining process (1173K quenching, 873K tempering) was performed, they were machined into two types shapes specimens; (a)TP for fatigue tests(stress concentration factor  $\alpha=2.3$ ) and (b)TP for wear tests(Fig.1). Two types specimens were performed SRIQ process. In addition, the hardened layer thickness of TP for fatigue tests and TP for wear tests were 0.5mm and 1.0mm. After SRIQ process, all specimens surface were polished into a mirror surface condition. After polishing the surface of the substrate, all specimens were coated DLC by using a UBMS method which can coat at low temperature comparatively. The structure of DLC coated in this study was shown in Fig.2. In order to improve adhesion strength, inter-layer which contains 10% Tungsten was formed into  $2\mu\text{m}$  thickness. And on the inter-layer, metal-DLC layer which contains 10% Tungsten and pure DLC layer were alternated in nano order thickness. This laminate layer thickness was  $1\mu\text{m}$ , so  $3\mu\text{m}$  thickness in total. Furthermore, only SRIQ specimen which was not coated and modified regular low-temperature tempering (423K, 2hours, vacuum furnace) was prepared. We refer to coated specimens as SRIQ/DLC series, and SRIQ only as SRIQ series.

Fatigue tests and wear tests were carried out by rotational bending fatigue testing machine (frequency: 50Hz, stress ratio:-1) and ball-on-disc wear test machine (opponent material: SUJ2, Load: 2N, rotational speed: 0.2m/s). After these tests, the each surfaces were carefully observed by a Scanning Electron Microscope (SEM) and Laser Microscope.

### **Results & Discussion**

#### **The observation and mechanical properties of laminate DLC coating**

First, DLC coating was observed by using a SEM(Fig.4) and atomic force microscope. It is clear that DLC coating was formed at our request and the values

of the surface roughness of DLC coating was  $R_a=24.2\text{nm}$ . Fig.5 shows the results of microscopic hardness and Young's modulus of DLC coating measured with an applied load of 0.2N. The values of the hardness and Young's modulus of DLC coating formed in this study were lower than commonly used DLC coating. The reasons are to contain Tungsten and to laminate metal-DLC layer and DLC layer.

#### **Discussion about tempering effects by heating history during DLC coating process**

Actual heating history of specimen in the vacuum chamber during DLC coating process was measured by using Pt electrode. It is clear that it is possible to keep temperature during the coating process not over 423K. Next, hardness distribution were measured by Vickers hardness tester (load:2.94N). It is observed that hardness of SRIQ series and of SRIQ/DLC series have same distributions. These results suggest that it is possible to perform regular low-temperature tempering by using a heating history during DLC coating process.

#### **The tribological properties of steel modified by SRIQ/DLC hybrid surface modification**

Fig.3 shows the results of wear tests. It is observed that, in the case of SRIQ series, the value of friction coefficient was increased soon after starting the wear tests, and was ranged widely on the average 0.50. Otherwise, in the case of L-DLC series, the value of friction coefficient 0.4 soon after starting the wear tests, however, subsequently the value was improved and stabilized about 0.1. Furthermore, the wear tests was continued through the sliding distance 5.0km, the value of friction coefficient was about 0.1 and the delamination of DLC coating and denudation of the substrate were not observed.

To clarify the reason for that, the wear trace (Disc) and opponent material (Ball) of each series after wear tests(sliding distance : 1km) was observed by SEM. Fig.4 shows the SEM observations and Table1 shows the values of specific wear rates. We can see that both Disc and Ball the values of specific wear rates of SRIQ/DLC series were much lower than that of SRIQ series. It is concluded that excellent tribological properties was created by DLC coating because DLC coating indicates excellent tribological properties and low aggressiveness to the opponent materials.

#### **The fatigue properties of steel modified by SRIQ/DLC hybrid surface modification**

Next, fatigue tests were carried out. Fig.5 shows the results of fatigue tests. It is observed that fatigue strength of SRIQ series and of SRIQ/DLC series have same stress level. Next, in order to specify the fracture origin, fracture surfaces were investigated by using an SEM. Fig.6 shows the case in point. It is clear that all fracture origin were started at specimen surface regardless of existence of DLC coating. These experimental facts that it is not difference in fatigue strength level

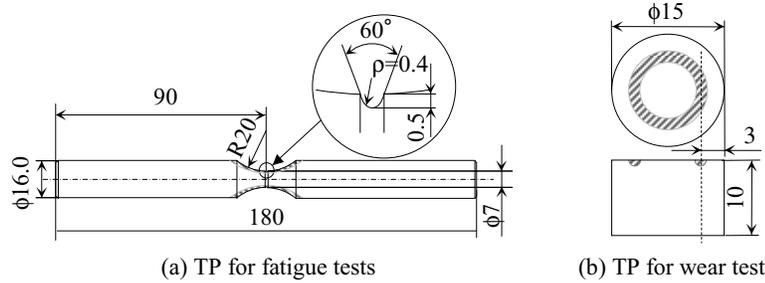
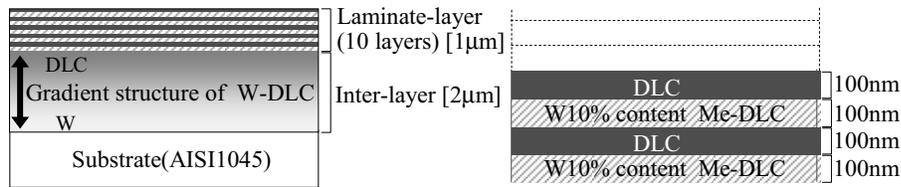


Fig.1 Specimen geometry



(a) Structures of laminate DLC coatings (b) Structures of laminate-layer

Fig.2 Structures of laminate DLC coatings

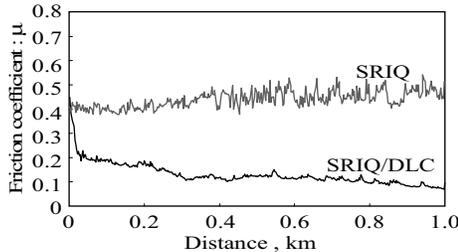


Fig.3 Result of wear tests

Table1 The values of specific wear rate

	Disc	Ball
SRIQ series	13.50	5.10
SRIQ/DLC series	0.57	0.06

( $\times 10^{-9} \text{ mm}^2/\text{N}$ )

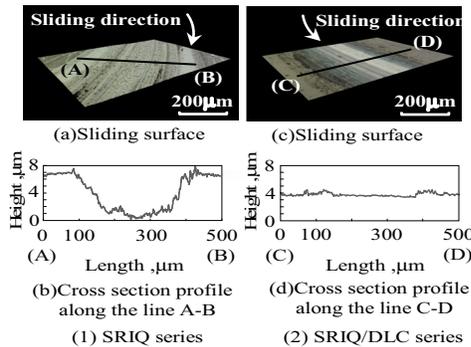


Fig.4 Observation of disk surface after wear tests

and fracture origin regardless of existence of DLC coating suggest that it is possible to create high tribological properties at surface of SRIQ series without lowering fatigue strength which was create by SRIQ process. Furthermore, Fig.7 shows the side surface at the crack initiation site in SRIQ/DLC series. It is clear that DLC coating contacted to the substrate strongly and macro crack or breaking of DLC coating was not observed.

These results were evidences to support that DLC coating cohered to the substrate until just before final fracture and that adhesion strength between the DLC

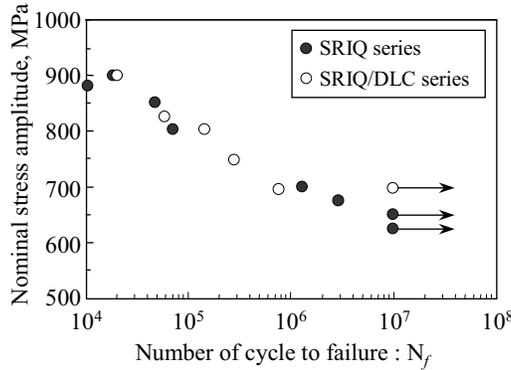


Fig.5 Results of fatigue tests

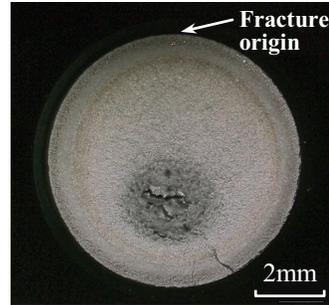


Fig.6 Fracture surface of SRIQ/DLC series

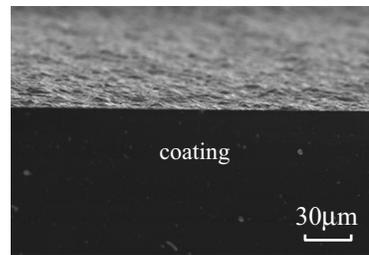


Fig.7 Side surface at the crack initiation site

coating and substrate was enough to apply for actual uses.

### Conclusions

In this study, in order to achieve power transmission parts like a compact gearwheel which indicates high performance properties, hybrid surface modification was performed by combining Super Rapid Induction Heating & Quenching (SRIQ) which creates high fatigue strength and Diamond Like Carbon (DLC) coating which are well known for their high hardness, low friction and excellent wear resistance. The results are summarized as follows:

1. it is possible to create excellent tribological properties at specimen surface without lowering fatigue strength by combined SRIQ and DLC coating.
2. It is possible to perform regular low-temperature tempering by using a heating history during DLC coating process, so to achieve process cut-down involved in compound of surface modifications.
3. As mentioned above, under the condition which was acted fatigue damage and wear damage at the same time such as compact gearwheel, the lowering the stress of root of tooth and the noise are expected. So the magnitude of the effect by performing hybrid surface modifications will be more larger.

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