Focussed on Crack Paths

Influence of vacuum carburizing treatment on fatigue crack growth characteristic in DSG2

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ABSTRACT.

The aim of this research is to clarify the influence of vacuum carburizing on the fatigue-crack progress characteristics of DSG2 steel. The test specimen tempering material (QT material) and vacuum carburizing material (VC material) has been used. The fatigue-crack progress was examined by subjecting the samples to four-point bending. The loading-capacity fixed experiment was done using a maximum load of $P_{max} = 4000$-7000 N. The ΔK fixed experiment was done using a load of $\Delta K = 18$-36 MPa$\sqrt{m}$.

The crack progress speed of VC material fell, after the high crack progress speed was shown, and after it showed the minimum, it showed the tendency to go up again. This is considered to be what is depended on the compressive residual stress given to the carburizing layer. From this, it is thinkable that there is a crack progress depression effect in a carburizing layer.

In VC material, a carburizing layer has a crack progress depression effect from a plunger-helix bottom to about 2.6 mm, and it turned out that it is larger than an effective carburizing layer. Moreover, in each ΔK, it was shown that depression effect revelation differs and the crack progress process accompanying it was able to be shown typically.

KEYWORDS. Vacuum carburizing; DSG2; Fatigue-crack progress characteristics.

INTRODUCTION

In recent years, longer life-span of the machine construction thing is called for from a viewpoint of earth environment. For longer life-span of a machine construction thing, the fatigue strength of material and wear-resistant improvement are especially required. In order to attain these, coexistence of a hardness and toughness becomes indispensable. The surface modification processing method is mentioned as an effective method for sharing these. It is a disposal method in which surface modification processing hardens the neighborhood of the surface of material, and an inside holds toughness. [1-3]. The surface modification processing methods include many processing methods including carburizing and a nitriding, such as a fine particle peening. [4-6].

The vacuum carburizing processing which is one of the surface modification disposal methods is a disposal method excellent in the improvement in fatigue characteristics, because oxygen is not included during carburizing atmosphere and

an internal oxidation etc. do not occur. Moreover, because this is pollution-free and there is little consumption of carburizing gas, it is saving resources and energy-saving technologies. [7-9].

There is gears as typical parts which perform carburizing processing. In recent years, also in the toothed wheels, a raise in a hardness and a miniaturization are strongly desired with low-fuel-consumption-izing and the weight saving of a motor-car, and also the engine higher power. The steel for DSG2 quantity hardness gears in which there were few internal-oxidation layers which have on the fatigue strength of carburizing material, and they aimed at improvement in the toughness of a carburizing layer from this is developed.

In old research, there are few measures of the research on the fatigue strength of vacuum carburizing material, and the research for DSG steel which is an exotic material is hardly found.

It is the purpose that this research clarifies influence of vacuum carburizing processing on the fatigue strength of steel for DSG2 quantity hardness gears.

TEST MATERIALS AND TEST PIECES

T est specimens were used for high strength gear steel DSG2. The chemical composition shown in Tab. 1. First, thermal refining (primary quenching 1163K × 30min after holding oil cooling, secondary quenching 1113K × 30min after holding oil cold, tempering 463K × 1h after holding air cooling) is performed. The specimen was processed into the shape and size which are shown Fig. 1, and were mirror-finished by polishing and water buffing. After creating these specimens, in order to remove the residual stress due to processing, vacuum annealing (873K 60 min) was performed.

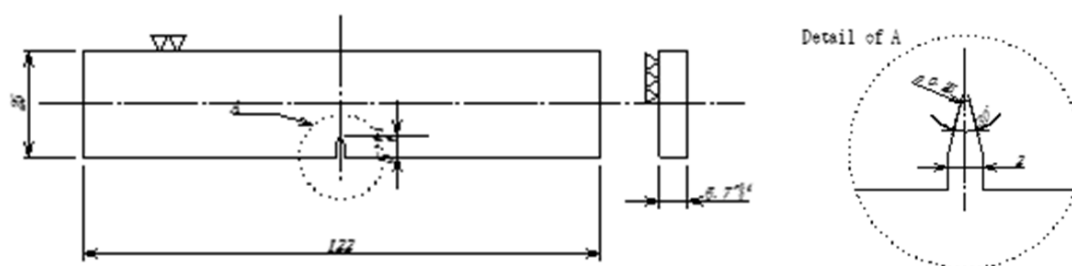| C	Si	Mn	Cu	Ni	C r	Mo
0.21	0.19	0.72	0.12	0.06	0.99	0.16

Table 1: Chemical composition (mass.%).

Figure 1: Shape and dimensions of specimen (in mm)

VACUUM CARBURIZING TREATMENT CONDITIONS

S pecimens were included in this study were two types. Tempered material (QT material) and carburizing material (VC material) were prepared. VC material vacuum carburization process is performed at a heat pattern shown in Fig. 2. In the vacuum carburization process of the present study were subjected to carburizing hardening rate is 38% in all specimens.

FATIGUE CRACK PROPAGATION TEST METHOD

T he fatigue-crack progress experiment was carried out with a four-point-bending fatigue-test system. The fatigue-crack progress experiment was carried out with a four-point-bending fatigue-test system. Usually, when doing a crack progress experiment, after introducing a crack beforehand, it is common to perform the stress relieving

anneal which removes the work-hardening region formed near the crack tip. However, in this research, because it was surface modification material, the vacuum anneal after crack generating was not performed. Electro-hydraulic servo fatigue testing machine was used to test. The loading-capacity fixed experiment was done for QT and VC material under the conditions of maximum load Pmax=4000 - 7000N. Moreover, the ΔK fixed experiment was done under the conditions of ΔK=18~36 MPa$\sqrt{m}$. The experiment was done by the stress ratio R= 0.1 and the sine wave with a frequency of f= 20 Hz. In addition, the crack measurements of length was performed by 100 times using the portable optical microscope. Moreover, the measurement of crack opening stress was called for from the relationship between a loading capacity and a strain using the strain gauges.
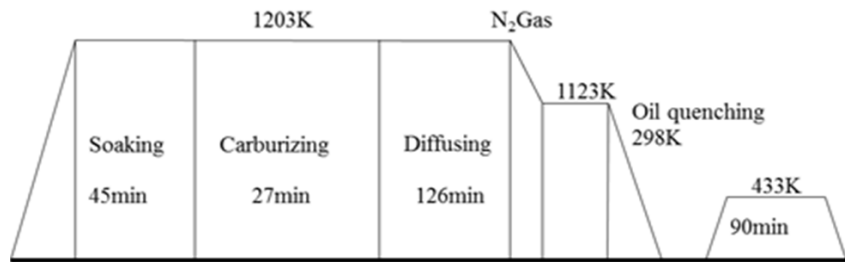

Figure 2: Heat pattern of carburizing

RESIDUAL STRESS, RESIDUAL AUSTENITE AND HARDNESS MEASUREMENT METHOD

The residual stress and the amount of retained austenites in the depth-of-cut direction were measured using the PSPC/MSF system. Each measurement condition is shown in Tab. 2 and 3. The hardness measurement was performed by the loading capacity of 2.94N using the micro Vickers measuring machine.

Measurement principle	Counter method
Characteristic X-ray	Cr-Kα
Diffraction	211
Diffraction angle (deg)	156.4
Stress constant K(MPa/deg)	-318
Slit diameter (mm)	4
Tube voltage (kV)	30
Tube current(mA)	20
Incident angle (deg)	5, 25, 35, 45
Analysis method	Half width method

Table 2: X-ray conditions for residual stress measurement.

Diffraction	α-phase:(211)
	γ-phase:(220)
Diffraction angle (deg)	α-phase:156.4
	γ-phase:128.4

Table 3: X-ray conditions for retained austenite measurements.

RESIDUAL STRESS, RESIDUAL AUSTENITE AND HARDNESS MEASUREMENT RESULT

The amount of retained austenites of the depth-of-cut direction of each processing material is shown in Fig. 3. As shown in a figure, as compared with QT material, the retained austenite of VC material is increasing greatly. This is considered to be what is depended on austenite having been stabilized when the Ms-point temperatures fell with the Increase of value in the amount of carbon by vacuum carburizing.

Residual stress distribution of the depth-of-cut direction in each processing material is shown in Fig. 4. As shown in a figure, VC material is about -100 MPa almost uniformly to 100 micrometers.

The depth-of-cut direction hardness distribution of each processing material is shown in Fig. 5. As shown in a figure, VC material showed the maximum hardness of HV800 on the surface, and went up about 2.6 times as compared with HV400 of QT material. Moreover, an effective hardening depth is 1.2 mm from the surface.
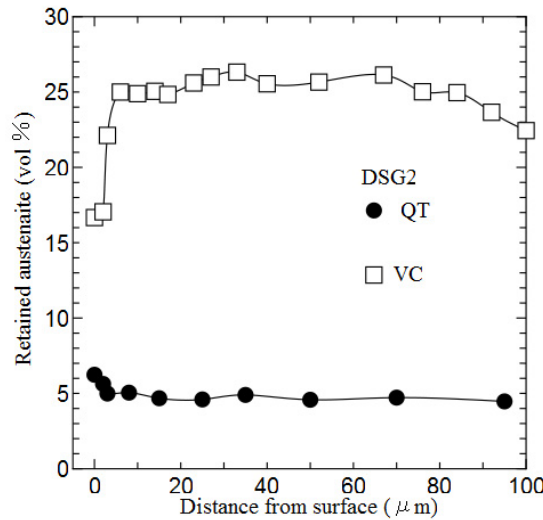
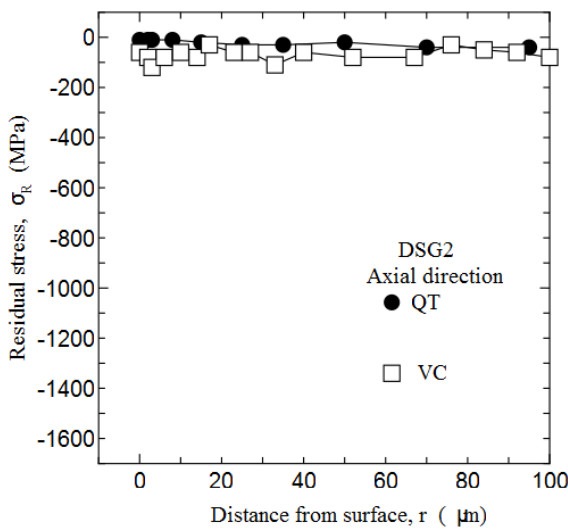Figure 3: Retained austenite distribution from surface

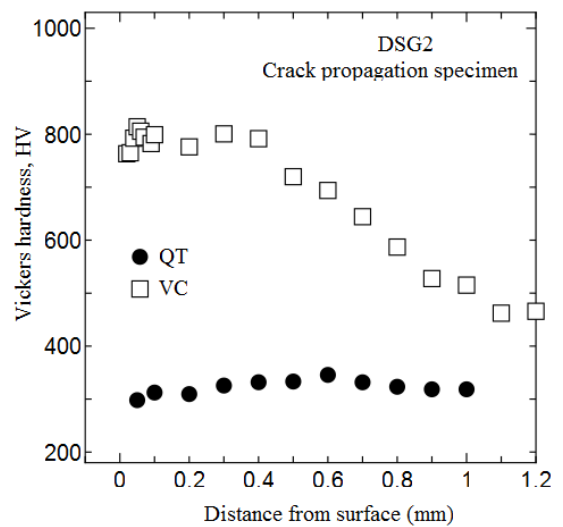Figure 4: Residual stress distribution from surface

Figure 5: Vickers hardness distribution from surface

RELATIONSHIP OF CRACK GROWTH RATE DA / DN AND STRESS INTENSITY FACTOR WIDTH ΔK

The relationship of crack progress speed da/dN and stress intensity factor width ΔK in the case of the conditions of P_{max}=7000 is shown in Fig. 6. In the case of surface modification processing material, the progress behaviors of a surface crack and an internal crack differ, and it is thinkable that a crack entering edge curves greatly. About this, by report of Egami et al [10], if the rate of internal crack pallet-length b to surface-crack length a is set to m, the following expressions of relations will be materialized among both.

$$b=ma-c \tag{1}$$

In the case of nitriding processing material, this value is 0.92, and it is clear that there is no big difference in a surface crack and an internal crack length. It is thought that it is because progress of a crack is controlled by internal toughness rather than the surface modification layer as this reason. Fig. 7 showed the observation state in that case typically. As shown in figure, the crack in case progresses in brittleness. However, crack progress is affected by the influence of base metal part, and progress is controlled. If only the hardened layer is observed, a crack progress speed will become early extremely by a brittle fracture, but because it is affected by the influence of a base metal part, it is thinkable to progress with configuration like illustration. Therefore, the surface-crack length and internal crack length of the surface modification material which has a surface-hardening layer are considered to be an almost comparable length. Therefore, it is thought that a stress intensity factor is computable using a surface-crack length.

VC material showed bigger crack progress speed da/dN than QT material immediately after crack generating. Then, after the crack growth rate of VC material became a low value and reached the local minimum rather than QT material, it showed the tendency to go up again. This reason is considered that crack progress was controlled because the opening of the crack was barred by the crack closure effect by the compressive residual stress given to the carburizing layer. Moreover, as Sugimoto et al.[11] is also described, when the retained austenite of a carburizing layer carries out a processing induction martensitic transformation with crack progress, a compression stress place is formed at the tip of a crack, and it is thought that crack progress was controlled. However, the area which has on crack progress is only a parts which has influence of a carburizing layer. The influence of a base metal part becomes large with progress of a crack. Therefore, after a crack progress speed shows the local minimum, a crack growth rate rises and shows the same crack progress speed as a base metal.

As mentioned above, it became clear that the carburizing layer has affected control of a crack progress speed. Moreover, it is thinkable that the crack progressed in brittleness in the carburizing layer as a reason which showed the value with a big crack progress speed immediately after crack generating.
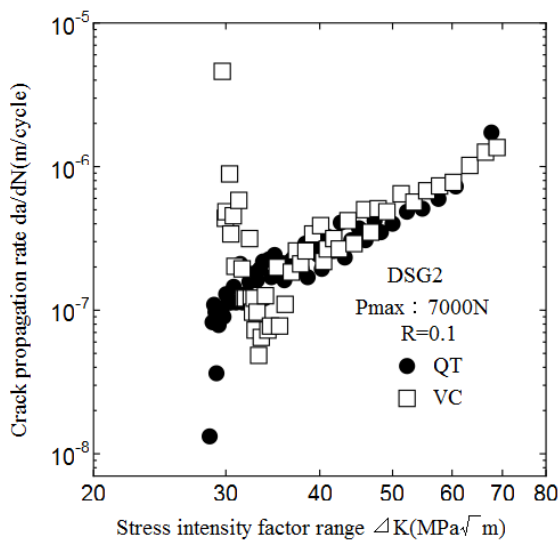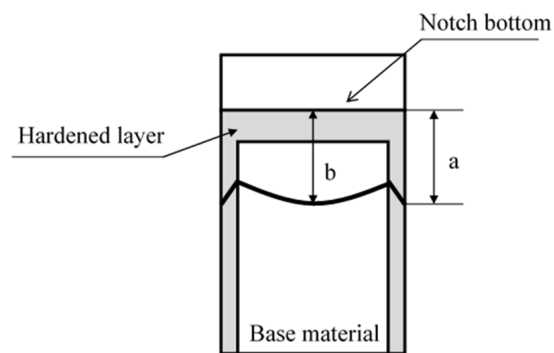

Figure 6: Relation between da/dn and ⊿K.

Figure 7: Schematic diagram of crack propagation.

ΔK CONSTANT TEST RESULTS

In the loading-capacity fixed experiment shown for the preceding clause, because ΔK also increases with progress of a crack, it is difficult to consider the influence of a carburizing layer in detail. Then, in order to consider the influence of a carburizing layer, the ΔK fixed experiment was done. The relationship of crack progress speed da/dN and crack length a in each ΔK was shown in Fig. 8.

The tendency to go up after a crack progress speed falls by the case of all the Δ K in VC material like the case of a loading-capacity fixed experiment, as shown in a figure. From this, the depth of a carburizing layer is presumed to be about 2.6 mm also from the crack length having been in agreement at about 2.6 mm. This shows that the carburizing layer has occurred until more deeply than an effective carburizing layer. (HV550). Although the value up to 1.2 mm is shown by

the hardness distribution mentioned above, the hardness of VC material decreases smooth and is in agreement with the hardness of QT material. The depth to converge is mostly in agreement with 2.6 mm of an above-mentioned carburizing layer.

The position of the local minimum of the crack progress speed to $\Delta K=30$ MPa√m is near a = 1.25mm. In $\Delta K=36$ MPa√m, the position of the local minimum is near 1.6 mm to it. Moreover, it became clear that a crack progress speed becomes fixed in a depth of 2.6 mm. In addition to it, it was also shown clearly the prohibitive power over crack progress of a carburizing layer and that ΔK followed on going up and had become weaker.

The reason the position of the local minimum in high ΔK changes from the above thing is explained. In crack progress, the crack progress resistance accompanying a crack closure formation process decreases with crack progress, and a steady value is shown. It is expected to it that the crack shielding effect by the processing induction martensitic transformation by the crack progress in a carburizing layer is decided by the value of retained austenite and ΔK. In order that retained austenite may show the tendency which decreases in the depth-of-cut direction, the shielding effect accompanying it also becomes the same. Because the assortment of these two effects serves as progress resistance, it is expected that the local minimum changes. Therefore, in higher ΔK, after the high crack progress speed after crack generating is shown, a speed falls gradually, and after a crack progress speed falls to a= 2.6 mm, without showing the tendency to go up after that again, becoming fixed is guessed.

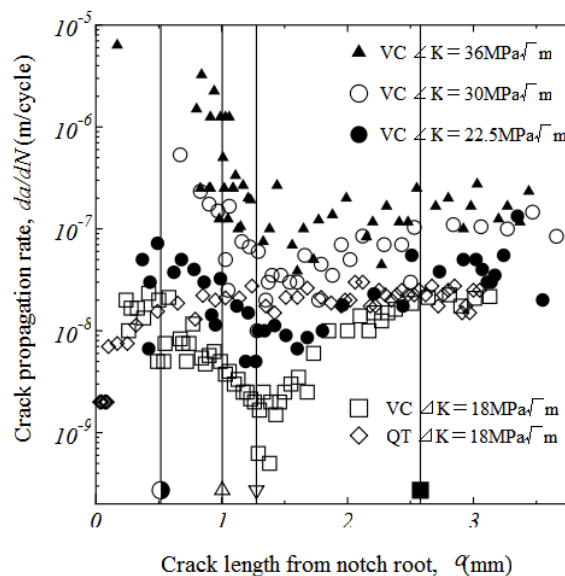Figure 8: Relation between crack length and crack propagation rate under constant ΔK.

EFFECTS OF ΔK THAT CAN BE PLACED ON EACH CRACK LENGTH

Next, in order to see the influence of ΔK in each crack length, the relationship between crack progress speed *da/dN* in a crack length and ΔK shown in Fig. 8 as a solid line was shown in Fig. 9. Moreover, it is thought that it is to 2.6 mm to have influence of a carburizing layer also from the 2.6-mm approximated curve and the gradual increase curve of QT material being in agreement. In addition, 0.5mm, 1.0mm, 1.25mm and ΔK do not match. This formation process of crack propagation mechanism or closing action which means different. On the other hand, because 0.5 mm, 1.0 mm, 1.25 mm, and ΔK are not in agreement, it is thinkable that the formation processes of a crack progress mechanism and a crack closure effect differ. Then, in order to consider the influence of the crack closure effect by a carburizing layer, effective stress expansion coefficient width ΔK_{eff} in Fig. 8 was shown in Fig. 10. As shown in a figure, in the case of a= 2.6 mm, it is thinkable that an crack closure effect and a progress mechanism are also almost the same. Moreover, if it arranges by ΔK_{eff} also in 1.25 mm, since an approximated curve is in agreement with QT material, it turns out that the crack progress speed was changing with the transitions of the crack opening loading capacity by the difference in the formation process of the crack closure by a carburizing layer. However, in a = 0.5 mm, since QT material and an approximated curve are not in agreement at all, it is guessed that the difference in a destructive configuration is a difference in a crack progress behavior.
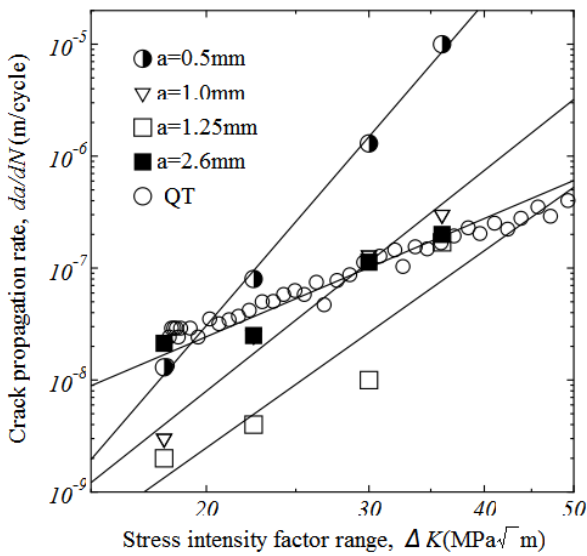
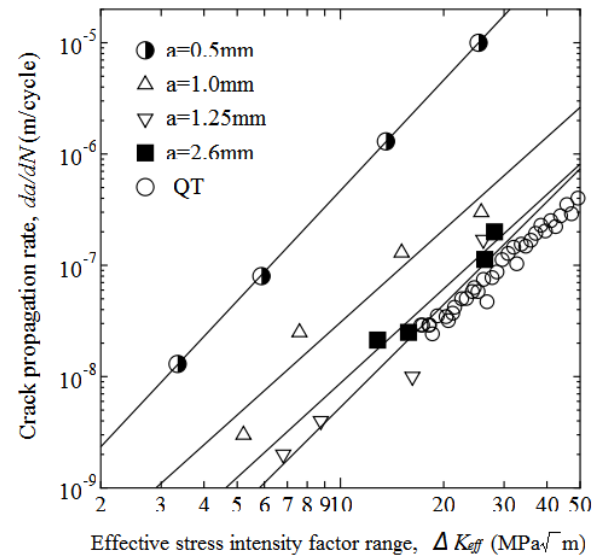Figure 9: Relation between ΔK and da/dn at each points.

Figure 10: Relation between ΔK_{eff} and da/dn at each points.

A STUDY ON THE CRACK PROPAGATION BEHAVIOR OF CARBURIZED LAYER

Then, the following conclusions were obtained from the result of fracture-surface observation. The crack progress process of VC material was classified into four stages from the crack progress behavior and the fracture-surface photograph. About each stage, the destructive configuration by the crack progress in VC material was shown. Facture surface in Fig. 11, schematic diagram is shown in Fig. 12. Each area is defined as follows.
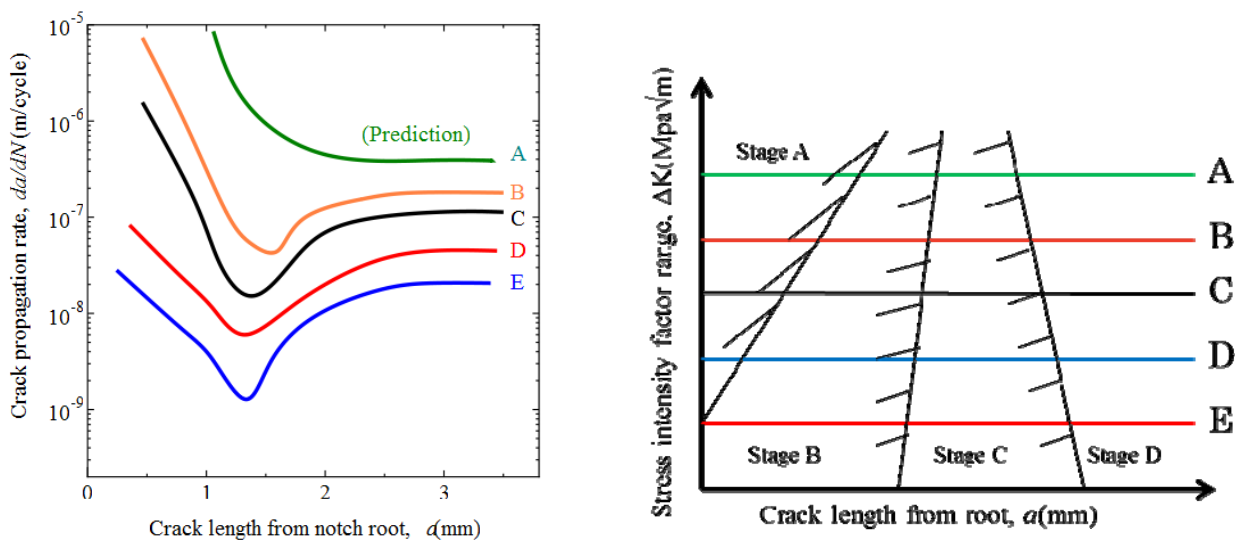

Figure 11: Change of fracture surface morphology with crack propagation.

- Stage A: In this stage, the influence of a crack closure effect is not shown by brittleness, but a quick crack progress speed is shown. Also in a fracture surface, an intergranular fracture is mainly shown, and some transgranular fracture follows.
- Stage B: The influence of the compressive residual stress by a carburizing layer and a processing induction martensitic transformation is an area which appears most, a crack progress speed falls and the local minimum is shown. Although

the mixed fracture surface of transgranular fracture and an intergranular fracture is shown in a fracture surface, an intergranular fracture is a dominant fracture surface.

- Stage C: Because the influence of a carburizing layer becomes weak, the influence of a plastic region appears and a crack progress speed rises gradually. In a fracture surface, it becomes a mixed fracture surface of a brittle fracture and a ductile rupture, and transgranular fracture is main.

- Stage D: Because a crack progresses considerably and the influence of a carburizing layer is lost completely, a crack progress speed turns into a fixed speed like QT material. A fracture surface is only a ductile rupture.
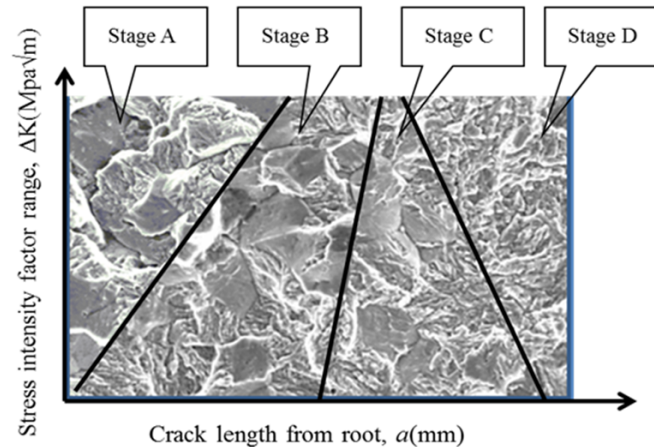

Figure 12: Change of fracture surface with applied stress intensity factor range and distance from notch root.

As shown in the schematic diagram, in high delta *K*-value, stage area A continued to some extent, the stages B and C were short, and going to the stage D immediately was checked. Moreover, the crack progress behavior which begins from a stage area B was shown by low delta K-value. Thus, also from the fracture-surface configuration which changes with external load or crack progress parts being shown, it was suggested that the crack progress behavior is governed by external load and the crack progress part. If in other words the maximum-stress value which acts on the application part of material is decided, it will be thought possible to decide the rate of optimal effective carburizing as all the lifetime. Moreover, about the point shown by Fig. 8~12, even if materials differed, it was suggested that these things are applicable to steel material by performing vacuum carburizing processing.

CONCLUSION

In this research, the surface modification effect over the fatigue-crack progress characteristic of DSG2 steel that vacuum carburizing processing was performed was examined, and the following results were obtained.
1. The maximum surface hardness of VC material showed one about 2.6 times the value of this as compared with QT material. Moreover, the compressive residual stress was about -100MPa.
2. The crack progress speed of VC material fell, after the high crack progress speed was shown, and after it showed the minimum, it showed the tendency to go up again. This is considered to be what is depended on the compressive residual stress given to the carburizing layer. From this, it is thinkable that there is a crack progress depression effect in a carburizing layer.
3. In VC material, a carburizing layer has a crack progress depression effect from a plunger-helix bottom to about 2.6 mm, and it turned out that it is larger than an effective carburizing layer. Moreover, in each ΔK, it was shown that depression effect revelation differs and the crack progress process accompanying it was able to be shown typically.

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