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Mechanical properties and deformation of ceramic coated steels heat-treated by scanning laser

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ABSTRACT

A new surface modification method "laser quenching after coating" using a high power diode laser equipped with a 2-dimensional galvano-scanner unit was developed to process a larger area of ceramic coated steel uniformly and efficiently. The laser irradiation tests for 3 kinds of ceramic-coated steels: CrAlN, TiAlN and CrN, were carried out with the scanning laser, and the appropriate irradiation conditions to achieve the uniformly quenched substrate without any surface damage were clarified for these ceramic-coated steels. The area of the substrate surface wider than the laser spot size could be easily quenched by the scanning laser. The adhesive strength, the film hardness of the laser-irradiated regions and the deformation caused by laser irradiation were evaluated. Laser quenching with the scanning laser can effectively improve the adhesive strength and substrate hardness without any detrimental effect on the film hardness of the ceramic-coated specimens. In the deformation of the laser-irradiated specimens, two features were recognized; one is the bending, and the other is the expansion of laser-irradiated part. It was found that the deformation of ceramic-coated steel by laser irradiation under the same heat input condition does not depend on the kind of ceramic thin film but on the steel type of the substrate. It was concluded that "laser quenching after coating" with scanning laser could easily improve the adhesive strength and substrate hardness without any detrimental effect on the film hardness of large surface areas in the tested all types of ceramic-coated specimens. Copyright © 2014 VBRI press.

Keywords: Laser; heat treatment; thin film; hardness; adhesive strength; deformation.

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Introduction

In general, when a steel substrate is coated with a ceramic thin film by PVD or CVD method, the substrate is first quenched and tempered, and the film is deposited after the heat treatment, as shown in **Fig. 1(A)** **[1, 2]**. In this case, when the deposition temperature is higher than the tempering temperature for a given type of substrate steel, the substrate hardness will typically decrease during the coating process.

To solve this problem, a method "substrate quenching after coating" as shown in **Fig.1 (B)** was proposed **[3]**, and it was found that substrate quenching after coating allows for adequate steel hardness control regardless of the deposition temperature **[3]**. Additionally, from a study conducted on TiN-coated steel, we were able to conclude that adhesive strength **[3, 4]**, wear resistance **[5]** and fatigue strength **[6]** of TiN-coated steels improved significantly through this method. These results suggest that this method can be applied as an effective way to improve the performance of TiN-coated steels.

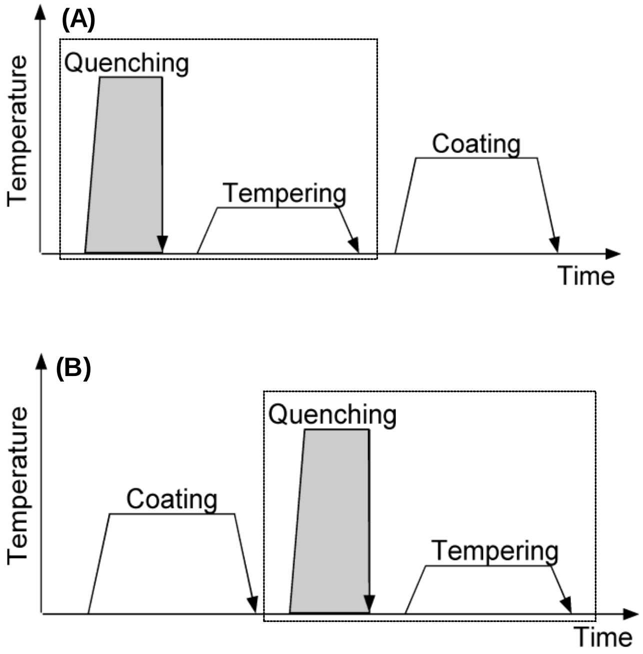

Fig. 1. Manufacturing procedures for ceramic coated steels, (A) Conventional procedure and (B) Proposed procedure.

In our previous studies **[3-8]**, ceramic coated steels were heat-treated in electric furnace. In this method, it is difficult to avoid thermal distortion due to bulk heat treatment, what is a disadvantage when high dimensional accuracy is required. Laser quenching was proposed to solve this issue due to the localized heat input and consequently very low thermal distortion **[9**, **10]**.

Fundamental studies on laser quenching for ceramic coated steels were carried out, and it was found that laser quenching after coating also allows for adequate steel hardness control without high thermal distortion. It was also found that adhesive strength of ceramic-coated steels improved significantly through laser quenching after coating **[11-13]**. These results suggest that this method can be applied as an effective way to improve the performance of ceramic-coated steels.

In these studies, laser heat treatments were carried out by linear scanning of Nd-YAG laser (wave length 1.06μm, maximum power 300W, beam mode TEM00) with a Gaussian type intensity distribution. Therefore, it was impossible to quench the region with the width larger than a laser spot size on the specimen surface. And the Gaussian type intensity distribution in the laser spot may result in non-uniform hardness distribution in the laser-irradiated region.

In this study, in order to quench a larger area of ceramic-coated steel uniformly and efficiently, we proposed a new method of "laser quenching after coating" using a high power diode laser equipped with a 2 dimensional galvano-scanner unit. The first objective of this study is to clarify the appropriate laser irradiation conditions to quench the regions with the width lager than the laser spot size and with no surface damages on the ceramic coated steels by this method. The second one is to investigate the effects of this method on the mechanical properties and deformation of ceramic-coated steels.

Experimental

Materials

The material used for the substrate was carbon tool steel JIS SK105 with chemical composition (wt.%) 1.00〜1.10 C, 0.10〜0.50 Mn, 0.10〜0.35 Si, < 0.030 S, < 0.030 P. The substrate dimentions were: 68 mm × 62 mm × 10 mm. The surface was finished by grinding, and the surface roughness *Ra* was about 0.2 μm.

Three kinds ceramic thin films: CrAlN (composition ratio, Cr:Al:N= 25:25:50), TiAlN (composition ratio, Cr:Al:N = 25:25:50) and CrN were tested. The oxidization temperature of CrAlN film, TiAlN film and CrN film is 1373K, 1173K and 1073K, respectively.

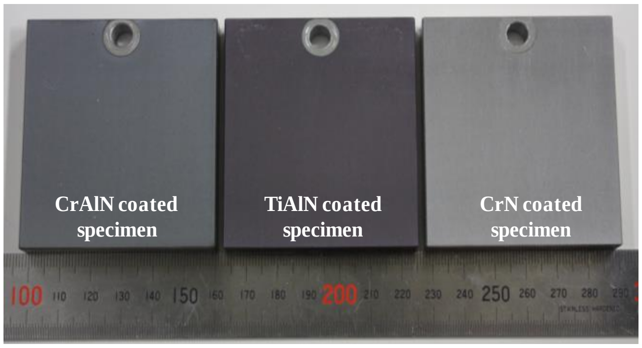

Fig. 2. Ceramic coated specimens

Specimens

Three kinds ceramic thin films: CrAlN, TiAlN and CrN were deposited onto the substrates by arc ion plating (AIP) method (NIPPON ITF, INC., Japan). The film thickness was 2.5 μm. The deposition temperature was approximately 723 K for all types of the ceramic films. **Fig. 2** shows three kinds of specimens, CrAlN coated specimen, TiAlN coated specimen, CrN coated specimen.

Laser irradiation

A high power diode laser (LDM1000-40, Laserline, Germany; Maximum laser power 1kW, Continuous wave) equipped with a scanner unit was used for the laser irradiation. **Fig. 3** shows the schematic illustration of the laser irradiation setup. The wavelength of the laser is 935 nm. The scanner unit includes an F-theta lens and a two axis galvano-scanner. The working distance in a focal position of this setup is 240 mm. The laser is transmitted through an optical fiber into the scanner unit. A 3 mm diameter laser beam, obtained at the working distance of 270mm, is scanned onto the specimen surface and it moves in the *y* direction at a speed f = 4 mm/s and in the *x* direction at scanning speed F = 2000 mm/s. The scanned area is 10 mm in *x* by 50 mm in *y*. These scanning conditions were listed in **Table 1**. The laser power *P* was varied from 560 W to 800 W. The maximum laser power was set at 800 W to prevent the failure of galvano-scanner.

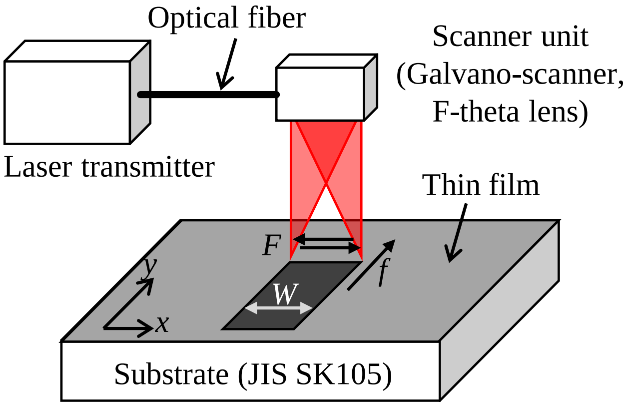

Fig. 3. Schematic illustration of laser irradiation setup.

Table 1. Laser irradiation conditions.

Scanning speed for x direction, *F* (mm/s)	2000
Scanning speed for y direction, *F*(mm/s)	4
Scanning width *W* (mm)	10
Scanning length *L* (mm)	50
Laser power, *P* (W)	560-800
Spot size of laser beam, S_d (mm)	3

Film hardness

The hardness of the ceramic thin films was measured using a nano-indentation tester (ENT-1100a, Elionix, Japan). A Berkovich diamond indenter was used for the measurement. The indentation depth was fixed at 0.25 µm, corresponding to 1/10 of the film thickness, to avoid the influence of substrate hardness.

Table 2. Conditions of scratch test.

Scratch length (mm)	18
Loading rate, (N/min)	78.4
Initial load, (N)	19.6
Maximum load, (N)	196
Table speed, (mm/min)	8

Adhesive strength

The adhesive strength is discussed based on the critical load L_c required to generate interfacial failure, as measured using a scratch tester (CSR-01, Resca, Japan). The conditions of the scratch test are listed in **Table 2**.

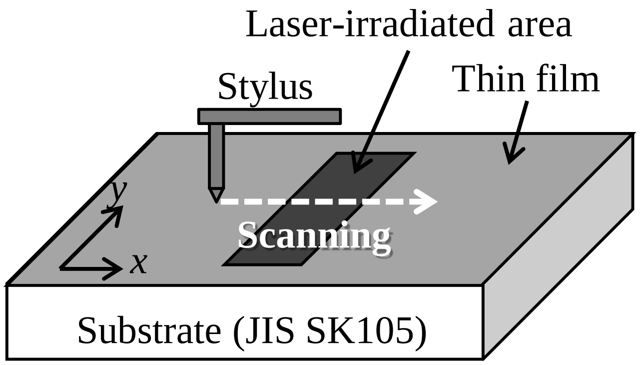

Fig. 4. Deformation measurement of laser-irradiated part.

Deformation accompanying laser irradiation

The deformation of laser-irradiated part was investigated using a "surface roughness and contour integrated measuring instrument" (SURFCOM 5000SD-3DF, Tokyo Seimitsu Co., Ltd., Japan). As shown in **Fig. 4**, a stylus was scanned on the specimen surface along a line parallel to *x*-axis direction and the surface profile on the scanned line was measured. Scanning length was 22 mm including laser-irradiated area of 10 mm.

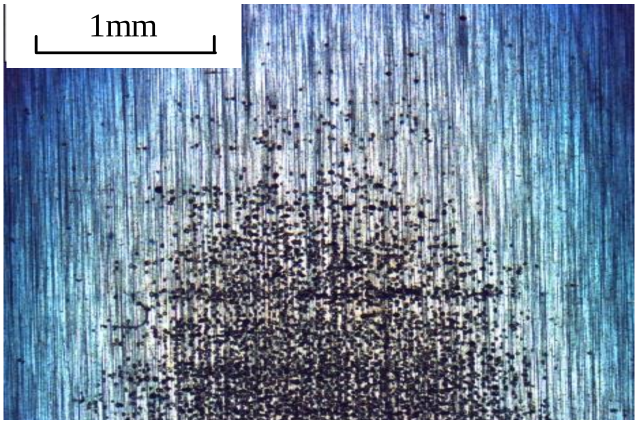

Fig. 5. Example of Type A surface obtained by laser irradiation under *P*=780W, for TiAlN coated specimen.

Table 3. Classification of laser-irradiated surface.

	Type A	Type B	Type C
Substrate	Quenched	Quenched	Not quenched
Surface	Damaged	Not damaged	Not damaged

Results and discussion

Results of laser irradiation tests

Laser irradiation tests were carried out on ceramic-coated specimens at different laser power *P*. The laser-irradiated surfaces can be classified into three types, depending on substrate properties and whether or not surface damage (i.e. melting or delamination) occurred. Type A: quenched but damaged by overheating, type B: quenched without surface damage, Type C: not quenched. **Fig. 5** shows an example of Type A surface obtained by laser irradiation under *P* = 780

W, for TiAlN-coated specimens. These surface types were summarized in **Table 3**. Our first objective was to obtain “Type B surface” for these ceramic coated specimens, and it was important to clarify the conditions under which we can obtain “Type B surface”. **Fig. 6** shows the classification results of the laser-irradiated surfaces into the three types: A, B and C represented as “ ▲ ”, “ ○ ” and “ ■ ”, respectively. With increasing laser power *P*, the laser-irradiated surface was changed from “Type C” to “Type B” to “Type A”. If the laser power *P* is not enough, substrate will not quenched by laser irradiation. But if *P* is too high, the surface will be damaged by over-heating. It is very important to choose a moderate laser power for the process of laser quenching after coating. In this study, laser quenching without surface damage was achieved for all 3 types of prepared specimens.

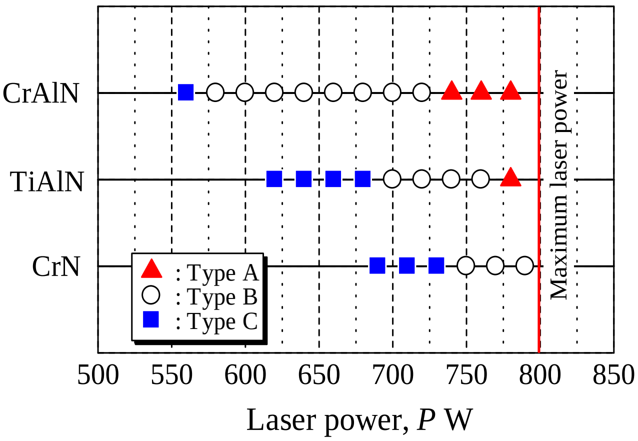

Fig. 6. Laser irradiation test results arranged by laser power. Type A: damaged by overheating, Type B: quenched without surface damage and Type C: not quenched.

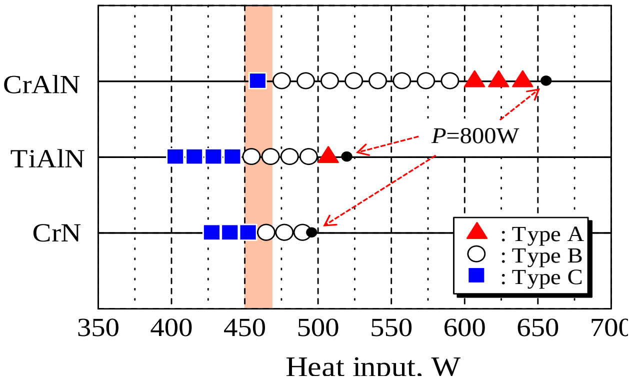

Fig. 7. Laser irradiation test results arranged by heat input Type A: damaged by overheating, Type B: no surface damage, Type C: not quenched.

The minimum laser power required to obtain Type B surface changed with the kinds of the thin film, and it was: 580 W, 700 W and 750 W, for CrAlN, TiAlN and CrN-coated specimens, respectively. For CrAlN-coated specimens, it was possible to quench the substrate effectively at the lowest laser power. It is thought that the difference in the minimum laser power required to obtain Type B surface for each type of specimen originates from the difference in the heat absorption of these films. Therefore, the heat absorption for the laser of wave length 935 nm of CrAlN, TiAlN and CrN was measured by an UV-VIS-NIR spectrophotometer (UV-3101PC, Shimadzu, Japan). The heat absorption of CrAlN, TiAlN and CrN was 85%, 65% and 62%, respectively. **Fig. 7** shows the same data as in **Fig. 6**, rearranged and organized by the heat input. The heat input was obtained from the product of laser power and heat absorption.

From this result, it was found that the minimum heat input in the Type B group was almost constant at approximately 460 W for all three kinds of specimens. It is confirmed that the minimum heat input required to quench the substrate does not depend on the kind of thin film but on the steel type of the substrate. The maximum heat input in the Type B group changed with the kinds of thin film. The maximum heat input for the CrAlN-coated specimens and TiAlN-coated specimens was 590 W and 490 W, respectively. For the CrN-coated specimens, the maximum heat input in the Type B group was unknown because no surface damage was observed even at heat input = 496 W (corresponding to the maximum laser power of this study, 800 W). The difference of the maximum heat input in the Type B group between CrAlN-coated specimens and TiAlN-coated specimens can be explained by the difference in heat resistance of these films.

Fig. 8. Micrograph of the cross-sectional surface of CrAlN-coated specimen laser-irradiated at *P*= 720 W.

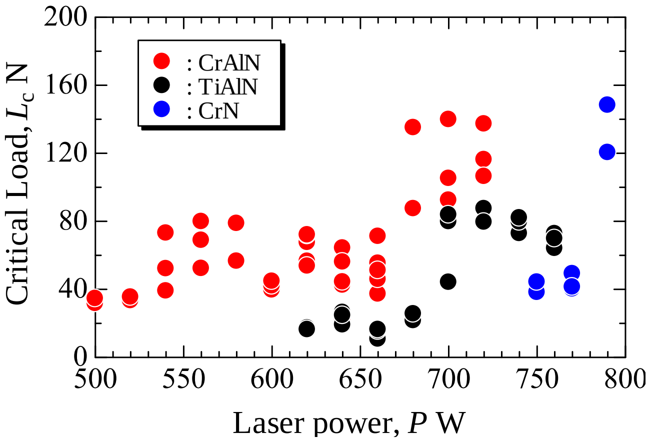

Fig. 9. Adhesive strength of thin films of the laser-quenched specimens.

Cross-sectional observation

For the specimens classified into Type B, the observation of the cross-sectional surfaces was carried out. The cross-sectional surfaces of the specimens were etched with 3% nital and observed by a microscope (BX60M, Olympus, Japan). **Fig. 8** shows a micrograph of the cross-sectional surface of a CrAlN-coated specimen processed at *P* = 720 W. The area wider than laser spot size 3.0 mm was quenched by the scanning laser and the hardness near the surface was almost constant at approximately HV 800 at the whole width. Similar results were obtained in the other types of specimens.

Measurement results of mechanical properties

Fig. 9 shows the measurement results of the adhesive strength obtained by scratch testing. It was confirmed that the improving the adhesive strength of the coating films was possible by laser quenching using the scanning laser.

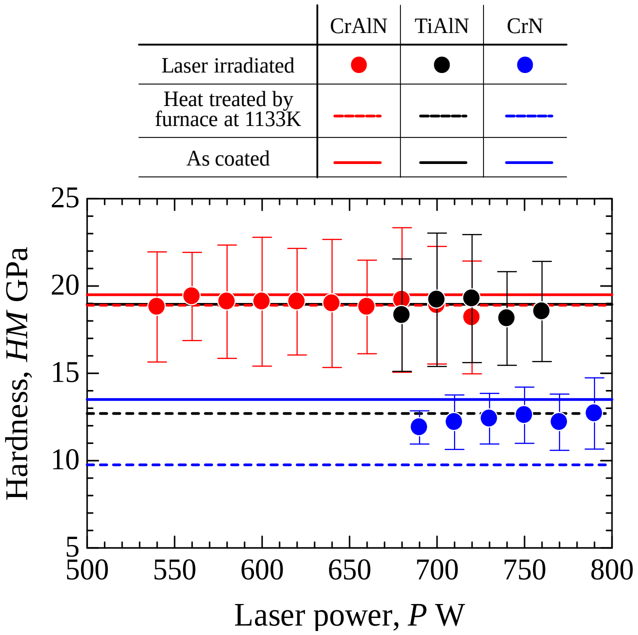

Fig. 10. Film hardness of the laser-quenched specimens heat-treated by laser.

Fig. 10 shows the results of the film hardness measurements of the laser-irradiated specimens. This figure also shows the averages of film hardness before laser irradiation, and after heat treatment in furnace at 1133 K. The furnace heat treatments were carried out in a nitrogen atmosphere using an electric furnace (TLG-40, Thermal Co. Ltd., Japan). The heating time was set to 20 minutes. These heating conditions were selected because the optimum heating conditions for the substrate quenching after coating by furnace for ceramic-coated SK105 steel were revealed as “at 1133K, for 20 minutes” in our previous research **[8]**.

The hardness of TiAlN and CrN films decreased considerably, and the hardness of CrAlN decreased slightly through furnace heating. The reason of the decrease of the film hardness could be explained by the decrease of the residual stress by furnace heating. However, the hardness of all coatings processed by scanning laser, remained practically unchanged. This reason could be explained by the difference of the process time. In the case of laser quenching, the process time, in which the film is exposed to an elevated temperature, is quite short. Therefore, no heat-induced change occurs within the film. But, in the case of furnace quenching, the film is exposed to an elevated temperature for a longer period because a certain time is required to heat the specimen uniformly.

From these results, it can be concluded that laser quenching by a scanning laser can effectively improve the adhesive strength and substrate hardness without any detrimental effect on the film hardness of the investigated ceramic-coated specimens.

Measurement results of deformation

For the ceramic-coated specimens laser-irradiated at various laser power *P*, the surface profiles of laser-irradiated parts were measured. **Fig. 11** shows a schematic illustration of the deformations observed in the laser-irradiated specimen, and **Fig. 12** shows an example of the measurement results of the surface profile around the laser-irradiated part. As shown in Fig.11, two features were recognized in the deformation of the laser-irradiated specimens; one is the bending, and the other is the expansion. It is considered that the compressive plastic deformation of laser-irradiated part, caused by the restraint from the circumference for the rapid and local thermal expansion by laser irradiation, would be the cause of the bending deformation of the specimen. The expansion of the laser-irradiated part would be caused by “the martensitic transformation” and “the plastic deformation caused by thermal expansion” of the laser-irradiated part.

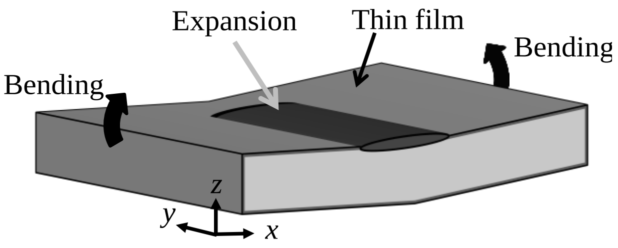

Fig. 11. Schematic illustration of the deformations of the specimen caused by laser irradiation

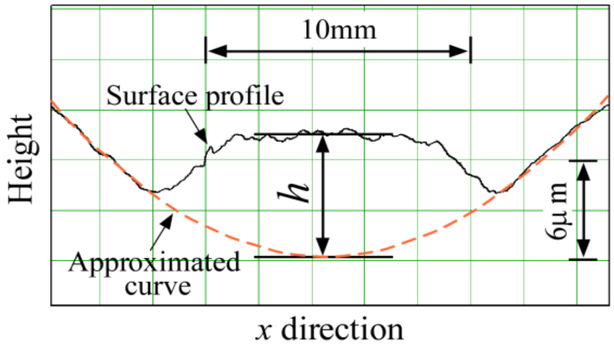

Fig. 12. Example of surface profile of laser-irradiated part (CrAlN-coated specimen, *P*=680W).

In this study, in order to clarify the deformation behaviour accompanying laser irradiation, the relationship between the height of expansion of laser-irradiated part and the laser power *P* was investigated. As described in **Fig. 12**, the height of expansion, *h*, was evaluated as the difference between the surface profile (Black solid line) and the curve obtained by approximating the profile of the both sides of the laser-irradiated part (Red broken line). **Fig. 13** shows the relationship between the height of expansion *h* and laser power *P*. The solid marks show the quenched specimens, and the open marks show the not-quenched specimens. For all three kinds of specimens, the height of expansion *h* increased with the laser power *P*.

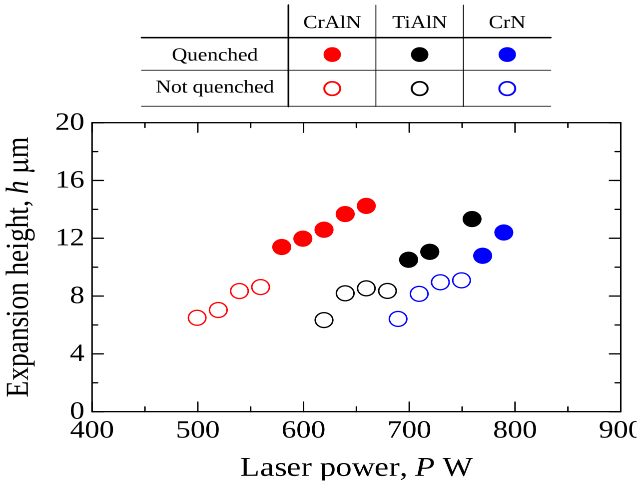

Fig. 13. Relationship between the expansion height of laser-irradiated part and laser power.

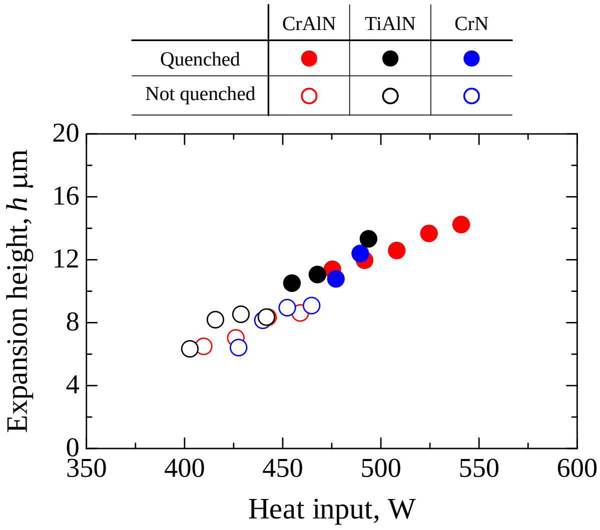

Fig. 14. Relationship between the expansion height of laser-irradiated part and heat input.

Fig. 14 shows the relationship between the height of expansion *h* and the heat input. As shown in **Fig. 14**, a good correlation was recognized between *h* and heat input. From this result, it is considered that the deformation of ceramic-coated steel by laser irradiation under the same heat input condition does not depend on the kind of thin film but on the steel type of the substrate.

Conclusion

Laser irradiation experiments by using a high power diode laser equipped with a galvano-scanner unit were carried out for three kinds of specimens: CrAlN coated specimen, TiAlN coated specimen and CrN coated specimen. Specimen surface areas of 10 mm × 50 mm were processed, and the effects of the laser irradiation on the deformations and the mechanical properties of the specimens; substrate hardness, adhesive strength and film hardness were investigated. The following conclusions were obtained:

- the laser-irradiated surfaces can be classified into three types, depending on substrate hardness and whether or not surface damage occurred,
- for all three kinds of specimens, laser quenching with no surface damage was obtained on the regions with the width lager than the laser spot size,
- for CrAlN-coated specimens, it was possible to quench the substrate effectively at the lowest laser power in these three kinds specimens,
- in the quenched and non surface damaged group, the minimum heat input was almost the same for all the three kinds specimens,
- in the quenched and non surface damaged group, the maximum heat input changed with the kinds of thin film because of the difference in the heat absorption ability of these films,
- the adhesive strength of CrAlN, TiAlN and CrN was improved by laser irradiation with the scanning laser,
- the film hardness of laser processed ceramic-coated specimen remained practically unchanged,
- two features were recognized in the deformation of the laser-irradiated specimens; one is bending, and the other is expansion,
- the deformation of ceramic-coated steel by laser irradiation under the same heat input condition does not depend on the kind of thin film but on the steel type of the substrate,
- improving the adhesive strength and substrate hardness without any detrimental effect on the film hardness of large surface areas in the tested all types of ceramic-coated specimens was possible by using the laser quenching technique.

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