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The interaction between a pulsed laser beam and a steel surface

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The interaction between a pulsed laser beam and the surface of a carbon steel has been investigated. The variables of the irradiation were the power intensity of the laser beam and the number of pulses. At the area of impact of the incoming laser beam concentric ripples were observed. The number of ripples and their displacement was found to be dependent on both the above parameters. No transformation products, such as martensite or bainite, or any evidence of a heat affected zone have been observed at the immediate vicinity of the impact area.

1. Introduction

Surface treatment by means of laser-beam radiation is a relatively new technology in the field of surface heat treatment. Laser treatment has advantages and of course disadvantages in comparison with conventional heat treatments. The most important advantages are the following:

(i) Radiation by a laser beam allows the treatment of the surface only, with very little damage to the bulk.
(ii) The properties which are obtained, for example hardness, are higher than those obtained by other means.
(iii) It is possible to heat treat a very small and localized region [1–5].

Commercial heat treatments such as surface hardening, welding, cutting and drilling are performed today on an industrial scale by using continuous CO_2 laser systems of very high power, of the order of up to 15 kW. The disadvantage of these systems is that they are large and complex. Another disadvantage of the continuous wave CO_2 laser beam radiation is the large reflectivity and the relatively large heat affected zone. This and other handicaps can be overcome by using Nd : YAG or excimer pulse laser beam radiation in the visible and UV wavelength ranges respectively. By this method it is possible to supply large energy densities in very short periods of time. The effect of parameters of continuous laser beam radiation on the various properties of the treated substrate is well covered in the literature [3, 4]. On the other hand, little is known concerning the influence of short pulse radiation on the properties and microstructures of metals, especially steels [2].

The purpose of this investigation was to study the properties and the microstructure of a carbon steel after interaction with very short pulses of high intensity laser beam. The laser system used in the study was pulsed Nd:YAG, and the steel was a plain carbon steel, SAE 1045. For the sake of comparison other materials were also irradiated, such as tantalum, a thin film of gold deposited on a glass substrate, and silicon.

2. Experimental procedure

Specimens prepared from a 1" diameter 1045 carbon steel were irradiated by means of a Q-switch Nd : YAG pulse laser with a wavelength of 532 nm. The pulse duration was 7 nsec and the maximum energy per pulse (E_p) was 1.7 J. The specimens were mounted on a computer controlled XYZ table. This arrangement allowed us to cover uniform areas with controlled overlapping at a constant pulse number on the entire surface. The experiments were performed in both air and nitrogen (99.8%) atmospheres in a specially designed cell.

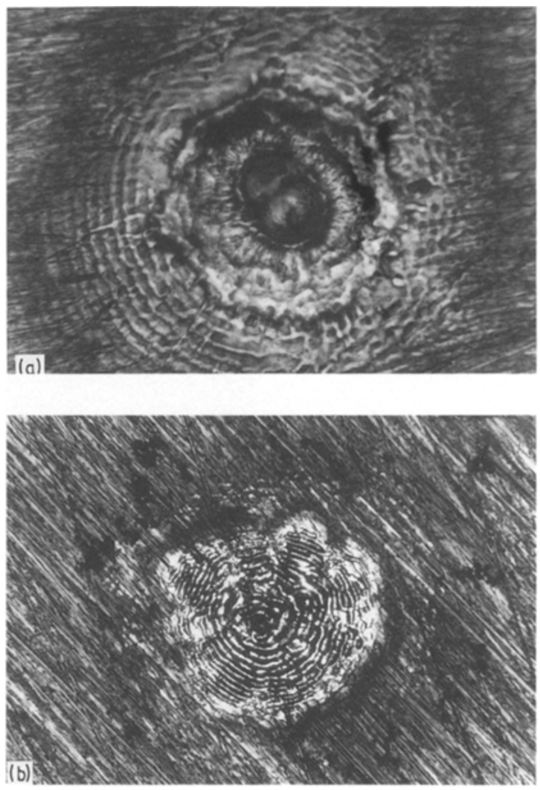

Figure 1 Laser radiation induced ripples (a) in the radiation affected zone (RAZ) and (b) in the irradiation zone (IZ). Magnification × 336.

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The effect on the beam–surface interaction was studied of two laser parameters: the number of pulses and the energy per pulse. In order to observe the influence of each laser parameter, all the experiments were carried out in such a way that one parameter was kept constant, while the other varied. The number of pulses was up to 10, since a larger number of pulses had no additional effect on the beam–surface interaction (ripple displacement). The intensity varied between 10^8 and 10^{11} W cm^{-2}.

The morphology of the substrate and its microstructure after irradiation were investigated by means of optical and electron microscopy and by Auger spectroscopy.

3. Results

The morphology of the surface was studied in order to characterize the changes which take place during the laser beam interaction with the substrate. This part of the study was conducted by optical microscopy. It was observed that the area of contact between the laser beam and the metal surface is divided into two major zones, the irradiated zone (IZ) and the radiation affected zone (RAZ). The typical appearance of these zones is shown in Fig. 1a, which shows the surface of the steel after irradiation by ten pulses at a beam intensity of 10^9 W cm^{-2}. The regions marked A and B are IZ and RAZ, respectively. By using a relatively simple calculation one can estimate that beam intensity which will cause melting of the steel surface at the point of impact [6].

$$T(0, t) = (1 - R)2I_0(kt/\pi)^{1/2}K^{-1}$$

where T (K) is the surface temperature at time t (sec), R is the reflectively, I_0 (W cm^{-2}) is the intensity of the beam on the surface, k (cm^2 sec^{-1}) is the thermal diffusivity and K (J K^{-1} sec^{-1} cm^{-1}) is the thermal conductivity. For the steel under study $K = 0.42$, $k = 0.077$, and $R = 0.25$ in the appropriate units. Since the melting temperature of the steel is 1768 K, the intensity required to cause melting is $I_m = 2.83 \times 10^8$ W cm^{-2}. Following this calculation, one can assume that the steel surface was melted during the pulse. The micrograph in Fig. 1a also shows concentrated rings (ripples) within the irradiated zone. When the intensity of the pulse was higher than 4×10^9 W cm^{-2} ripples were observed only in RAZ, as

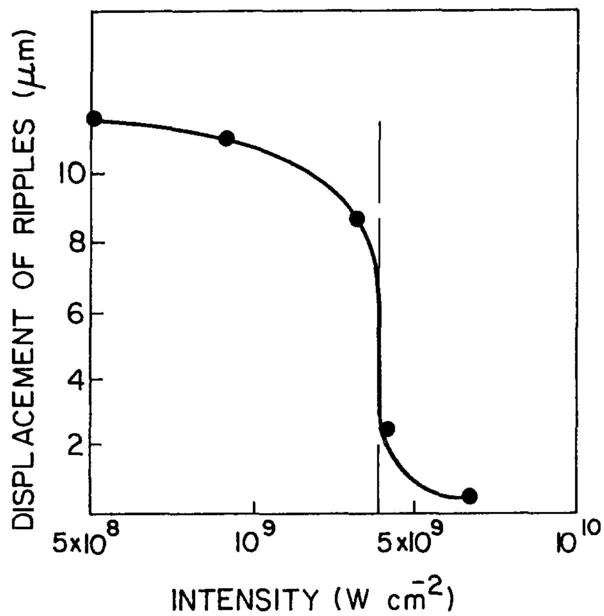

Figure 3 Variation of the inter-ripple distance with the laser beam intensity in the melted irradiated zone.

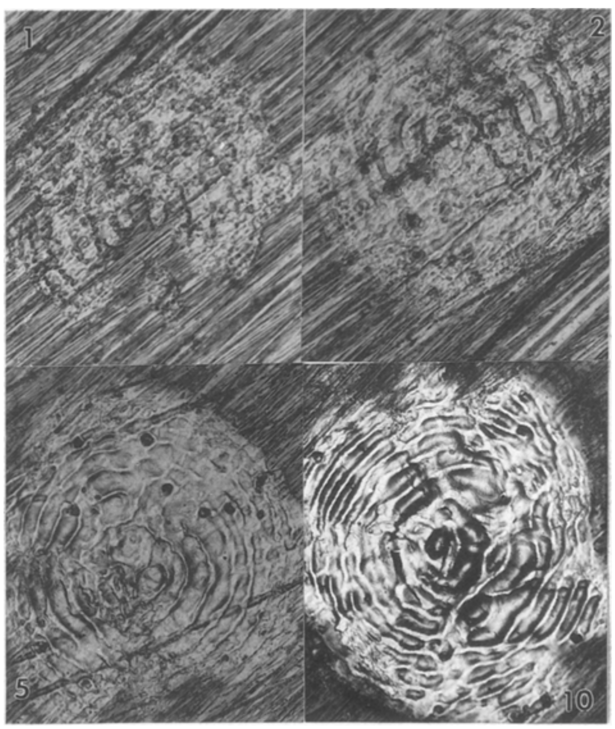

Figure 2 The effect of pulse number on ripples in the melted surface. The number of pulses is shown in each micrograph.

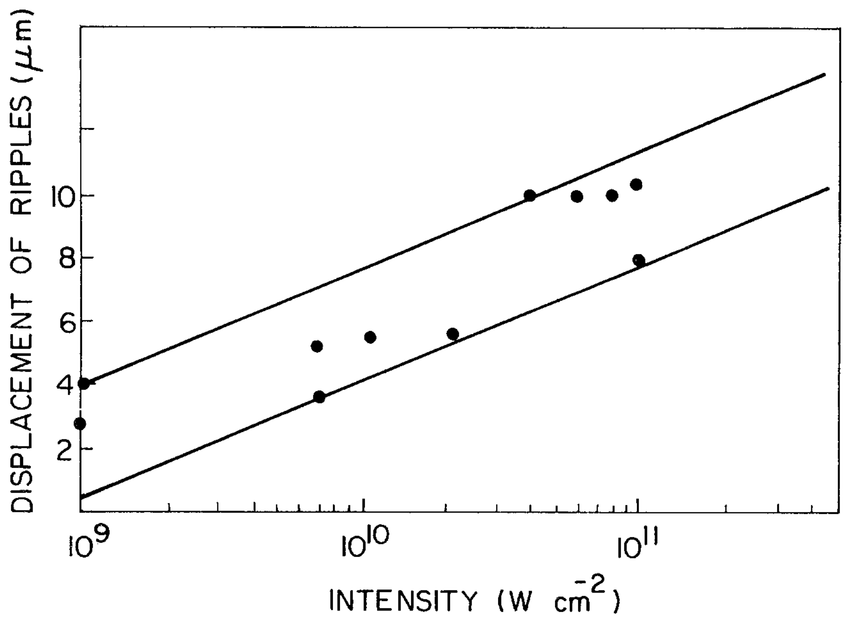

Figure 4 Variation of the inter-ripple distance with the laser beam intensity in the radiation affected zone.

shown for example in Fig. 1b. The number of ripples and the inter-ripple displacement (IRD) were measured in both regions and were found to be dependent on both the intensity of the laser beam and the number of pulses. Fig. 2 for example shows the influence of pulse number at constant intensity on the appearance of the ripples in the IZ. It can be seen that ripples are observed even after a single pulse, however after 1 or 2 pulses their appearance is not clear. This behaviour was independent of the beam intensity. At least 10 pulses were required to obtain a clear picture; more pulses did not change the number of ripples or their appearance.

The IRD was measured for the various conditions of irradiation in both regions. Fig. 3 exhibits the variation of IRD with the laser beam intensity for a constant pulse number (10 pulses) in the melted irradiated zone. This graph shows that there is a critical intensity at which the inter-ripple displacement increases to a very small value. Accordingly, no ripples can be observed in the IZ at intensities greater than 4×10^9 W cm^{-2}. In the radiation affected zone on the other hand, the IRD continuously increases with the intensity, in a more or less linear fashion, as shown in Fig. 4. The distance between the ripples in the IZ is larger than in the RAZ. Ripples were also observed on the other substrates; tantalum, gold and silicon. The results were similar to that of the steel, though the IRD was different for each substrate.

Following the examination of the surface, the regions of interaction were also studied to the depth by two different methods: scanning electron microscopy (SEM) and Auger spectroscopy (AES). Fig. 5 shows the cross-section of the interaction region of the steel irradiated by a beam density of 2.7×10^{10} W cm^{-2} in natural atmosphere (air). It can be seen that at the region of impact of the laser beam a relatively deep indentation (5 μm) is created and it is covered with a 1 μm thick oxide layer. Below the oxide layer the typical structure of this steel is observed, which consists of fine lamellae of pearlite and large ferrite columns. The micrograph of Fig. 5 shows that the pearlite lamellae are almost perpendicular to the surface and no deformation whatsoever can be seen below the oxide layer. The average interlamellar spacing in the pearlite was exactly the same in the region of impact or far from it. Moreover, one would expect to observe some transformation product in the immediate vicinity of the impact region. Many regions like the one shown in Fig. 5 were examined but no traces of martensite, bainite or retained austenite were observed.

The oxide layer was analysed by both AES and electron diffraction in TEM. It has been established that the oxide film is built from different layers. The upper part of the film is Fe_2O_3 and the lower part is Fe_3O_4. There is a region of non-stoichiometric composition in the middle.

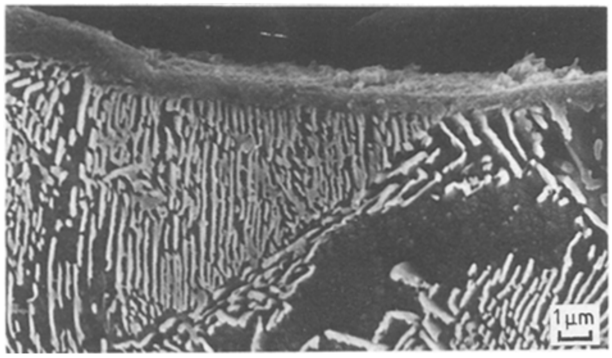

Figure 5 Micrograph showing cross-section of the interaction region of the steel irradiated in air.

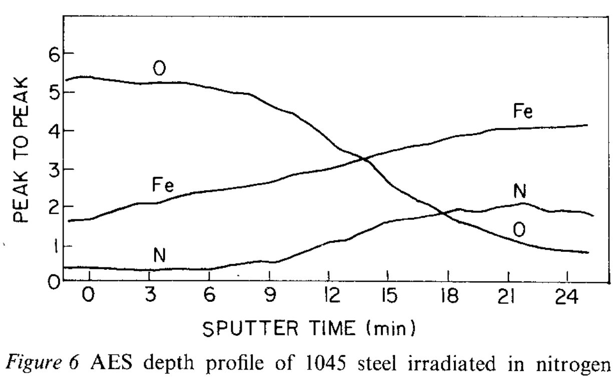

Figure 6 AES depth profile of 1045 steel irradiated in nitrogen atmosphere.

Some of the steel samples were irradiated under nitrogen. The appearance of the impact region was exactly the same as before. Also a very thin oxide layer covering the indentation was observed. Below the oxide film a thin ferrum-nitride region was obtained. Figure 6 shows the Auger depth profile of a typical film. TEM electron diffraction identified the nitride as Fe_4N.

4. Discussion

The results of this investigation will be discussed in two sections: (i) surface ripples and (ii) microstructure of the beam–surface impact region.

4.1. Surface ripples

As mentioned in the previous section, upon interaction of the laser beam with the surface, concentrated rings, (ripples) are formed, both in the irradiated zone (IZ) and in the radiation affected zone (RAZ). Such ripples are observed on all the materials studied in this investigation. Ripple formation is not an unknown phenomenon, and has been reported in the relevant literature [7–12]. Since ripples were observed on many different types of materials, it can be concluded that they are not a material property.

The following is a qualitative explanation of the mechanism of ripple formation in the IZ. It has been shown (see the equation above) that if a laser beam with the pulse intensity of 10^8 W cm^{-2} strikes a steel surface, the impact region melts in a time interval of 70 psec. This period of time is very small compared to the pulse duration, which is 7 nsec. Due to the reflectivity of the metal surface a quantity of the radiation waves is reflected and interferes with the incoming waves. During this process, constructive or destructive interference creates high and low density concentric energy fields. Accordingly, the steel on the surface evaporates selectively and creates ripples in the molten material. Since all this takes place during an extremely short period, there is no time for the melt to flatten and the whole region freezes with the ripples.

The number of pulses, according to this model, has no effect on the overall picture, except that one or two pulses do not create well-defined ripples. It was shown that at least 5 pulses are needed for obtaining clear, sharp ripples. With increasing beam intensity, the width of the high density energy field increases at the expense of the low density fields and therefore the inter-ripple distance decreases. When the beam intensity becomes high enough to cause evaporation of the entire impact region, no more ripples are observed, as shown in Fig. 3.

It was shown that when the beam intensity is high, the ripples are formed in the RAZ. It is reported [13–16] that for intensities of over 10^9 W cm^{-2} plasma formation is induced by the laser beam. The pressure on the surface by this plasma can reach 2.5 GPa [15]. High pressure like this during the period of 7 nsec cause shock waves at the steel surface. It is assumed that the ripples in the RAZ are created by these shock waves.

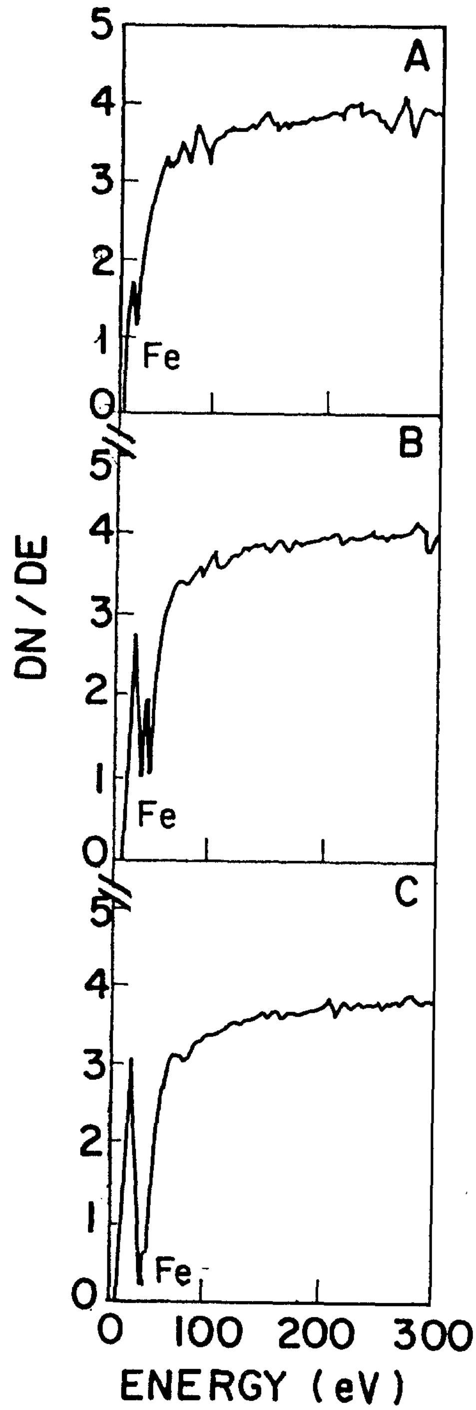

Figure 7 AES analysis of steel irradiated in air atmosphere: (A) surface analysis before sputtering; (B) spectrum of the iron peaks in depth of 120 nm; (C) as (B) but in 300 nm depth.

4.2. Microstructure of the impact region

Perhaps the most interesting observation was the complete lack of heat affected zone in the closest vicinity of the beam impact region. Microscopic observation of many such regions lead to the following characterization:

(i) some material is removed from the surface;

(ii) there are no transformation products such as bainite, martensite or retained austenite;

(iii) there is no change in the interlamellar spacing in the pearlite;

(iv) an approximately 1.5 μm thick oxide layer covers the impact area, or a nitride layer below it, when the experiment is done in a nitrogen environment.

All the observations summarized above can be explained by the fact that the very large quantity of energy is supplied in a very short period of time. The power density of 2.7×10^{10} W cm^{-2} is about 20 times larger than that necessary to evaporate 1 μm deep surface material at the impact area. It can be assumed therefore that all this material transforms into plasma. The plasma creates a charged zone of iron atoms which easily react with oxygen or nitrogen atoms, depending on the environment.

The heat penetration depth is $D = (4kt)^{1/2}$, where k is the thermal diffusivity and t is the pulse duration. For steel during a pulse of 7 nsec the heat can penetrate to a maximum depth of 0.5 μm. The heat affected zone therefore cannot be deeper than this depth. It is quite possible that the entire heat affected zone is disguised by the oxide.

The oxide film covering the impact region is built of various layers. Figure 7 shows the Auger spectrum of the oxygen-sensitive iron peaks at three different depth of the oxide film [17]. The shape of the peaks and their location (their kinetic energy) varies with depth. In the upper part of the film the peak of 41 eV is only slightly larger than the peak of 51 eV. In the depth of 12 nm the 51 eV peak becomes larger and at the depth of 300 nm the 41 eV peak disappeared. Accordingly, the oxide of the upper layer is richer in oxygen than that of the lower layer. Electron diffraction by TEM confirmed the above, identifying the oxide in the lower layer as Fe_3O_4.

In contradiction with the oxide film, the nitride film is quite homogeneous (see Fig. 6). It is assumed that the nitride film is formed by a mechanism similar to that of the oxide film.

5. Conclusions

Irradiation of a 1045 carbon steel surface by a pulsed laser beam yielded the following results:

1. The impact area can be divided into two characteristic regions: the irradiated zone and the radiation affected zone.
2. In both regions concentric rings (ripples) were observed. The number of ripples and their displacement were found to be dependent on the number of pulses and the beam intensity.
3. At the area of impact a small crater is created, covered by oxides or nitride and oxide, depending on the environment.
4. No transformation products or any evidence of a heat affected zone has been observed.

It is suggested that this or similar processes can be used for selected area surface treatments or metal removal, without affecting the bulk. It may be also possible to apply this method for selected area nitriding.

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References

1. A. TIZIANI, L. GIORDANO and E. RAMUS, "Laser Surface Treatment by Rapid Solidification", ASM Conference on Application of Lasers in Materials Processing, Los Angeles, CA (ASM, Metals Park, Ohio, 1983).
2. M. A. FOLCO, *Practical Metallogr.* **14** (1977) 269.
3. D. S. GNANAMUTHU, "Laser Surface Treatment", Proceedings of a Conference on Application of Laser in Materials Processing, Washington, DC (ASM, Metals Park, Ohio, 1979) p. 177.
4. M. F. ASHBY, K. E. EASTERLING and W. B. LI, "Modelling the Laser Transformation Hardening of Steel", Proceedings of a Symposium on Laser Processing of Materials (*Met. Soc.*, AIME, 1984) p. 225.
5. M. FISHMAN and J. ZAHAVI, *J. Mater. Sci.* **23** (1988) 1547.
6. S. CHARSCHAN, "Lasers in Industry", (Laser Institute of America, Van Nostrand, New York, 1972).
7. G. N. MARACAS, G. L. HARRIS and C. A. McFAIRLANE, *Appl. Phys. Lett.* **33**(5) (1978) 453.
8. J. C. KOO and R. E. SLUSHER, *Appl. Phys. Lett.* **28**(10) (1976) 615.
9. H. J. LEAMY, G. A. ROZGONYI and T. T. SHANG, *Appl. Phys. Lett.* **32**(9) (1978) 535.
10. E. W. KREUTZ, M. KREOSCHE, H. G. TREUSCH and C. HERZINGER, *Laser Proc. Diagnostic Proc. Chem. Phys.* **39** (1984) 107.
11. R. M. OSGOOD and D. J. EHRLICH, *Optics Lett.* **7**(8) (1982) 285.
12. D. J. EHRLICH, S. R. BRUECK and J. Y. TSCA, "Surface Electro-Magnetic Waves in Laser Material Interactions", Laser-Solid Interaction and Transient Thermal Processing of Materials, MRS Symposium, Vol. 13 (North Holland, Boston, 1982) p. 191.
13. B. STEVERDING and H. P. DUDÉL, *J. Appl. Phys.* **47**(5) (1978) 1940.
14. B. P. FAIRLAND and A. H. GLAUER, *J. Appl. Phys.* **50**(3) (1979) 1497.
15. A. H. CLAVER and B. P. FAIRLAND, "Interaction of Laser Induced Stress Waves with Metals", Proceedings of the Conference on Laser Processing and Diagnostics, Linz (Springer Verlag, Berlin, 1984) p. 291.
16. H. H. MADDEN, *J. Vac. Sci. Technol.* **18**(3) (1981) 677.
17. S. CRAIG, G. L. HARDING and R. PAYLING, *Surf. Sci.* **124** (1983) 591.

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