# THE EFFECT OF ION IMPLANTATION ON THE FATIGUE FRACTURE OF STRUCTURAL STEEL

**A. V. Fyodorov and E. V. Vasilyeva**

*Moscow Aviation Institute 125080, High Technical School by ZIL, Moscow 109068, USSR*

ABSTRACT

Ion implantation ($N^+$ and $C^+$) effect on fatigue strength of structural chromo-nickel-manganese steel is investigated after austempering. A noticable increase of fatigue strength is shown under the influence of ion implantation. It is found, that the depth of hardening is far larger than the length of ion path.

KEYWORDS

Fatigue strength; cyclic strength; fatigue rupture; fatigue fracture; endurance; structural steel ion implantation dispersion of fatigue test results; ion energy; radiation dose; ion current density.

INTRODUCTION

Ion implantation, the primary aim of which was to improve service characteristics of microelectronic schemes and to dope semiconductors, is at present successfully used also for increasing the auxiliary properties of metallic alloys. To a considerable extent, this was conducive to the manufacture in the Soviet Union and abroad of new high-effective installations which could provide treatment of working surfaces of not only specimens but also machine parts and assemblies. Lately, ion implantation has been ever more widely used as a controlled method for simultaneous introduction of radiation-induced defects and microadditives in order to increase the mechanical, physical, optical and other properties of metals and alloys. Special possibilities are offered by ion implantation as a method of increasing the fatigue strength because the level of this characteristic to a considerable extent depends on the state of surface and properties of surface layer. This technique takes precedence over other methods of surface strengthening in the universality of the process enabling practically any element to be introduced into any material in strictly controllable amounts as well as controlling its distribution in depth by changing the radiation doses and energies. In recent years, a number of papers on the effect of ion implantation on the cyclic strength of metals and alloys have been published [1-4] but present, knowledge concerning the nature of the influence of different ions is to a certain extent contradictory. However, the majority of authors point

out rather a positive impact of ion implantation on cyclic strength although in a few works they underline the complicated character of this influence [5,7] .
The information available now is applicable primary to copper [8,9] , alloys of titanium [3] and aluminium [11] .
The data on steels have been obtained mainly for stainless steels [6] . In all the above work, the method of ion implantation is used as a means of changing the properties of surface and pre-surface layers to increase the cyclic strength. There is practically no information about the nature of fatigue failure of implanted specimens and pieces.

In the present paper, a research is carried out on the influence of ion implantation upon the cyclic strength of structural steel 30XΓCHA. The composition of steel according to the All-Union State Standard 4543-71 is given below

TABLE 1 Chemical composition of steel 30XΓCHA (percentage by mass)

| C | Mu | Si | P | S | Cr | Ni | Cu | Mo |
|---|---|---|---|---|---|---|---|---|
| 0.29 | 0.94 | 1.02 | 0.009 | 0.005 | 1.09 | 1.61 | 0.18 | 0.05 |

Tests have been carried out with cylindrical specimens of 64 mm length and diameter of the gauge-length - 7.52 mm. The shape of a specimen's gauge-length was a straightened hyperbola. The value of the theoretical notch-sensitivity index was $K_t=1.07$. The gauge-length of specimens have been exposed to ion implantation of $N^+$ and $C^+$ on the installation IBA-3 (ionnic-beam accelerator) in vacuum, by the residual pressure in the test chamber of $5.10^{-5}$ torr. The temperature in the chamber did not exceed 100°C. Four specimens were exposed simultaneously to radiation by one beam. The radiation dose by implantation was $10^{17}$ ion/cm$^2$ with an energy of 40 keV. The implantation time for one specimen was 28 minutes with the ion current density of 20 MA/cm$^2$.
Fatigue tests have been carried out in the conditions of pure circular bending to failure of a specimen with the load frequency of 3000 rpm on the installation FTM-6000 (fatigue testing machine) at room temperature and by standard technique (the All-Union State Standards 2860-65). For comparison, the fatigue tests have been carried out with non-implanted specimens of the same steel. The fatigue curves were plotted on the base of $10^7$ cycles. The parent fatigue curve is shown on Fig. 1 (curve 1).
There is a considerable spread in the values of fatigue limit which is usually observed when testing steels of high strength. The fatigue limit value obtained under these conditions was 528 MPa.
The fatigue curves of steel specimens exposed to ion implantation by nitrogen and carbon are given on Fig. 3 and Fig. 5. The values of fatigue limit of specimens subjected to of implantation have increased to 684 MPa (ions of $C^+$) and 720 MPa (ions of $N^+$). The spread of values of fatigue limit sharply decreases (practically disappears).



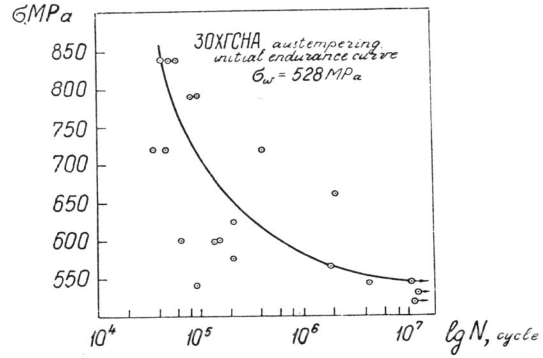


Fig. 1. The parent fatigue curve

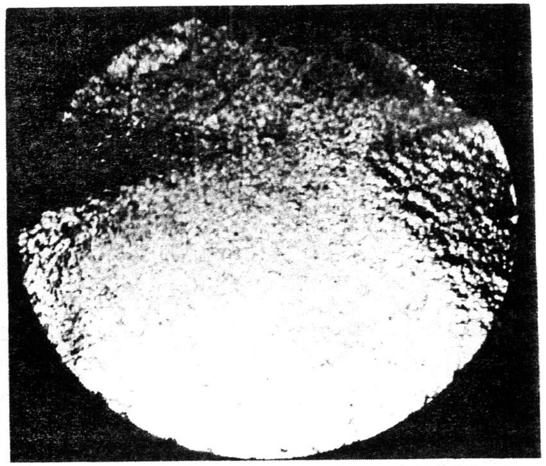

Fig. 2. The fracture of the parent specimen

For specimens implanted by ions of nitrogen and carbon, the endurance (i.e. time to failure under the certain stress exceeding the endurance limit), under all stress values studied, increases by a factor of $10^2$ compared with that of the parent specimens.
On Figures 2, 4, 6 (with a magnification of 10 power) are illustrated typical appearances of fractures of specimens failed in the process of testing when in the parent and implanted states.

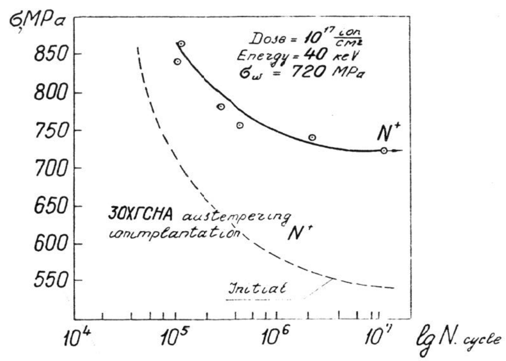


Fig. 3. The endurance curve after implantation by nitrogen $N^+$

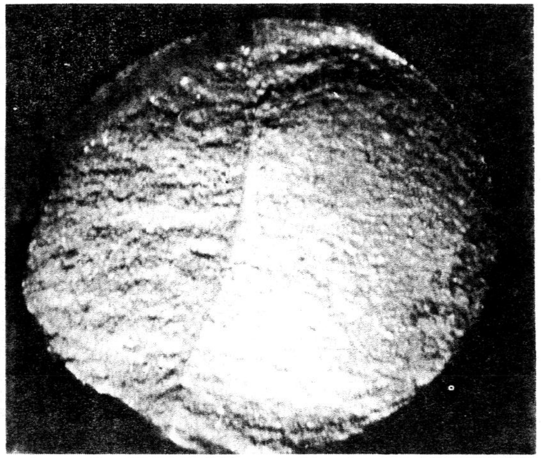

Fig. 4. The specimen's fracture after implantation by nitrogen $N^+$

The fractures are of the fatigue type. One can observe on them all zones (12) which are mentioned in literature. It is typical of ion implantation to change the relation between the area occupied by the fatigue crack and the zone of breaking. The former is increased and the latter is decreased. To explain the nature of the fatigue strength increase and that of the longevity, as well as the specific appearance of



fatigue fractures of implanted specimens, a number of investigations have been undertaken to set up factors determining the above phenomena. First of all, a thorough investigation has been carried of the surface of implanted specimens, for it is known that the condition of surfaces exerts an essential effect on the incipience and propagation of fatigue cracks.

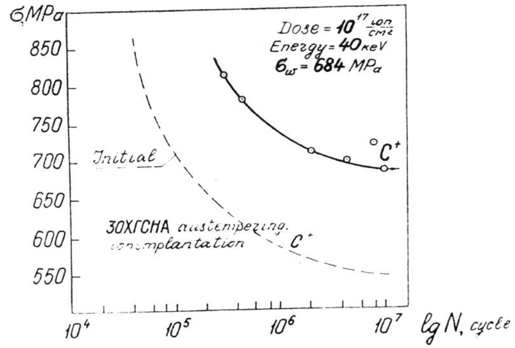


Fig. 5. The endurance curve after implantation by carbon $C^+$

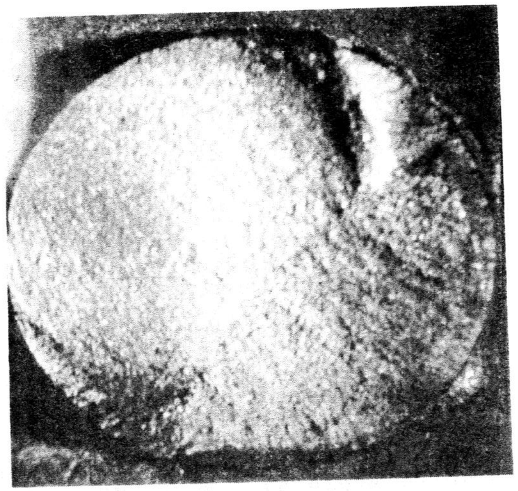

Fig. 6. The specimen's fracture after implantation by carbon $C^+$

The surface roughness was defined by the profileometer instrument "Petro-meter, Petro-grapher" and its morphology was studied by means of an SEM "Stereoscan - S-180" (Scanning Electron Microscope).
The comparison of profilograms obtained showed that the implanted surface was, in general, less rough than the parent one. The morphology of the implanted surface was characterized by a considerable in comparison with the parent state grindability of its projection as well as by the formation of a large number of pores, and this occured evidently in the result of "driving" of the implanted ions into the surface of the target or due to their re-emission. It is of interest to note that the depth of penetration of the implanted ions determined with the help of the Auger effect in the conditions studied made up only 0.4 Mk while the general effect of hardening from implantation according to the measurements of microhardness has propagated to a depth of 3 mm. The X-ray diffraction method was used to determine residual stresses in the implanted layer. However, the data obtained showed no essential residual stresses in the surface layer created by ion implantation. The average level of such stresses in the parent steel made up 272 MPa and after ion implantation by nitrogen and carbon - 298 MPa and 292 MPa, correspondingly. Data on the electron-microscopical study of fine foils (implanted by ions of $N^+$ and $C^+$ with the regimes accepted) of the studied steel 30XICHA have illustrated the formation in the process of ion implantation of the specific dislocation structure which was characterized under general increase of dislocation density by the formation of a considerable number of dislocation loops as well as very small nuclei of depositing phases, them being apparently small-variance carbides and nitrides in the given case.
The analysis of results of the research carried above enables in the following hypothetical description of the mechanism of increasing the fatigue strength and resistance to endurance failure the result of ion implantation under given conditions. It is pointed out in literature [12], that, in the process of repeated loading, there takes place a considerable change of dislocation structure in the surface layers, the most intensive changes being observed in the surface layers of metal of about 5 in depth. It is in these layers of the metal where the incipience of fatigue crack occurs.
Since the ion implantation method strengthens the pre-surface layers of metal of such depth, its application permits to essentially increase the endurance limit and longevity of the structural steel. It is at this depth, as the spectroscopic results showed, (the Auger effect), where one can observe maximum concentration of atoms of elements introduced which can interact with dislocations formed in the result of impact of alternating loads fixing them and thus impeding their movement, all that leading to an increase in yield point and, hence, to an increase in the endurance limit. Besides, the aggregate of implanted atoms by themselves to a certain extent arrest the incipience of fatigue cracks just in the zones where these cracks are usually being formed. Hindering the latter's propagation are the specific defects which are created by implantation and which appear and spread at a great



depth of about 3 mm. One could have observed these defects in the form of dislocation loops with the pile-ups of fine-dispersed particles of nitrides and carbides as well as a great number of "radiation-induced", mainly, pin-hole defects. Apparently, these are the main reasons which, on the one hand, can explain increasing of the fatigue strength level and, on the other hand, - the inherent appearance of fatigue fractures of implanted specimens. They determine the ability of the metal implanted under these conditions to operate ever longer in the already damaged state.
Thus, ion implantation can serve as a highly effective technique for increasing not only the longevity but the reliability of parts and elements of structures operating in the conditions of cyclic loads.

## REFERENCES


Gooseva, M. I. (1982). Surface. Physics, chemistry, mechanics. 4, 27.

Kao Po-We, Byrne, I. G. (1981). Fat. Enging. Nat. and Struct. v. 3, p. 271.

Fujishero, S., Eylon D. (1980). Met. Trans. v. 11 A, N 8, p. 1259.

Hirvonen, et al. (1979). Thin Solid Films. v. 63, p. 5.

Chakrabortty, S. B., Kujore, A., Starke, E. A. ibid 1980, v. 73, p. 209.

Sleeswyk, A. W., Kok, H. I. G., Boom, G. (1980). Scripta met, v. 14, p. 919.

Kujore, A., (1981). et al. Nucl. Instr. and Meth., v. 182, p. 949.

Bakhru, H. (1981). et al. ibid p. 959.

Bibole, M., Le Hazif, R., Mathie, J. (1980). Scripta Met., v. 14, p. 1147.

Dearualey, G., Hartley, N. W. (1978). Thin Solid Films, v. 578, p. 215.

Kujore, A., Chakrabortty, S. B., Starke, E. A. Jr., Legg, K. O. (1981). Nucl. Instr. and Meth., v. 182/183, p. 949.

Ivanova, V. S., Terentyev, V. F. (1975). Nature of fatigue of metals. M., Metallurgy, p. 455.