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Track formation in metals by electronic processes using atomic and cluster ions

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Abstract

It is shown here that electronic excitation and ionization arising from the slowing-down of swift heavy ions can lead to structural modifications in some metallic targets as it has been known for a long time in insulators. This damage is always created in the close vicinity of the projectile path and can exhibit various forms.

The first "tracks" in metallic targets were observed a few years ago in some crystalline compounds, such as $NiZr_2$ [1] (Fig. 1), NiTi [2], Ni_3B [3] ··· irradiated with GeV heavy ion beams. These tracks consist of *amorphous* matter located around the path of each projectile. They are only formed when the amount of linear energy deposition

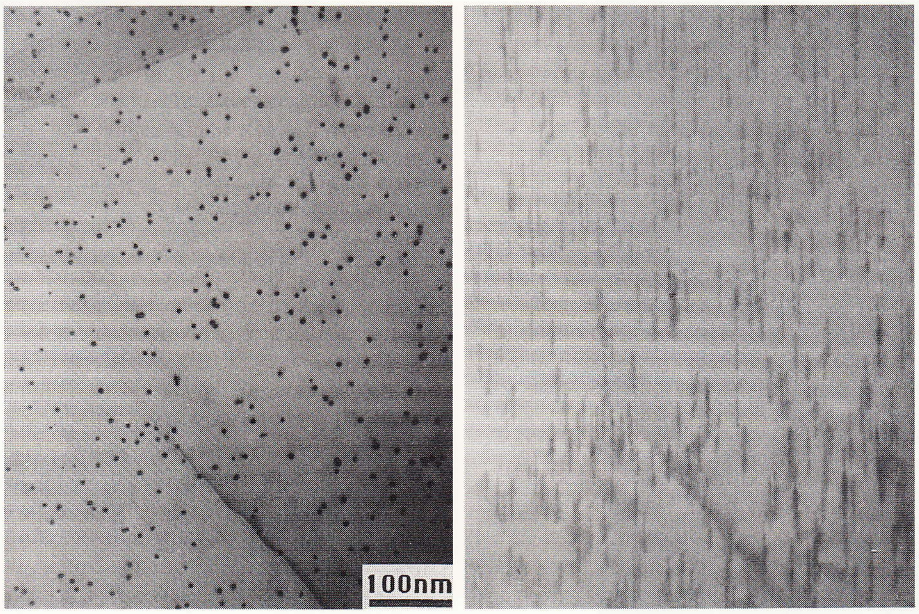

Fig. 1. Amorphous latent tracks induced in an intermetallic alloy, $NiZr_2$, irradiated at 300 K with 750 MeV lead ions ($(dE/dx)_e \approx 50$ keV/nm) up to a fluence of 5×10^{10} cm^{-2}. On the left part of the figure, the incident beam direction is parallel to the electron beam, whereas on the right part of the figure the sample has been tilted by 20° in the electron microscope. The density of observed tracks corresponds to the impinging ion fluence. At such high electron excitation levels, inhomogeneously cylindrical damaged zones are visualized.

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in electronic processes $(dE/dx)_e$ is higher than a threshold value $(dE/dx)_t$ of a few 10 keV/nm. As previously observed in insulators, when $(dE/dx)_e$ increases above the threshold, the configuration of the tracks gradually evolves from strings of separated droplets to continuously damaged cylinders.

More recent work proved that "tracks" can also be observed in some pure metallic targets, for example in titanium [4], after irradiation with GeV heavy ions. The tracks consist here in *highly defective crystalline zones* located in the vicinity of the projectile path and are again observed only when high rates of energy deposition are achieved. For example, after irradiation with GeV Pb and U beams, *discontinuous* damage located within an average diameter of 5 nm is observed in irradiated Ti [4,5] (Fig. 2).

New specific effects take place during irradiation of metals with high energy fullerene beams. Electron microscopy observations were performed at room temperature on prethinned Ti and Zr samples after irradiations with a few 10 MeV fullerenes [6]. After cluster irradiation of Ti targets, the observed damage is *quasi-continuous* and confined inside ~ 20 nm diameter cylinders around the projectile paths (Fig. 3), which has to be compared to the very discontinuous damage obtained after GeV heavy ion irradiation.

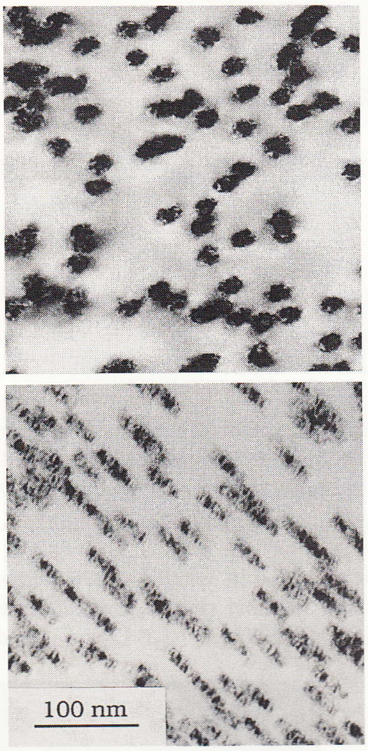

Fig. 3. Continuous tracks induced in a titanium target irradiated at 300 K with 18 MeV C_{60} projectiles ($(dE/dx)_e \approx 43$ keV/nm) up to a fluence of 6×10^{10} cm^{-2}. In the upper part of the figure, the incident beam direction is parallel to the electron beam, whereas in the lower part the sample has been tilted by 30° in the electron microscope. The damaged zones entirely go through the sample thickness and have an almost constant diameter of 20 nm.

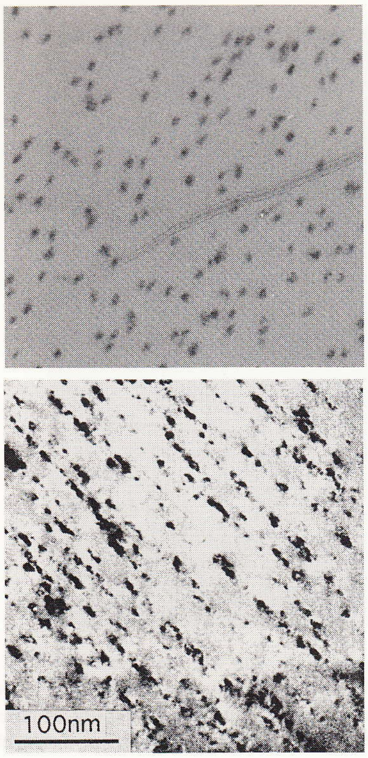

Fig. 2. Dotted tracks induced in a titanium target irradiated at 300 K with 845 MeV lead ions ($(dE/dx)_e \approx 36$ keV/nm) up to a fluence of 10^{11} cm^{-2}. In the upper part of the figure, the incident beam direction is parallel to the electron beam, whereas in the lower part the sample has been tilted by 26° in the electron microscope. The observed contrast, consisting of small dots of average diameter 5 nm, is associated to dislocation loops generated along the projectile path.

In the case of Zr targets [6], the results are even more spectacular: after fullerene irradiation, strongly damaged cylindrical zones are seen, whereas after GeV heavy ion irradiation, no damage is visible in the electron microscope.

Finally one should point out that the creation of latent tracks in metallic targets should be very difficult to explain as the *very numerous mobile conduction electrons* present in the target will: (i) favour a very rapid spreading of the deposited energy and (ii) efficiently screen the space charge created following the ionization of the target atoms located in the vicinity of the projectile trajectory. Two different mechanisms were proposed to explain how the energy deposited in the electronic system of a metal induce permanent lattice defects [7,8].

The comparison of the damage extent induced in titanium targets by monoatomic and cluster beams can be accounted for as follows: although the rates of *linear energy deposition* in electronic excitation are close using these two types of projectiles, the much larger extention of the damaged zones after cluster irradiations might result from the strong spatial localization of the deposited energy during the slowing-down process. The *deposited energy density* is related to the maximum range of the emitted δ-electrons. Using GeV Pb or U ions, the radial range of the δ-electrons is of some 1000 nm, whereas using fullerene beams, this radial range falls to a few interatomic distances. The density of deposited energy reaches then values as high as a few 100 eV/atom.

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