Localized phase transformations by x-ray-induced heating[1]

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Introduction

Recent years have seen the development of synchrotron-radiation (SR) sources for a number of novel applications. For example, the potential of x-rays for submicron parallel processing has given rise to the field of x-ray lithography, and the deep penetration properties of high-energy x-rays have made possible the development of micromachining. The advent of third-generation, high-power, insertion-device (ID)-based SR sources offers the possibility of utilizing x-rays for another novel type of materials processing--localized, volumetric heating.

X-ray beams from IDs are capable of producing heat fluxes of greater than 10^4 watts/cm^2 and several kilowatts of total power. Such high-power beams are capable of melting or even vaporizing a wide variety of materials. Managing such high powers has presented challenges to designers of modern-day SR accelerators and beamlines. However, since x-rays in the range 3–200 keV have penetration lengths on the order of 0.001 to 50 mm for a number of materials, they have the potential for volumetric heating.

Electron beams (EBs) and lasers may also be used for surface transformation hardening. For example, EBs can be used to harden components made from carbon or alloy steel. An EB directed at the component can produce a hardened surface consisting of 99.9% martensite to a depth of more than 1 mm. The EB is defocused so that it will rapidly heat, but not melt, a volume consisting of the target area to a depth determined by the range of the electrons, which is dependent on the accelerating voltage of the beam (30–150 keV). It is less straightforward to perform surface hardening with the laser. Since a defocused beam must be used to avoid melting and vaporization, the high surface reflectivity of metals at the infrared wavelengths usually necessitates coating the surface with a black absorptive material, which is an additional processing operation. However, the CO_2 laser (using a focused beam) is able to melt a metallic surface, since the reflectivity decreases as the temperature rises, and it has found many applications in hardening by surface alloying.

In this report, we present results of experiments that demonstrate the potential for using high-power x-rays for surface transformation hardening. Experiments on 1018 cold-rolled (CR) steel indicate that significant metallurgical changes can be induced to depths of several mm.

Methods and Materials

The heat-treating studies on 1018 CR steel were performed on beamline 20-ID, which incorporated undulator A with a 4.5 x 4.5 mm fixed mask located at 26 m from the source to aperture the beam. This resulted in a total power output of ~2.7 kW at 100 mA beam current and an ID gap of 11 mm. The 1018 CR steel (25 mm x 44 mm x 6.6 mm) samples were obtained commercially. They were mounted in a fixture and positioned so the x-ray beam was normal to the surface. "Bead-on-plate" spot melt trials were performed by irradiating a spot on the sample. The experiments were carried out in a shielded work area, in air, with a slight He purge.

Results and Discussion

Localized steel heat-treating trials were performed as a function of ID gap. As the gap increases, the total power decreases, and the energy of the first harmonic increases. However, the critical energy decreases. The gap settings and related parameters are shown in Table 1.

Figure 1 shows the results of irradiating a 1" x 3.5" x 0.25" piece of 1018 CR steel for 2 seconds at 78 mA of beam current and different undulator gaps. The middle part of the figure shows cross-section micrographs of the exposed regions while the right side shows the results of hardness scans through these regions, where localized melting occurred. The hardness scans were performed by taking measurements starting at the top surface and progressing through the sample in the irradiation direction. For gaps of 14 and 18 mm, uniform hardening occurred to depths of 1–2 mm. The hardening results from rapid quenching of the liquid. This produces martensite and bainite, both of which are harder than the base metal (which has a ferrite and pearlite structure). These different phases are visible in the scanning electron microscope (SEM) micrographs shown on the left side of the figure for the 14 mm irradiated sample. Hardening also occurs at the highest power (G = 11 mm), but extends deeper into the material. At the shorter undulator gap, the critical energy is higher and the penetration depth longer.

Acknowledgments

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Reference

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Table 1: Relevant Parameters for Steel Hardening Trials

Gap (mm)	Power (kW, 100 mA) (4.5 x 4.5 mm aperture)	First harmonic energy (keV)	Critical energy (keV)
11	2.5	3.6	26.2
14	1.4	5.4	18.9
18	0.6	8.2	12.6
21	0.3	12	9.4

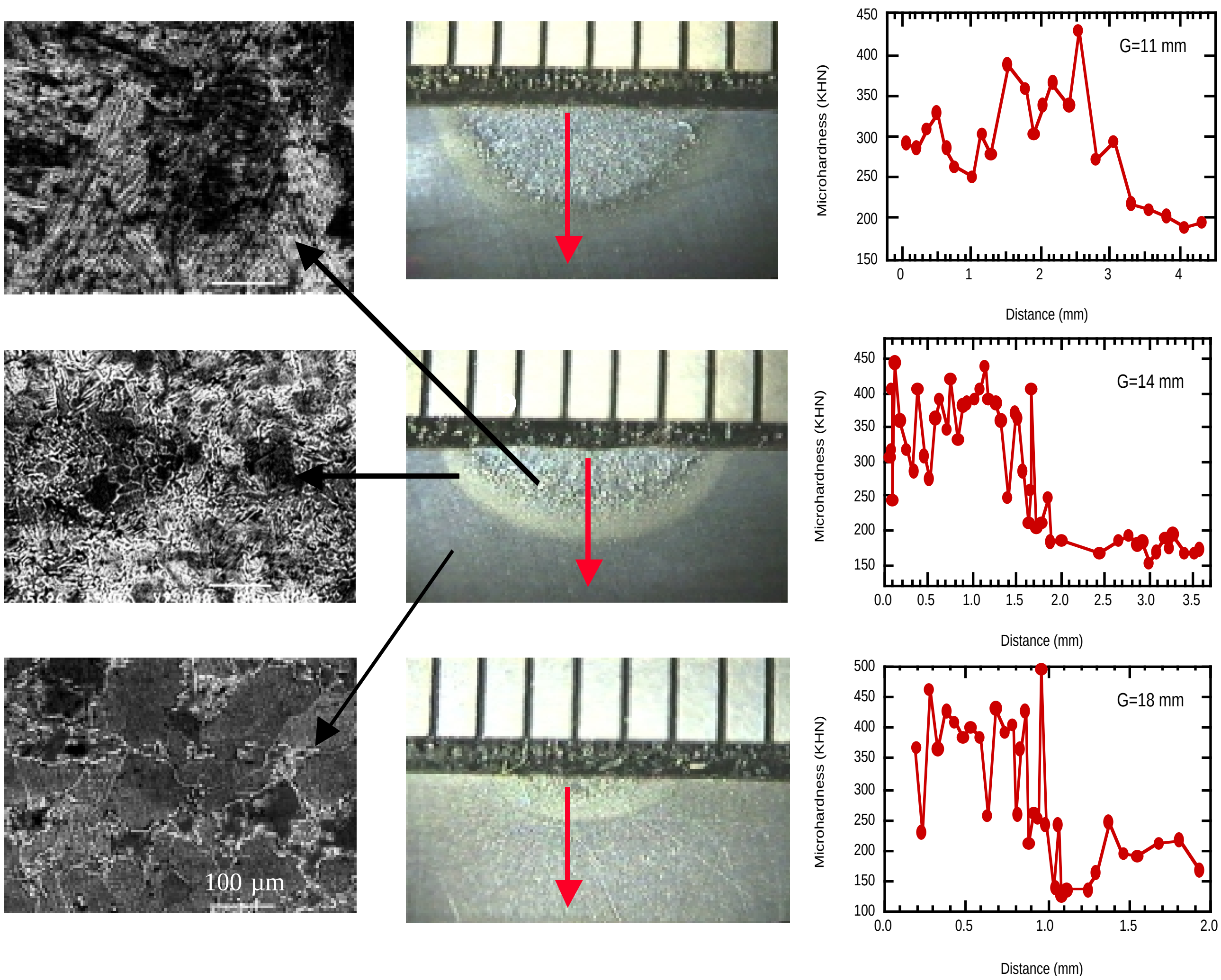

Figure 1: In the center, photographs of cross sections of 1018 CR steel irradiated with undulator radiation at gap settings of 11 mm (top), 14 mm (middle) and 18 mm (bottom). On the right are microhardness scans taken through these cross-sections in the direction shown by the arrows. On the left is a series of SEM micrographs of different areas of the 14 mm irradiated sample as designated by the arrows. The scale divisions are 1 mm.