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Effect of laser peening on the hydrogen compatibility of corrosion-resistant nickel alloy

C. San Marchi,[a,*] T. Zaleski,[b] S. Lee,[a] N.Y.C. Yang[a] and B. Stuart[b]

[a] *Sandia National Laboratories, Livermore, CA 94550, USA*
[b] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

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Laser-peening surface treatments have demonstrated benefits for improving resistance to stress-corrosion cracking and extension of fatigue lifetimes. The effects of laser peening on hydrogen compatibility of structural metals have not been documented. In this study, annealed and laser-peened alloy 22 (corrosion-resistant nickel-base alloy) is thermally precharged with hydrogen and tested in tension. Laser peening is found to have no significant effect on the solubility of hydrogen in alloy 22 and enhances hydrogen-assisted fracture.

Keywords: Laser treatment; Nickel alloys; Hydrogen embrittlement; Mechanical properties testing; Tension test

Laser-peening surface treatments are being studied as a means of increasing fatigue damage lifetimes by imparting deep residual compressive stresses from the surface of components. Laser-peening treatments have also been shown to reduce stress-corrosion cracking (SCC) in components subjected to corrosive environments. Moreover, these studies have demonstrated a significant improvement with laser-peening compared with conventional peening processes [1]. Surface treatments have also been considered for improvement of resistance to hydrogen-assisted fracture in structural materials subjected to high-fugacity hydrogen, with some emphasis on the effects of hydrogen transport through the hardened surface layers. Generally, residual surface stresses have been reported to have little, if any, effect on hydrogen diffusivity in steels [2–4]. The potential benefit of residual stresses for moderating hydrogen-assisted fracture in tension has not been realized [3], and remains largely unexplored in fracture and fatigue testing.

Stress-corrosion cracking and hydrogen embrittlement have similar phenomenology, thus processes that moderate SCC have the potential to improve resistance to hydrogen-assisted fracture in high-pressure gaseous hydrogen environments. Moreover, hydrogen gas is documented to degrade the fatigue properties of structural steels [5]. Thus laser peening would seem to have significant potential to improve resistance to hydrogen-assisted fracture in structural metals. Alloy 22 is of particular interest for its corrosion resistance and has been the focus of laser-peening studies [6]. In this study, we focus on the degradation of ductility in tensile tests of alloy 22 subjected to high concentrations of internal hydrogen, which has been thermally precharged from the gas phase. The effects of laser peening on hydrogen-assisted fracture are explored along with consideration of hydrogen transport in the laser-peened materials.

Alloy 22 (UNS N06022, also called Hastelloy C-22) is a nickel-base alloy often used in the chemical processing industry due to its excellent resistance to environmental effects. The alloy 22 plate that was used in this study was received in the annealed condition and its composition is provided in Table 1. Alloy 22 (Ni–22Cr–13Mo–3Fe–3W) is a solid-solution alloy that is similar to other nickel-base alloys, such as Hastelloy C-276 (Ni–16Cr–16Mo–5Fe–4W) as well as the 600-series nickel-base alloys: alloy 600 (Ni–15Cr–8Fe), alloy 625 (Ni–22Cr–9Mo–3Fe–4Nb), and alloy 690 (Ni–28Cr–8Fe).

The laser-peening process is discussed elsewhere [6]. Briefly, specimens are coated with an ablative layer prior to each layer of peening, in this study each surface is laser peened three times to ensure uniform coverage. A constant irradiance of 10 GW cm^{-2} with a pulse duration of 18 ns was used. The spot size was

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[*] Corresponding author. Tel.: +1 925 294 4880; fax: +1 925 294 3410; e-mail: cwsanma@sandia.gov

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Table 1. Nominal composition (wt.%) of alloy 22 (ASTM B575-97) used in this study

Ni	Fe	Cr	Mo	W	Mn	Si	C	Co	V
Bal	3.8	21.8	13.0	3.0	0.34	0.08	0.002	0.5	0.18

2.8 mm × 3.1 mm, corresponding to an energy input to the specimen of about 16 J per pulse. Each spot has a linear overlap of about 0.1 mm with the spot from the previous pulse.

ASTM E8 subsized rectilinear tensile bars were machined from the plate stock. The specimens had a square gauge section of 6.4 mm× 6.4 mm. A knife-edged extensometer with a gauge length of 12.7 mm was used for strain measurements during tensile testing. Testing was performed at a constant displacement rate corresponding to strain rate of $\sim 2 \times 10^{-3}\ \mathrm{s}^{-1}$ (in the plastic regime prior to necking). Lower strain rates are generally employed for environmental testing [7]; however, hydrogen-precharged tensile specimens of this type tend to be insensitive to strain rate in the range 10^{-3} and $10^{-5}\ \mathrm{s}^{-1}$ [8]. In addition, length scales for hydrogen transport are much smaller than the size of the specimens; therefore, hydrogen will not redistribute during testing [8]. The yield strength (0.2% offset, S_y) and tensile strength (maximum engineering stress, S_u) are reported as well as the uniform elongation (engineering strain at maximum load, El_u) and total elongation (engineering strain at failure, El_t). The reduction of area (RA) is measured post-mortem at the fracture surface. Two or three specimens were tested at room temperature for all conditions.

Vicker's microhardness was used to probe the residual stresses and strain hardening imparted by laser peening. Hardness was measured on polished cross-sections of undeformed regions of broken tensile specimens at 0.1 mm steps with a load of 100 g. The gripping surfaces of the tensile bars were avoided since deformation on these surfaces was found to substantially increase the hardness to a depth of 0.5–1 mm.

The effect of internal hydrogen was studied by precharging both annealed and laser-peened materials in 138 MPa hydrogen gas at 573 K. In addition, witness specimens (25 mm long cylinders with a diameter of 6.4 mm) of both annealed and laser-peened materials were precharged simultaneously with the tensile specimens. Precharging was conducted for 34 days to ensure uniform hydrogen saturation through the thickness of the specimens; details of the thermal precharging procedures are given elsewhere [9]. Upon removal from the thermal precharging apparatus, specimens were stored in a freezer at about 253 K until testing, which was always less than three days. Broken specimens were also stored at 253 K to prevent hydrogen off-gassing prior to hydrogen analysis. The witness samples, as well as approximately 6 mm thick pieces cut from the grip sections of the tensile specimens, were sent to a commercial testing laboratory for hydrogen analysis by inert-gas fusion.

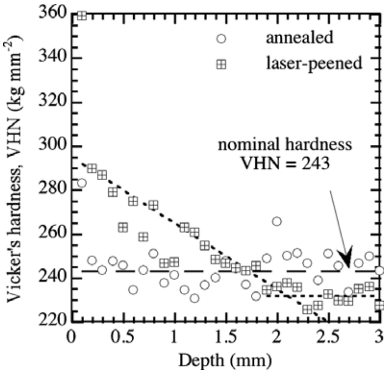

Figure 1. Vicker's microhardness (100 g load) as a function of depth for the annealed and the laser-peened alloy 22.

Microhardness profiles (Fig. 1) show an increase of hardness near the surface of the laser-peened specimens; the individual hardness values are an average determined from two indentations at approximately the same depth relative to the surface. The hardness of the laser-peened material decreases approximately linearly from a depth of 0.2 mm to a depth of almost 2 mm. In the center of the laser-peened specimens, the nominal hardness is slightly lower than in the annealed specimens (232 vs. 243 VHN). A significant surface effect was observed for both annealed and laser-peened conditions; however, the hardness was fairly uniform in the annealed material for depths from 0.2 mm to the center of the specimen (∼3 mm depth).

The laser-peening process increased the yield strength of these alloy 22 tensile specimens by almost 25%, while the ductility was slightly decreased: approximately a 15% reduction in uniform elongation, although virtually no change in RA was observed (Table 2). This increase in strength implies strain hardening of the surface region consistent with reports in the literature for laser-peened materials [1]. Presumably the dislocation density and structure are changed in the surface layer [1], although no effort was made to characterize dislocation structures as part of this study. Residual compressive stresses are produced near the surface of laser-peened materials, which induce residual tensile stresses far from the surface [1,6]. These residual stresses also contribute to changes in hardness [10], which explains the slightly lower hardness observed in laser-peened material at depths greater than 2 mm, i.e., in areas that are subjected to tensile residual stress and are not strain-hardened. Ductility in metals typically scales inversely with yield strength, thus a reduction in ductility in material with higher strength (e.g., due to laser peening) is expected. We should note that the change in apparent properties due to laser peening will be a function of specimen size (and laser-peening parameters). A larger tensile specimen, for example, will show a smaller change in yield strength for the same laser-peening parameters, because

Table 2. Tensile properties of alloy 22 in the annealed and laser-peened conditions, for material without internal hydrogen (non-charged) and with internal hydrogen (precharged)

Material condition	Environmental condition	S_y (MPa)	S_u (MPa)	El_u (%)	El_t (%)	RA (%)
Annealed	Non-charged	383	810	58	89	72
	Precharged	426	793	52	56	41
Laser peened	Non-charged	473	822	50	78	70
	Precharged	508	779	32	34	29