Impact Behavior of Additively Manufactured Stainless Steel Auxetic Structures at Elevated and Reduced Temperatures

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Metamaterials produced using additive manufacturing represent advanced structures with tunable properties and deformation characteristics. However, the manufacturing process, imperfections in geometry, properties of the base material as well as the ambient and operating conditions often result in complex multiparametric dependence of the mechanical response. As the lattice structures are metamaterials that can be tailored for energy absorption applications and impact protection, the investigation of the coupled thermomechanical response and ambient temperature-dependent properties is particularly important. Herein, the 2D re-entrant honeycomb auxetic lattice structures additively manufactured from powdered stainless steel are subjected to high strain rate uniaxial compression using split Hopkinson pressure bar (SHPB) at two different strain rates and three different temperatures. An in-house developed cooling and heating stages are used to control the temperature of the specimen subjected to high strain rate impact loading. Thermal imaging and high-speed cameras are used to inspect the specimens during the impact. It is shown that the stress–strain response as well as the crushing behavior of the investigated lattice structures are strongly dependent on both initial temperature and strain rate.

Additively manufactured auxetic metamaterials represent lattice structures that are being intensively investigated thanks to their broad range of possible applications ranging from deformation energy mitigation to biomaterials. Herein, a deep understanding and knowledge of the coupled thermomechanical behavior, strain rate sensitivity, and temperature-dependent mechanical properties are crucial since such phenomena seriously affect the response and performance of the lattices at high strain rates. However, in the case of coupled thermomechanical behavior of additively manufactured (AM) materials, particularly during dynamic impact conditions, this topic is still not fully explored and only a few research studies are available. Commonly, only wrought metallic materials have been investigated. In the case of the austenitic stainless steel, strain rate sensitivity and coupled thermomechanical behavior of the bulk specimens have been investigated in research studies covering topics like microstructure characterization, adiabatic heating, or constitutive modelling. Kluczyński et al. dealt with the influence of additive manufacturing production parameters on the resulting mechanical parameters. In their study, the specimens produced with different settings of laser power, exposure velocity, hatching distance, and layer thickness were subjected to microstructural analysis, hardness measurement, and a combination of quasi-static and dynamic compression. The authors concluded that the observed mechanism of material cracking during dynamic loading is affected by the energy dissipation capacity of the resulting structures. The effects of laser energy density in terms of point distance and exposure time on the resulting porosity, surface finish, microstructure, density, and hardness of the samples were studied by Cherry et al. It was shown that surface roughness was primarily affected by point distance with increased point distance resulting in increased surface roughness, whereas laser energy density was shown to affect total porosity. Relationships between porosity, microstructure, and mechanical properties of additively manufactured stainless steel were investigated by Ronneberg et al. through heat treatment. Heat treatment of the additively manufactured austenitic steel is considered as a suitable approach to modify and improve the mechanical properties of the as-built material.

Strain rate- and temperature-dependent properties of the additively manufactured materials have been investigated in papers focused mainly on strain rate dependency of polymers.
mechanical characterization of the Inconel superalloy,\textsuperscript{[16]} the thermomechanical model of a titanium alloy,\textsuperscript{[17]} and strain rate dependency of the printed bulk stainless steel.\textsuperscript{[18]} In the case of similar materials, temperature-dependent penetration resistance of the aluminum foam sandwich panels has been investigated numerically.\textsuperscript{[19]} Lattice structures and auxetic metamaterials have been studied at both quasistatic\textsuperscript{[20]} and dynamic loading conditions.\textsuperscript{[21–29]} However, coupled thermomechanical effects related to changes of strain rate and temperature are scarce. For polymers, the performance of additively manufactured Nylon 12 lattice structures at different temperatures has been investigated using the drop-weight dynamic loading conditions.\textsuperscript{[30]} To our knowledge, there is no publication dedicated to thermomechanical effects of strain rate dependency of additively manufactured metallic auxetic lattices.

In this article, a split Hopkinson pressure bar (SHPB) apparatus was used together with in-house developed heating and cooling stages to investigate the coupled thermomechanical effects of 2D re-entrant auxetic lattices having in-plane negative Poisson’s ratio (NPR) at high strain rates. The lattices were additively manufactured from the powderd stainless steel using laser powder bed fusion (LPBF) and subjected to dynamic uniaxial compression at two different strain rates and three different temperatures. Temperature- and strain rate-dependent changes in deformation behavior were investigated and the important trends related to changes in temperature and impact velocity were identified and described. It was found out that the stress–strain response of the auxetic lattices as well as their crushing behavior were strongly dependent on both initial temperature and strain rate. With an increasing strain rate, lateral motion of the individual lattice layers during their collapse was suppressed. Therefore, the densification of the structure occurred at lower strain with elevated stresses. Moreover, the initial temperature strongly affected the stress–strain response of the structure as the measured stresses exhibited lower values with increasing temperature and temperature-related softening of the lattice could be identified.

Experimental Section

Specimens: Re-entrant honeycomb auxetic lattice having in-plane NPR was selected for the study as the mechanical response of this microarchitecture has already been described in previous studies conducted at room temperature.\textsuperscript{[24,25]} The designed dimensions of the structure and its unit cell are shown in Figure 1a. The re-entrant angle of 70° was selected to maximize the auxetic effect in the lattice structure over the whole range of deformation. The thickness of the cell walls of 0.6 mm was selected to elevate the thermomechanical effects induced by stress concentration in individual struts and joints during crushing of the lattice. The other specific dimensions of the unit cell were derived from the cell-wall thickness and re-entrant angle to achieve overall dimensions of the structure with respect to the specifics of the SHPB measurement (specimen cross-sectional dimensions to height ratio and diameter of the bars).

The specimens were additively manufactured from the powderd SS316–0407 austenitic stainless steel using the LPBF technique in AM250 device (Remishaw, UK). During the AM process the structures were oriented perpendicularly to the powder bed plane and thus the particular layers of the fused base material were parallel to the direction of loading (see scheme in Figure 1a). The metal powder granularity was 15–45 μm, the layer thickness was 50 μm, and the maximal laser power was 200 W. The chessboard scanning strategy was used and the specimens were produced in Argon 5.0 protective atmosphere. No heat treatment of the specimens was carried out. The size of the AM produced specimens was 14.0 × 14.0 × 15.2 mm\textsuperscript{3}. Each specimen was composed of 5 × 4 planar re-entrant auxetic cells with a nominal strut thickness of 0.6 mm. In total, 35 specimens were produced and tested. Figure 1b shows scanning electron microscopy (SEM) of the investigated lattices. Both the surface roughness on the as-built sample as well as the porosity in the microstructure of the polished surface were captured. Furthermore, the micrographs with the higher resolution show the resulting microstructure in the area of the strut joint as a result of the printing strategy.

Experimental Setup: To obtain reference data, the specimens were tested in quasistatic conditions at room temperature. The quasistatic tests were carried out using 3382 testing system (Instron, USA) equipped with 100 kN load cell and an optical setup for noncontact strain measurement. The imaging was carried out using bi-telescopic zoom revoler TZR072 (OptoEngineering, Italy) attached to a monochromatic CMOS camera Manta G504B (AVT, Germany) at full-frame resolution of 5 Mpx (2452 × 2056 px) and 1 fps readout rate. The uniaxial loading of the samples was carried out with the cross-head speed of 0.03 mm s\textsuperscript{–1} (strain rate 0.002 s\textsuperscript{–1}) and readout rate of displacement and force data of 10 Hz.

The SHPB equipped with the heating and cooling stages was used to subject the specimens to impacts in six scenarios combining two impact velocities and three temperatures. In the setup incident and transmission bars with a diameter of 20 mm and with an identical length of 1600 mm were used. The bars were manufactured from a high-strength aluminum alloy (EN-AW-7075-T6). The strain waves in the Hopkinson bar were induced by an impact of a striker bar with the same diameter of 20 mm, accelerated using a single-stage gas-gun, onto the impact face of the incident bar. The striker bar was manufactured from the identical aluminum alloy as the other bars. While the compressive strain of the specimen is proportional to the striker bar length and its impact velocity, two striker bars with various lengths were used to compress the specimens to a nominal engineering strain of at least 0.25: 1) 750 mm for the lower impact velocity of 30 ms\textsuperscript{–1} and 2) 500 mm for the higher impact velocity of 45 ms\textsuperscript{–1}. The SHPB bars were instrumented using the foil strain-gauges (3/120 LY61, HBM, Germany) with an active length of 3 mm connected in a Wheatstone half-bridge arrangement (measurement point) for compensation of a possible very small bending of the bars during the experiment. Conventional arrangement with a single strain-gauge measurement point located in the middle of each bar was selected for its simplicity and straightforward calibration. Each bar was supported by four high-performance polymeric slide bearings (drylin TJUM, IGUS, USA) mounted in the adjustable stainless steel housings. Soft copper pulse-shapers with a diameter in the range of 5–7 mm and thickness of 0.5–1 mm were mounted at the incident bar impact face to produce smooth incident strain pulse, to reduce the wave dispersion effects in the bars, and to stabilize the resulting strain rate. More information and technical details about the used SHPB apparatus (e.g., data acquisition system, experiment triggering, etc.) can be found in our previous study.\textsuperscript{[25]} The SHPB experimental apparatus is shown in Figure 1c. The experiments were observed using a pair of high-speed cameras (Fastcam SA-Z, Photron, Japan). The first camera was used for the high-speed optical inspection of the specimen at the highest achievable frame rate. In this case, the frame rate of the camera was set to 252 kfps and image resolution was 256 × 168 px with spatial resolution of ≈100 μm. The specimen before the impact was projected to an area of ≈153 × 138 px. The images acquired by this camera were further processed using an in-house digital image correlation (DIC) algorithm to obtain displacement and strain fields of the specimen and to evaluate the deformation response of the lattice at different strain rates and temperatures. The second camera was used for the optical inspection of the experiment and provided a general overview of the experimental setup at the moment of the impact. This camera was operated at 80 kfps with image resolution of 512 × 424 px. Illumination of the scene was performed using a pair of high-intensity light emitting diode light sources (Multiled QT, GS Vitec, Germany).

A high-speed thermal imaging camera (SC7600, FLIR, USA) equipped with an actively cooled focal plane array (FPA) InSb photon-counting
detector and 50 mm f/2 silicon-based lens with an antireflection coating were used for thermal imaging. Full frame resolution of the camera was 640 × 512 px and the detector operates in the spectral range of 1.5–5.0 μm (short-to-medium wavelength infrared band—SWIR to MWIR). Thermal imaging was used for the inspection of the specimen’s temperature before the experiment and for estimation of the temperature increase and heat distribution during the impact. The camera-lens assembly system was calibrated for a temperature range of −5 to 300 °C. To maximize the frame rate of the camera for the dynamic experiments, the image resolution was downscaled to 96 × 44 px by sensor image windowing. In this configuration, the maximum frame rate was ≈2 kfps. A MgF₂ protective window was mounted in the shatterproof polycarbonate specimen shield to make the infrared imaging possible, while guaranteeing the safety of the thermal imaging optics.

Figure 1. a) Geometry of the auxetic lattice; b) SEM micrographs of the printed specimen; and c) SHPB experimental setup with the high-speed camera, thermal imaging camera and the heating/cooling stages.
The specimens were tested at three different temperatures to reveal the possible strain rate and temperature-dependent behavior. Based on the performance of the used heating/cooling stages, the thermal conductivity of the specimen and its surrounding components, the following temperatures were selected for the experiments: 1) lowered temperature of \( \approx -5 \, ^\circ\text{C} \), 2) room temperature of \( \approx 20 \, ^\circ\text{C} \), and 3) elevated temperature of \( \approx 120 \, ^\circ\text{C} \). The in-house developed cooling/heating stages were used to control the temperature of the specimen before the impact.

The heating stage consisted of ceramic heating elements with a rated output power of 40 W that are commonly used for the construction of hot-ends (printing heads of the thermal 3D printers). The heating elements were connected to the aluminum clamps that were in contact with the specimen. The clamps with the heating elements were mounted in the servo-based actuator that was used for a quick remote control removal of the heating elements just before the impact. The servo system was controlled by a custom electronics. The output temperature was regulated using an open-loop control circuitry with pulse width modulation (PWM). The heating stage was capable to raise the temperature of the specimen to \( \approx 220 \, ^\circ\text{C} \).

The cooling stage consisted of a pressure vessel with a volume of 6.7 L containing 5 kg of liquid CO\(_2\), a thermally isolated box containing dry ice \((\text{CO}_2 \text{ in a solid state})\) with a temperature of \( \approx -78 \, ^\circ\text{C} \) and a piping system. Inside the thermally isolated box, the low-temperature compatible piping coil was submerged in a mixture of dry ice and 1 L pure ethanol. During the cooling process, the gas from the reservoir was released at a pressure of 1.5 MPa and was rapidly cooled further down by contact with the mixture of ethanol and dry ice. Then, the supercooled gas was led directly to the specimen using the low-temperature compatible hoses and nozzles. Using this system, it was possible to cool the specimen to \( \approx -27 \, ^\circ\text{C} \).

**Experimental procedure:** In total, 35 specimens were tested at three different temperatures. Five specimens were tested using the standard electromechanical testing rig under quasistatic conditions and room temperature to obtain the reference data for comparison with the dynamic experiments at different temperatures. The experimental campaign was carried out according to the following scheme: 1) quasistatics, room temperature \((\approx 20 \, ^\circ\text{C})\) : five specimens. 2) SHPB, room temperature \((\approx 20 \, ^\circ\text{C})\), strain rate \(\approx 1150 \, \text{s}^{-1}\) : five specimens. 3) SHPB, low temperature \((\approx -5 \, ^\circ\text{C})\), strain rate \(\approx 1150 \, \text{s}^{-1}\) : five specimens. 4) SHPB, high temperature \((\approx 120 \, ^\circ\text{C})\), strain rate \(\approx 1150 \, \text{s}^{-1}\) : five specimens. 5) SHPB, room temperature \((\approx 20 \, ^\circ\text{C})\), strain rate \(\approx 2300 \, \text{s}^{-1}\) : five specimens. 6) SHPB, low temperature \((\approx -5 \, ^\circ\text{C})\), strain rate \(\approx 2300 \, \text{s}^{-1}\) : five specimens. 7) SHPB, high temperature \((\approx 120 \, ^\circ\text{C})\), strain rate \(\approx 2300 \, \text{s}^{-1}\) : five specimens.

![Thermomechanical response of the 2D re-entrant auxetic lattice: (a) stress–strain curves for three different temperatures at strain rate of \(\approx 1150 \, \text{s}^{-1}\); (b) stress–strain curves for three different temperatures at strain rate of \(\approx 2300 \, \text{s}^{-1}\); (c) stress–strain and strain rate curves for temperature of \(20 \, ^\circ\text{C}\) at two different strain rates—vertical bars represent the interval of the approximately constant strain rate where the average plateau stress was calculated. (d) Average plateau stress for different temperatures and strain rates.](image-url)
Figure 3. a) Scheme explaining calculation of the area difference. b) Area difference for 2D re-entrant lattice at three different temperatures at strain rate of \( \approx 2300 \, \text{s}^{-1} \). c) Area difference for temperatures of 20°C and 120°C at two different strain rates. Crushing behavior of the auxetic lattice at temperature of 20°C and strain rate of d) \( \approx 1150 \, \text{s}^{-1} \) and e) \( \approx 2300 \, \text{s}^{-1} \). f) Series of thermograms—the heated specimen subjected to strain rate of \( \approx 1150 \, \text{s}^{-1} \) loading showing concentration of deformation in the first two layers of cells near the impact face of the specimen.
Coupled temperature- and strain rate-dependent properties: Stress–strain curves for the individual temperatures and strain rates were evaluated from the strain-gauge signals according to the standard 1D wave propagation theory valid for SHPB. The average dynamic stress–strain diagrams for all the tested temperatures at a strain rate of \(\approx 1150 \text{ s}^{-1}\) are compared with the average quasistatic curve in Figure 2a. For all the temperatures, the stresses in dynamic compression were considerably higher than in the case of the quasistatic loading conditions (\(\approx 30\%\) higher at the room temperature). The stresses in the experiments with the low temperature were higher than the stresses during the experiments conducted at room temperature. The same trend was observed in the experiments at the elevated temperature, where the stresses were significantly lower than during the room temperature testing and even approached the values of the quasistatic room temperature curve. The average dynamic stress–strain diagrams for all tested temperatures at a strain rate of \(\approx 2300 \text{ s}^{-1}\) are compared with the average quasistatic curve in Figure 2b. Note that the trends are identical to the previous case. Average stress–strain diagrams and strain rate histories for room temperature and three different velocities (quasistatic, strain rate \(1150 \text{ s}^{-1}\) and \(2300 \text{ s}^{-1}\)) are compared in Figure 2c. Note that the difference between the two strain rates is particularly distinct at a nominal strain higher than 0.15, where a different densification behavior can be identified. With an increasing strain rate, the densification of the structure occurred at the lower strain. To quantify the strain rate and temperature-related sensitivity of the lattice structure, the average plateau stress was calculated from the stress–strain diagram, in a strain range of 0.05–0.25 (see black vertical lines in Figure 2c). This range was selected as the strain rate in this interval remained approximately constant and was not affected by the initial ramp-in phase of the strain pulse or rapid strain rate decrease during the densification. The average plateau stress values for all the temperatures and strain rates are shown in Figure 2d. Here, the coupled thermomechanical behavior of the lattice structure was very profound as the average plateau stress was increasing with the strain rate at low and room temperature. The rate of its increase was marginally higher for the low temperature. Different behavior was observed in the experiments conducted at the high temperature, where the average plateau stress was decreasing with the strain rate, revealing the thermal-related softening of the lattice structures. The revealed coupled thermomechanical behavior was similar to the trends observed during heat treatment of the additively manufactured stainless steel specimens that, in horizontal orientation of the printed structure, exhibited a decrease in yield stress and increase in elongation at break with the increasing heat treatment temperature[14].

The changes in the crushing behavior of the auxetic cells were investigated using the DIC to reveal possible changes of the crushing mechanism of the individual structures and to compare the results with the stress–strain response shown in Figure 2. DIC was used to track the positions of correlation points created at the nodes of the lattice structures. The difference between the area defined by the actual edges of the deformed specimen and the area defined by the points in the four corners of the specimen was used to characterize the change in the crushing behavior. The area difference \(D_A\) was calculated according to

\[
D_A = A_T - A_C
\]

(1)

where \(A_T\) represents the area of a polygon with its vertices defined by the nodes at the edges of the auxetic structure tracked by the DIC and \(A_C\) represents the area of the trapezoid defined by the four corner nodes of the auxetic structure tracked by the DIC. According to this relation, the auxetic behavior of the structure results in the negative area difference. The scheme explaining calculation of the area difference is shown in Figure 3a. Area difference of the auxetic lattice for all the temperatures and strain rate of \(\approx 2300 \text{ s}^{-1}\) is plotted against nominal engineering strain in Figures 3b,c. Note that at all the temperatures, the structures exhibited NPR with no significant difference in the crushing behavior. The area difference of the lattice for the room temperature and both strain rates is compared with the area difference for the high temperature at both strain rates in Figure 3c. Note that at the room temperature and the lower strain rate, the crushing behavior of the lattice was different as the area difference was considerably less compared with the high strain rate. Interestingly, this trend was not observed at the high temperature, where the area difference was approximately identical for both strain rates. The area difference in both cases approximately to the area difference at room temperature and higher strain rate. Unfortunately, this trend could not be investigated at the low temperature as the frozen specimens were covered by frost that made the tracking of the lattice by DIC in most cases impossible. Nevertheless, the lattice response was strongly affected by both strain rate and temperature. Crushing behavior of the re-entrant lattice at lower and higher strain rates at room temperature is compared in Figure 3d,e. Here, the changes in deformation behavior at a nominal strain higher than 0.15 are clearly apparent. At a strain rate of \(\approx 1150 \text{ s}^{-1}\), the structure exhibited extensive lateral movements, whereas at a strain rate of \(\approx 2300 \text{ s}^{-1}\), the lateral movements were prevented by the velocity of the impact and inertia effects. Therefore, the principal mode of deformation of the lattice changed with the increasing strain rate. During the quasistatic and dynamic tests at the lower strain rate, the structure exhibited a slow rotation of the strut joints followed by self-contact induced densification of individual unit cells. During the dynamic tests at the higher strain rate, the structure exhibited longitudinal displacement of strut joints and bending of outer struts in the cell layers.

Qualitative analysis of the deformation processes was carried out by studying the heat distribution in the acquired thermograms. The data showed that the initial temperature of the sample not only trivially influenced the highest observable temperature of the deforming microstructure, but also more importantly affected the difference between the initial and the highest measured temperature during the given experiment. As such, the highest temperature difference \(101^\circ \text{C}\) was calculated for the room temperature samples at high strain rate loading, whereas the lowest difference \(30^\circ \text{C}\) was assessed for the elevated-temperature samples loaded at a lower strain rate. In terms of relative temperature difference in dependence on strain rate, i.e., the ratio of temperature increase between the low and the high strain rate loading, the lowest value of 23% was calculated for the low-temperature experiments, whereas the highest value of 113% was assessed for the high-temperature experiments. Furthermore, the thermograms can be used as a mean for inspection of concentration of deformation within the specimen microstructure, as shown in Figure 3f. Here, it is possible to reveal, e.g., localized heating in the joints of struts and overall distribution of deformation over the microstructure including possible localization of deformation to certain cell layers.

The additively manufactured 2D re-entrant auxetic lattices produced from the powdered austenitic steel were subjected to high strain rate uniaxial compressive loading in SHPB at three different temperatures and two different rates of deformation. It was found out that both the studied auxetic lattice constructs and the base material exhibited considerable strain rate and temperature sensitivity. Coupled thermomechanical behavior of the lattice structures was investigated. The structure exhibited a strain rate-related hardening with thermal softening effects. It was identified that the crushing behavior of the construct was strain rate dependent as the lateral movements of the structure were effectively prevented with the increasing strain rate by the inertia effects and short time duration of the impact.

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Conflict of Interest

The authors declare no conflict of interest.
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