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Experimental Investigation of Dynamic Strain Aging in 304L Stainless Steel

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ABSTRACT

We seek to develop a fundamental understanding of dynamic strain aging through discovery experiments to inform the development of a dislocation based micromechanical constitutive model that can tie to existing continuum level plasticity and failure analysis tools. Dynamic strain aging (DSA) occurs when dislocation motion is hindered by the repetitive interaction of solute atoms, most frequently interstitials, with dislocation cores. At temperatures where the interstitials are mobile enough, the atmospheres can repeatedly reform, lock, and release dislocations producing a characteristic serrated flow curve. This phenomenon can produce reversals in the expected mechanical behavior of materials with varying strain rate or temperature. Loss of ductility can also occur. Experiments were conducted on various forms of 304L stainless steel over a range of temperatures and strain rates, along with temporally extreme measurements to capture information from the data signals during serrated flow. The experimental approach and observations for some of the test conditions are described herein.

Keywords: dynamic strain aging, stainless steel, strain rate, dislocation, elevated temperature

BACKGROUND

DSA is a phenomenon that has been known and documented for some time [1, 2]. It has been observed in several materials, including austenitic stainless steels [3, 4] and welded stainless steel alloys [5]. Our past studies into various aspects of coupled thermomechanical and time dependent behavior of stainless steel alloys and weldments have consistently shown high levels of susceptibility to DSA phenomenon at certain temperatures and strain rates [6-9]. DSA usually manifests itself as repeated load drops or serrated flow that is evident on a tensile stress versus strain loading curve. It can also be responsible for the development of negative strain rate sensitivity, reduction in tensile ductility, and reversals in the material temperature dependence. The resulting convoluted rate and temperature material behavior makes it impossible to fit reasonable parameters to our continuum level plasticity models. Hence, we set out to develop a dislocation-based, micromechanical constitutive model that is physically based and draws on experimental measurements and microstructural observations. Successful capturing and mathematical description of DSA related physics will ultimately enable accurate finite element modeling of structures that are exposed to temperatures and strain rates that experience DSA.

MATERIAL AND SPECIMENS

Several types of 304L stainless steel were used in this study, each with a unique material specification and material form including: wrought bar stock, seamless tube, and two methods of additively manufactured (AM) material. Two specimen sizes were used, with gage diameters of 8.9 mm (0.35 inches) and 3.2 mm (0.125 inches). The specimen size had no effect on the mechanical response or behavior, but the smaller specimens were used when necessary to fit specimens within the material stock dimensions such as the tube wall or AM builds.

EXPERIMENTAL APPROACH

The fixtures and instrumentation were designed to operate on an MTS 50 Kip axial-torsional test frame. Heat was supplied to the specimens by a three-zone resistance furnace and controller and monitored by type K thermocouples spot welded to both specimen ends. Tensile tests were conducted in displacement control with resulting strain rates over the range of 1E-05/s to 1/s. A contacting extensometer was used to measure specimen strain. Experiments were conducted on the various 304L stainless steel alloys at several temperatures and strain rates to develop a map of DSA active regimes. Measurements of applied load, displacement, specimen strain, and temperatures were recorded through the MTS test frame software at, typically, the maximum achievable rate. Additionally, these same signals were recorded at extremely high data acquisition rates on an oscilloscope to ensure complete capture of DSA related serrations and load drops. This will enable correlation of DSA types and signatures to the experimental parameters. Microstructural measurements are not included in this paper.

EXPERIMENTAL RESULTS

Several experiments have been completed on a wide range of 304 stainless steel materials and forms. DSA was evident at temperatures as low as 200C and up to 700C. DSA often caused strain rate inversions or simply an apparent disappearance of rate dependence. Several distinct types or signal signatures of serrated flow were evident, these signatures changed with rate and temperature. The specific details of these signals are currently being studied in detail. A sampling of some of the typical results are included below.

The tensile response of a 304L VAR bar stock material at 400C is shown in Figure 1. Experiments were conducted from 1E-05/s to 0.1/s. Note that a complete reversal in the expected strain rate response was recorded such that the highest strain rate test resulted in the lowest tensile strength. With decreasing strain rate, the tensile strength continually decreases, counter to expected or typical elevated temperature behavior. The serrations during plastic flow are shown in Figure 2 for the same data, zoomed in to highlight the distinct signatures that develop during DSA dominated loading. The data for the same bar stock material tested at 700C is shown in Figure 3. At 700C, the strain rate reversal has disappeared and the rate dependence is more typical. However, as seen in Figure 4, DSA serrated flow is still occurring for the two highest strain rates and seems to have ended by 0.001/s.

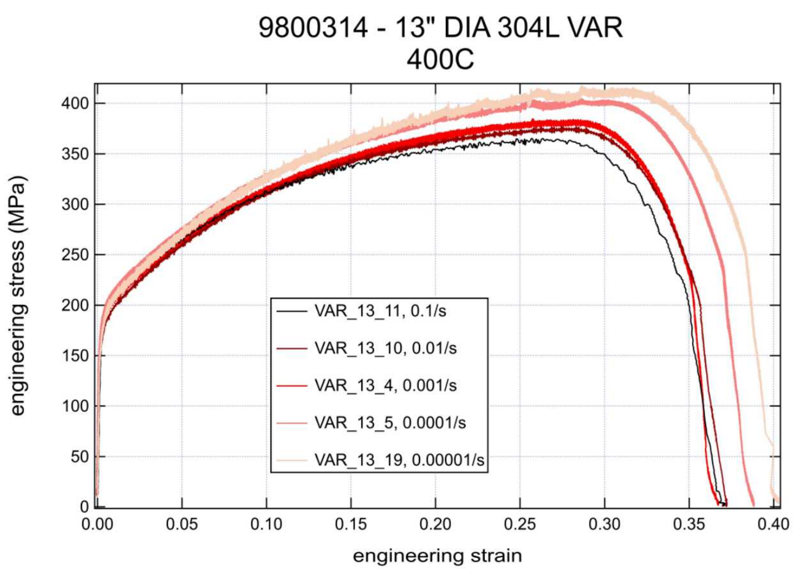

Fig. 1 Tensile response of 304L VAR bar stock material at 400C over several strain rates.

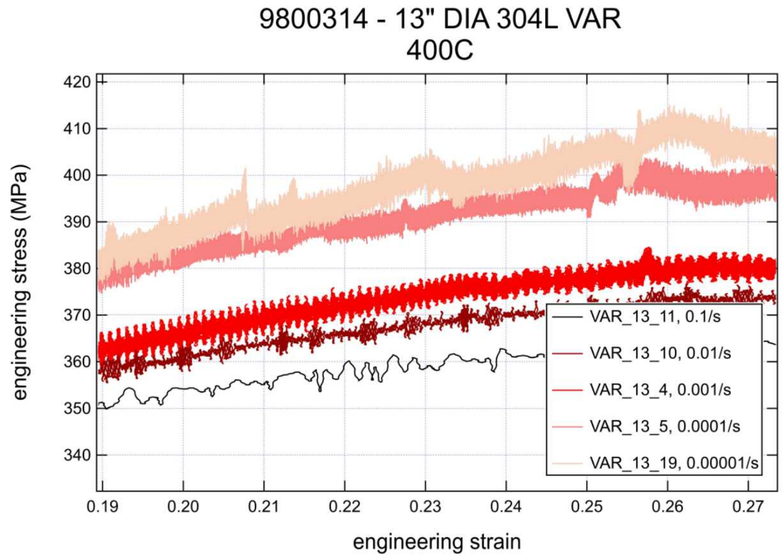

Fig. 2 DSA signals of 304L VAR bar stock material at 400C over several strain rates.

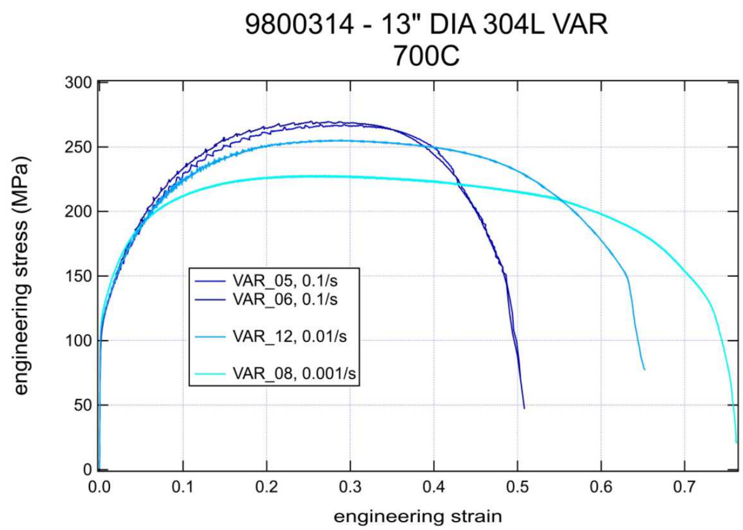

Fig. 3 Tensile response of 304L VAR bar stock material at 700C over several strain rates.

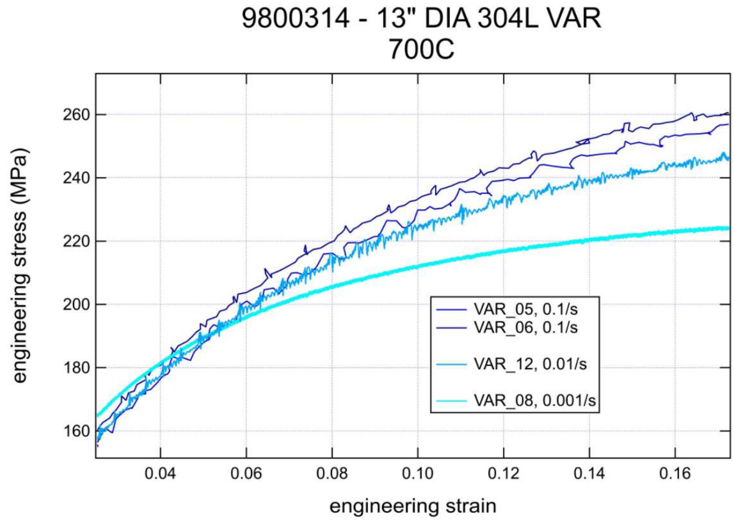

Fig. 4 DSA signals of 304L VAR bar stock material at 700C over several strain rates.

The tensile response of a 304L tube material at 400C is shown in Figure 5. Note that strength increases with decreasing strain rate for another example of strain rate reversal. Figure 6 shows the same data, but zoomed in to see details of the loading serrations during plastic flow that differ for the three strain rates. The data for the same tube material tested at 600C is shown in Figure 7. Here, a strain rate dead zone was observed since the tensile stress strain response is nearly identical for the four highest strain rates over four orders of magnitude. In the test series at 600C, we were searching for a strain rate high or low enough to return to indication of a normal strain rate dependent response. This was not achieved by going to the highest rate possible on the test frame (almost 1/s was achievable for this specimen size), but was eventually achieved by going to a very low rate of nearly 1E-05/s which resulted in a test duration of over ten hours. Serrations caused by DSA are shown for this 600C data in Figure 8. Note that some of the curves were separated vertically just to enable viewing of each of the test condition DSA responses. Very distinct serration signals were recorded for each strain rate. The data shown throughout this paper is the lower rate data from the MTS test frame software. Processing of the higher rate oscilloscope recorded data is in progress.

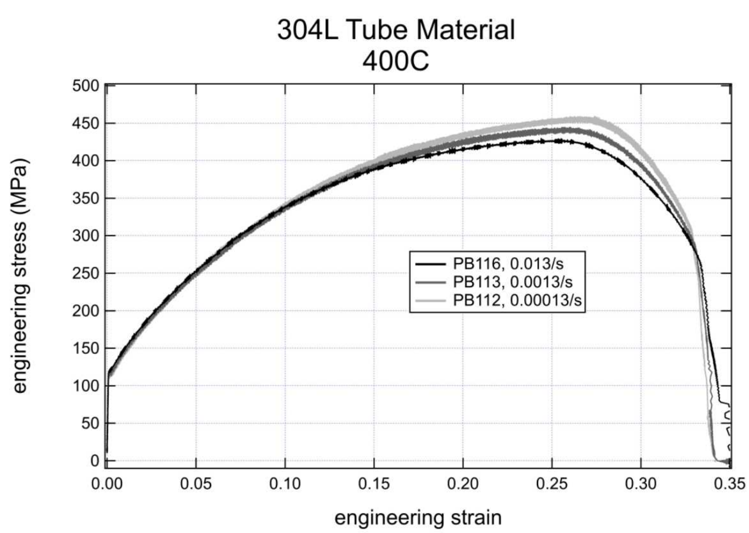

Fig. 5 Tensile response of 304L tube stock material at 400C over several strain rates.

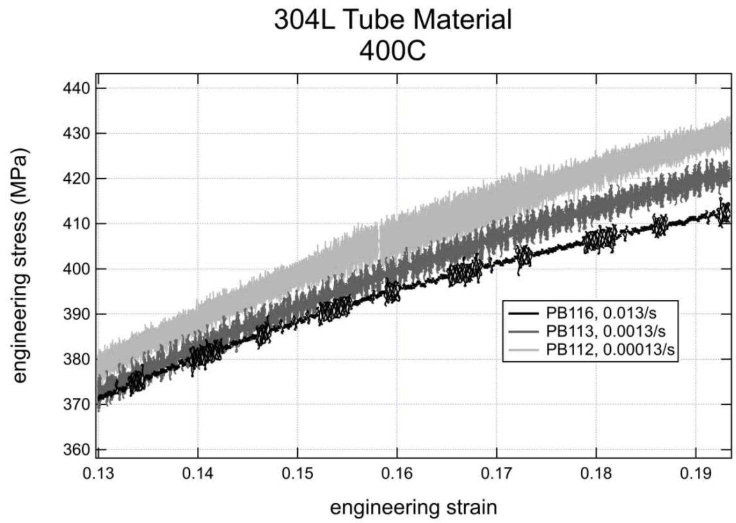

Fig. 6 DSA signals of 304L tube stock material at 400C over several strain rates.

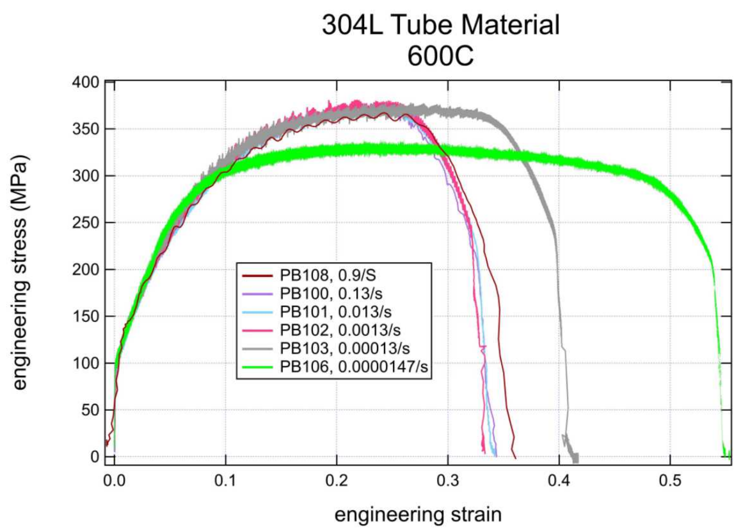

Fig. 7 Tensile response of 304L tube stock material at 600C over several strain rates.

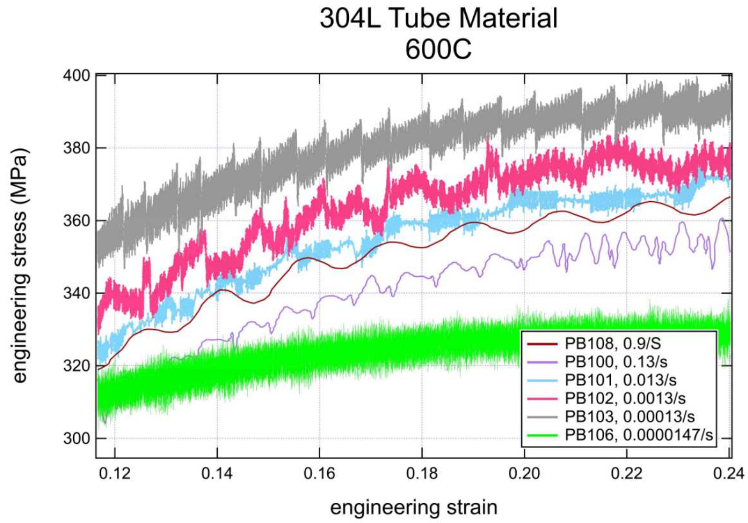

Fig. 8 DSA signals of 304L tube stock material at 600C over several strain rates (some curves shifted vertically for improved viewing).

The tensile response of a third example material, P70 which is a machinable grade of 304L, tested at 500C is shown in Figure 9. Although a moderate to strong strain rate dependence would be expected at this temperature, none was observed which is interpreted as strong indirect evidence of DSA. A detailed view of the serrations caused by DSA are shown for this data in Figure 10. It was necessary to shift the curves in this figure vertically to enable viewing of each tests DSA response. Note that the DSA serration signal is nearly identical for the repeated tests (P70-1 and P70-4), which are different than the slower rate test (P70-7). Analysis of the data and interpretation of the DSA serration signals is underway.

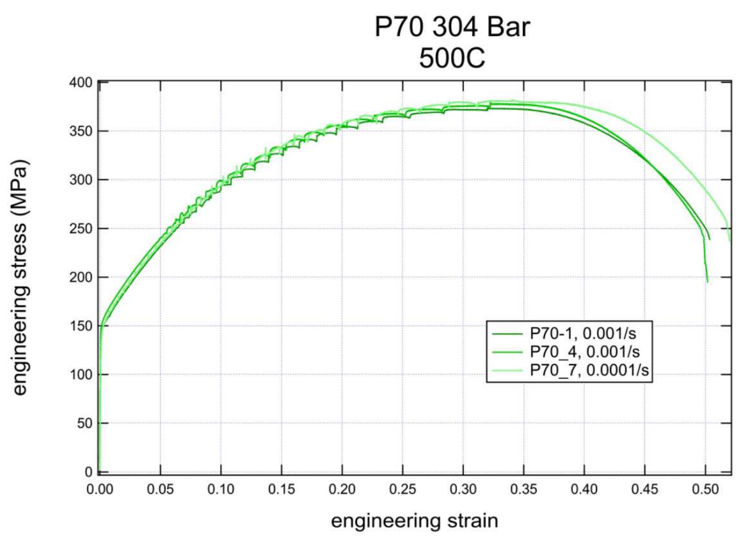

Fig. 9 Tensile response of P70 bar stock material at 500C at two strain rates.

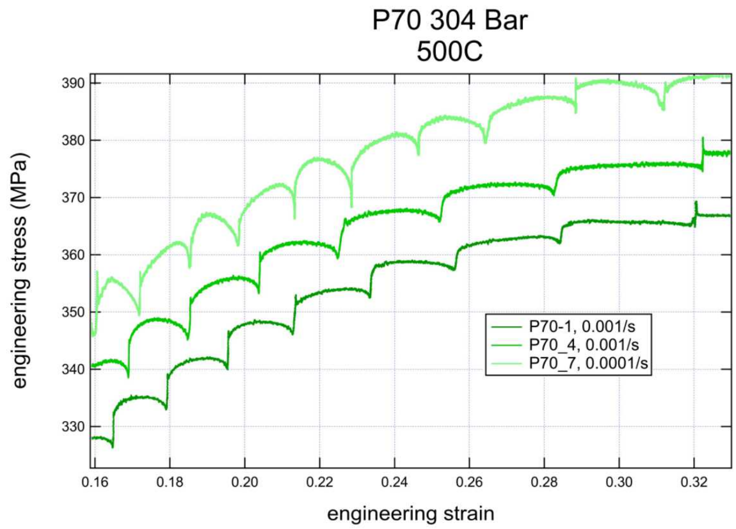

Fig. 10 DSA signals of P70 bar stock material at 500C over several strain rates (some curves shifted vertically to separate for improved viewing).

SUMMARY

Prompted by several years of observing DSA in 304L stainless steel materials of various manufacture form and the unusual and problematic resulting mechanical response, we developed and commenced a targeted study to understand and quantify DSA and its effects. Several different 304L materials were tested under a wide range of temperatures and strain rates and a sampling of typical results are shown here. The serrated flow data and notable signatures that were unique to loading condition, and likely microstructural conditions, certainly contain valuable information related to the dislocation pinning that is causing them. Serrated flow was a certain indication of being in the strain rate – temperature regime where DSA is active. But the absence of serrated flow does not necessarily equate to an DSA inactive regime, other indicators such as strain rate reversal should also be considered.

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