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# Aging-induced anisotropy of mechanical properties in steel products: Implications for the measurement of engineering properties☆

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ABSTRACT

Strain aging in low-carbon steels is a well-known strengthening phenomenon, the typical results of which are an increase in yield stress and/or an increase in the extent of discontinuous yielding. Aging effects are generally characterized through the use of results from mechanical tests in which the strain path prior to aging (prestrain) and the strain path after aging are in the same direction. However, these tests do not completely characterize the properties of aged materials, since the effects of aging are reduced when materials are tested in directions different than the direction of prestrain. The result is anisotropy of properties which can affect the performance of industrial products. In this paper, the effect is demonstrated in two examples of industrial products made from low carbon steels, the aging of which during processing results in performance changes that are not predicted through standard tensile testing of as-fabricated products. The first example compares the effect of aging on yield strength and dent resistance of stamped hood panels on an electro-galvanized, Al killed, bake hardenable sheet steel for auto body panel applications. The second example shows the effect of aging on the anisotropy of tensile data from two American Petroleum Institute (API) grade X100 pipe steels in the as-received condition.

The data show that the performance gains realized from strain-aging in the tensile tests on base material are not apparent in the tensile data from the stamped panels after aging, but the dent resistance clearly demonstrated the beneficial effect of aging. The high degree of anisotropy in the yield strength and yielding behaviors between the circumferential and longitudinal tensile data in the two pipe steels demonstrates the effect of strain path on a materials response to aging, which may occur during downstream processing or in field service. The manifestation of material properties that are dependent upon the relationship between the pre-aging strain direction and the post-aging strain direction underscores the importance of correct evaluation of mechanical performance in the design of structural components in materials which undergo aging.

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## 1. Introduction

The process of strain aging is of considerable commercial interest due to its applicability to many types of structural components typically manufactured from steel. In the mechanical design of these components, the yield strength obtained from uniaxial tensile tests is often an important criterion for assessment of material performance and suitability for service. Strain aging can result in a significant increase in the uniaxial yield strength when the test direction is collinear with the direction of the prestrain. However, when these directions are not collinear, additional time and temperature are required to achieve equivalent aged performance [1]. Processing, fabrication and service conditions influence the presence or absence of changes to strength induced by aging. Understanding these influences is of critical importance in determining the fitness of a component for service, as well as evaluation of the effectiveness of aging as a strengthening process.

### 1.1. Review of strain aging

Strain aging in steel is a strengthening mechanism where point defects, such as interstitial carbon and nitrogen atoms, within the body-centered cubic (BCC) iron lattice, interact with free dislocations, increasing their resistance to motion under an applied shear stress. The high mobility of carbon and nitrogen atoms at relatively low temperatures (∼200 °C) makes strain aging an industrially feasible strengthening mechanism. However, aging at room temperature can also occur, with the timeframe ranging from several months to several hours (depending on numerous factors). The Cottrell and Bilby model for strain aging [2] developed in 1949 is still seminal in describing certain aspects of the strain aging

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process. When a tensile specimen is prestrained, unloaded, aged and subsequently reloaded in uniaxial tension, the stress–strain relationship of the aged specimen exhibits some typical characteristics [1,3–6]:

- A rapid return of the sharp yield point, accompanied by an upper yield stress and a load drop to a lower yield stress that is greater than the flow stress at the point of unloading during prestraining;
- A return of discontinuous yielding and yield point elongation (YPE);
- Depending upon numerous factors, an increased strain hardening rate, increased tensile strength and decreased total elongation.

The effectiveness of strain aging, as it is measured during loading in a given direction, is highly influenced by the degree of collinearity of that loading with the prestrain path. Typically, strain aging is characterized under conditions for which the pre- and post-aging strain paths are collinear and in the same direction. Situations in which the strain path of the prestrain and post-aging deformations is significantly different require a deeper level of understanding and care in the approach to determining yield strength, in order to ensure that appropriate mechanical properties are employed for engineering applications.

In the extreme case, the direction of post-aging deformation is aligned, but reversed from that of prestraining, as is the case during a test to evaluate the Bauschinger effect [7]. The significant implications of material flow behavior under strain reversal are the loss of a distinct transition between elastic and plastic deformation, typically termed a “sharp” yield point, and greatly diminished flow stress in the reverse direction, as compared with the original direction of strain. The decreased flow stress in the reversed direction has been attributed to the reversed motion of large groups of dislocations [8] due to short-range dislocation phenomenon and long-range internal stresses, typically caused by dislocation pile-ups that assist reversed dislocation motion [9–16]. Richards et al. [17] evaluated the *in situ* Bauschinger effect of three medium carbon steels from room temperature up to temperatures in which dynamic strain aging is effective. They found that while the aging mechanisms significantly improve the resistance to strain reversal at elevated temperature, the materials still exhibited reduced reversed flow stress values than those exhibited at the same accumulated strain in uniaxial tension and very soft yielding behavior. Similar results for static strain aging were demonstrated by Aran and Demirkol [9].

In situations where the prestrain path and post-aging deformation are not aligned, the combination of strain aging effect and Bauschinger effect (due to residual elastic lattice strains) complicates characterization of final material properties. Microstructural factors can also influence the effect of strain path on effectiveness of the strain aging process. For example, Wilson and Ogram [18] performed experiments on steel plates with grain sizes between 50 grains × $mm^{-2}$ and 3900 grains × $mm^{-2}$, where the post-aging deformation was transverse to the prestrain orientation. These investigators showed that after a tensile prestrain along the longitudinal direction, the effect of aging on the return of the YPE in tensile specimens taken transverse to the prestrain direction depended upon the grain size. Ultrafine and fine-grained materials achieved a return of YPE and sharp yield point in 100 min to 300 min, respectively, at 89 °C, whereas the coarse-grained material exhibited no return of the YPE even after $10^5$ min at 89 °C, as opposed to approximately 10 min for the case in which the prestrain and post aging strain paths were collinear [18]. Wilson and Ogram [18] achieved similar results from reversed torsion Bauschinger effect tests by use of coarse and fine grain sized low carbon steel tube. Wilson and Ogram [18] suggested that grain boundaries are sites of high dislocation density, and in coarse-grained materials the time delay for sufficient solute diffusion from the grain interior to saturate dislocations in the grain-boundary region is prohibitively long. Differences in post-aging yielding behavior in the aligned and non-aligned conditions with respect to the prestrain condition may be caused by the operability of different dislocation sources for each situation. For the non-aligned case, the dislocations required for the accommodation of plastic deformation are generated from grain boundaries instead of the grain core as in the aligned case, grain boundaries have significantly higher dislocation densities and the time required for sufficient solute segregation from the grain core to the boundary region to fully pin the dislocations there is significantly longer. Therefore the strain energy required to generate dislocations from the grain boundaries is much lower than that for the fully pinned grain core. The directional aspects of the strain aging process can reduce the reliability of tensile test measurements to accurately characterize material properties under complex loading conditions.

Certain steelmaking processes take advantage of the directional nature of aging behavior. The most well known of these is temper rolling which, through the suppression of the return of YPE and therefore the formation of Lüders bands[1], results in improved surface quality in stamped steel parts. The significance of temper rolling was shown by Tardif and Ball [19], who compared the effect of aging on the return of YPE on a low-carbon sheet steel that had been either prestrained in tension or temper rolled. Temper rolling, followed by tensile loading along the rolling direction after aging, lengthened the time period required for the return of the yield point by over 2 orders of magnitude compared to that for tensile prestrain and tensile post-aging loadings. The complex deformation induced during temper rolling was of sufficient misalignment to the post-aging deformation to realize the delayed response to aging. Additional temper-rolled specimens were prestrained in tension by a given amount, aged for various periods and subsequently tested in tension. As the tensile prestrain increased from 0.25% to 2.0%, the delay in the return of YPE diminished and exhibited behavior similar to that for a prestrained sheet as opposed to a temper-rolled sheet without prestrain. Elliot et al. [20] observed similar results for fully reversed torsion. Thus, even small levels of deformation are sufficient to decay the dislocation structure and residual lattice strains formed during temper-rolling and become reformed and aligned with the most recent strain path. Jeong [21] observed similar results comparing results from tensile tests on low carbon sheet steel in the tensile prestrained condition and in stamped door panels, where the strength increase exhibited in the tensile prestrain condition was not exhibited in the stamped door panels after aging for 17 days.

The nature of the metallurgy and processing of pipeline steel results in their susceptibility to strain aging [22,23]. Plastic strains are introduced during the forming process in the circumferential orientation, the extent of which is dependent on the diameter, thickness, through thickness microstructural variations in the baseplate due to thermo-mechanical processing and accelerated cooling practices, and yield strength of the material. Aging can be introduced in a pipe during the period at which it is at elevated temperature during the coating process, during welding, while the

[1] In an aged material, such as an annealed, low-carbon steel, yielding typically occurs within a localized deformation band in the reduced gauge section of the test piece, typically accompanied by a sharp drop in applied load. Deformation proceeds through propagation of distinct bands of intense plastic deformation, called Lüders bands. Lüders bands propagate in a staggered, discontinuous manner during which the applied force remains essentially constant in magnitude with small fluctuations. This can result in a series of ridges on a stamped steel part, which is detrimental to the surface uniformity.