Chapter 5
Evaluation of Yield Locus of Cast Iron at High Strain Rate by Inverse FE Approach

M. Utzeri, G. Chiappini, M. Rossi, and M. Sasso

Abstract Modern industrial applications require cast iron to operate ever closer to their mechanical limits thus cast irons with enhanced mechanical properties are required. Solid solution-strengthened ferritic ductile iron (SSFDI) proposes as a solution to this need, exhibiting superior thermomechanical properties compared to conventional ductile cast iron such as strength, hardness and toughness. Therefore, industries are strongly interested in exploring the SSFDI thermomechanical properties and defining numerical models capable of predicting their mechanical response, from plasticity to damage. Against this backdrop, the study investigated the elastoplastic response of SSFDI under quasi-static and dynamic loading conditions, evaluating the yield locus with tensile, compression, shear and torsion tests. The experimental test setup allows for local measures of the strain and temperature during the mechanical tests, simultaneously recording the sample with video and thermal cameras. The SSFDI exhibits a yield surface and hardening response dependent on the stress states coupled with compressible plasticity behaviour. Therefore, a compressible elastoplastic model was calibrated with an inverse finite element method aiming to predict the yield locus evolution in the function of strain rate and temperature.

Keywords Dynamic · Cast Iron · Inverse Method · Hopkinson bar · Impact

Introduction

Cast irons remain a key class of structural materials for a wide range of industrial applications due to their excellent castability, cost-effectiveness, and favorable combination of mechanical and thermal properties. In recent years, however, increasingly demanding service conditions—such as higher mechanical loads, complex multiaxial stress states, and dynamic or impact loading—have pushed conventional ductile cast irons close to their performance limits. This trend has driven significant interest toward advanced grades of cast iron capable of offering enhanced strength, toughness, and reliability without sacrificing manufacturability[1]. Among these materials, solid solution-strengthened ferritic ductile iron (SSFDI) has emerged as a promising alternative to conventional ferritic and pearlitic ductile irons. By exploiting solid solution strengthening mechanisms while retaining a predominantly ferritic microstructure, SSFDI exhibits improved yield strength, hardness, and toughness, together with enhanced thermal stability. These characteristics make SSFDI particularly attractive for safety-critical components operating under complex thermomechanical loading conditions, where accurate prediction of material response is essential[2]. Despite the growing industrial relevance of SSFDI, a comprehensive understanding of its mechanical behavior under multiaxial and dynamic loading conditions is still lacking[3]. Most existing studies focus on uniaxial quasi-static tests, which are insufficient to fully characterize the material response under realistic service conditions. In particular, the shape and evolution of the yield surface, the role of stress state on yielding and hardening, and the influence of strain rate and temperature remain open questions. These aspects are critical for the development of reliable constitutive models suitable for numerical simulations involving plastic deformation and damage. In this context, the present study aims to experimentally investigate the elastoplastic response of SSFDI under both quasi-static and dynamic loading conditions. A comprehensive

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Piyush Thakre et al. (eds.), *Mechanics of Additive and Advanced Manufacturing, Inverse Methods and Machine Learning, Volume 5, 2026*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/rp-9788743815983

experimental campaign was conducted, including tensile, compression, shear, and torsion tests, in order to directly probe the yield locus under different stress states. Advanced full-field measurement techniques were employed to locally measure strain and temperature during deformation, enabling a detailed interpretation of the mechanical response. Based on the experimental evidence, particular attention is devoted to the identification of yield surface characteristics and their dependence on stress state, strain rate, and temperature. The observed behavior motivates the adoption of a compressible elastoplastic constitutive framework, which is calibrated through an inverse finite element approach. This modeling strategy is aimed at accurately reproducing the experimentally observed yield locus and its evolution, ultimately providing a robust predictive tool for engineering applications involving SSFDI under extreme loading conditions.

Materials and Methods

The material investigated in this study is a spheroidal graphite cast iron supplied in the form of as-cast ingots. Since the ingots represent the final outcome of the industrial casting process, particular care was devoted to the definition of suitable strategies for specimen extraction in order to ensure a representative mechanical characterization of the material while minimizing any alteration induced by machining. Following a preliminary literature survey, electro-discharge machining (EDM) was selected as the preferred technique for specimen extraction. This choice was motivated by the need to limit thermal and mechanical disturbances typically associated with conventional machining, especially when dealing with large-thickness cast components. In particular, a coring strategy based on wire EDM was adopted. A three-dimensional CAD model of the ingot was developed, and the various specimen geometries—previously defined for tension, compression, torsion, shear, and multiaxial testing—were optimally distributed within the ingot volume. This procedure allowed the evaluation of maximum extractable dimensions, material utilization efficiency, and potential geometric constraints related to the EDM process. Circular cores were then extracted from the ingot by wire electroerosion, enabling the subsequent machining steps required to obtain the final specimen geometries. Figure 1 shows the coring process carried out on a cast iron ingot; you can also see the optimization of spaces and scraps.



Fig. 1 Cast iron ingot and samples. (a) Cast iron ingot utilized as the source material and machined cast iron ingot from which samples were extracted for mechanical tests. (b) Cast iron samples for mechanical testing: tension, torsion, compression, shear, and multiaxial tests.

For quasi-static torsion tests, thin-walled hollow cylindrical specimens were machined from the extracted cores and designed to be compatible with the gripping system of a ZwickRoell Z50 universal torsion testing machine. The specimens were subjected to pure torsional loading under displacement control at a constant rotation rate of 10°/min, while actively ensuring zero axial force throughout the test. Shear strain was measured using Digital Image Correlation (DIC)[4]. A dedicated incremental correlation algorithm was employed to track tangential displacements between successive image pairs, enabling accurate shear strain measurements that are not achievable using traditional extensometric techniques. Dynamic mechanical tests were conducted in both tension and compression to investigate the strain rate sensitivity of the material. Specimens were tested at strain rates up to approximately 500 s^{-1}. The experimental setup and data reduction procedures allowed direct comparison between quasi-static and dynamic responses[5].

Results and Discussion

The mechanical response of the cast iron under quasi-static loading conditions is summarized in Figure 2, where the engineering stress–strain curves obtained from tension, compression, and torsion tests are compared. Under pure torsional

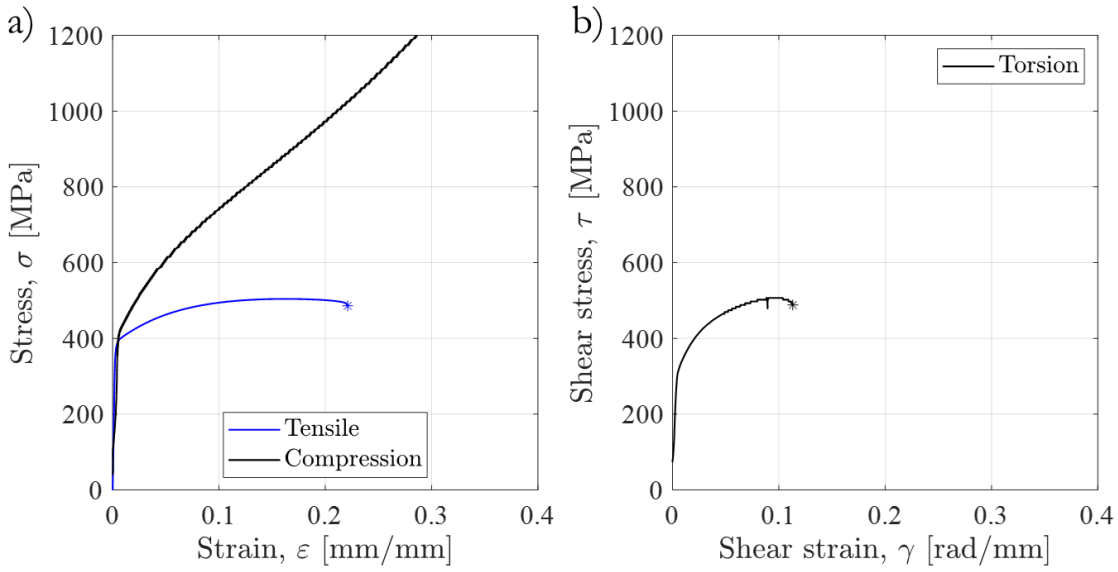

Fig. 2 Mechanical response of SSFDI cast iron under multiaxial load. a) Engineering stress-strain compression and tensile curves. b) Engineering shear stress-strain curve obtained through torsion test on thin-walled cast iron tube. (* into the chart identifies failure).

loading, the material exhibits a remarkable combination of strength and ductility, with shear strains reaching approximately 15% prior to failure.

The torsional response is characterized by significant strain hardening, consistent with the behavior observed under uniaxial tension and compression. This indicates a robust plastic deformation capability under multiaxial stress states. The shear modulus, determined from the initial linear portion of the torsion curve using DIC-based strain measurements, was found to be approximately 68 GPa. This value is fully consistent with the Young's modulus of 195 GPa and Poisson's ratio of 0.26 previously identified from uniaxial tests, confirming that the material can be considered macroscopically isotropic in the elastic regime. A key result of the torsion tests is the experimentally measured shear yield stress of approximately 305 MPa. This value significantly exceeds the shear yield stress predicted by the classical Von Mises yield criterion, which would estimate a critical shear stress of about 230 MPa based on the uniaxial yield strength. This discrepancy clearly indicates that the yield surface of the investigated cast iron cannot be accurately described by a Von Mises-type isotropic criterion. The experimental evidence suggests a yield surface that is expanded along the shear stress axis, highlighting the need for alternative yield criteria or modified constitutive descriptions capable of capturing the multiaxial yielding behavior of this material.

The dynamic mechanical response of the cast iron is shown in Figure 3, which compares quasi-static and high strain rate true stress–strain curves in both tension and compression. At a strain rate of approximately 500 s^{-1}, the material exhibits a pronounced strain rate sensitivity, with the yield stress increasing by a factor of about 1.45 relative to quasi-static conditions. Specifically, yield stresses of approximately 562 MPa in tension and 581 MPa in compression were measured. Despite the significant increase in yield strength, the overall shape of the stress–strain curves under dynamic loading remains similar to that observed under quasi-static conditions, particularly in terms of strain hardening behavior. This indicates that the strain rate sensitivity of the material primarily affects the onset of plasticity, while the post-yield hardening mechanisms remain largely unchanged. A moderate reduction in ductility was observed under dynamic conditions, with fracture strains decreasing from approximately 20% in quasi-static tests to about 14% at high strain rates. However, this observation requires further investigation, as the dynamic tests revealed the formation of localized deformation bands. Such bands were also observed during elevated-temperature testing and are likely associated with adiabatic heating effects occurring during high strain rate deformation. The apparent change in hardening behavior at large strains observed in dynamic compression tests can be attributed to a combination of strain rate reduction and temperature increase during the final stages of deformation. Both effects are well captured by rate- and temperature-dependent constitutive models such as Johnson–Cook or Cowper–Symonds formulations, which are therefore suitable candidates for modeling the dynamic behavior of SSFDI cast iron.

By combining the quasi-static multiaxial results with the dynamic uniaxial data, it emerges that the yield surface of SSFDI cast iron is not only non-Von-Mises in shape but also strongly dependent on strain rate. The upward shift of the yield stress under dynamic loading can be interpreted as an isotropic expansion of the yield surface with increasing strain rate,

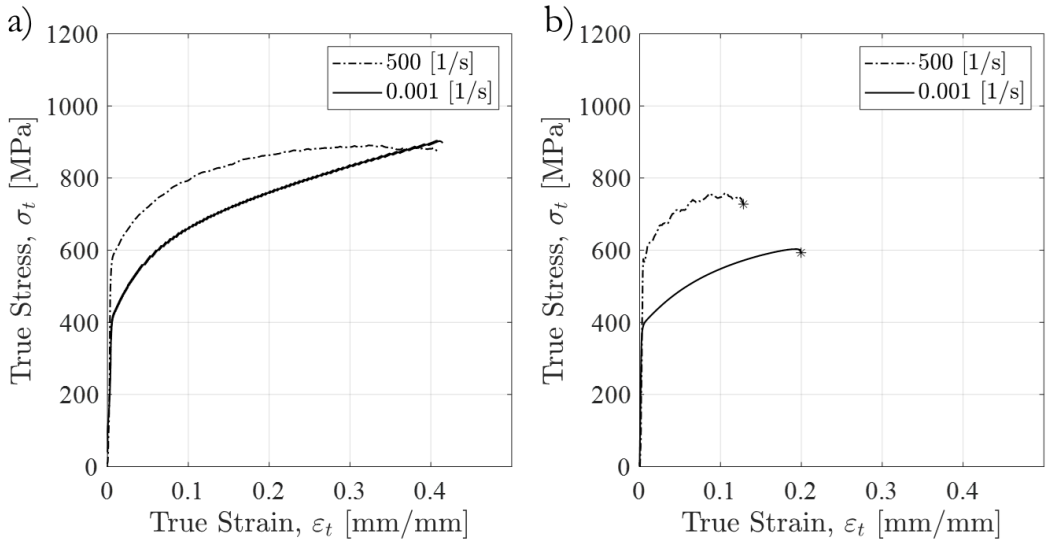

Fig. 3 Strain rate sensibility of SSFDI cast iron. a) True stress-strain compression curve at quasi-static, 0.001 1/s, and high strain rate, 500 1/s. b) True stress-strain tensile curve at quasi-static, 0.001 1/s, and high strain rate, 500 1/s. (* into the chart identifies failure).

while its overall shape—particularly the enhanced shear strength—appears to be preserved. The figure 4 clearly illustrate this combined effect, providing a visual representation of both the yield surface distortion under multiaxial loading and its strain rate sensitivity. Such results underline the importance of incorporating both multiaxial stress effects and rate dependence in constitutive models intended for reliable structural simulations involving SSFDI cast iron under extreme loading conditions.

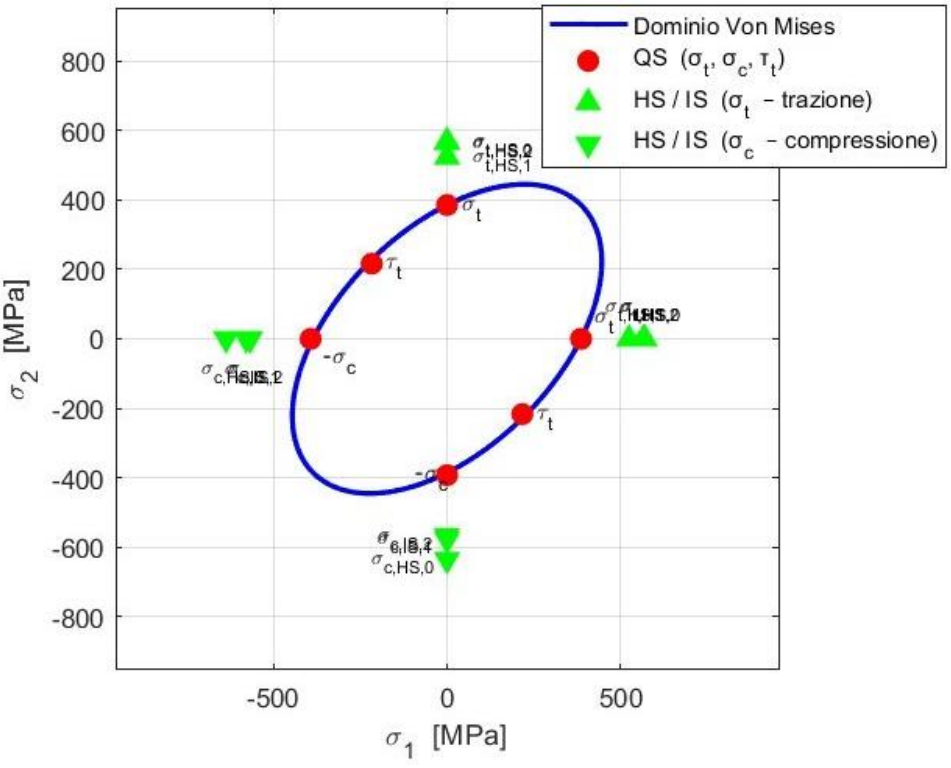

Fig. 4 Yield behavior of SSFDI cast iron on the principal stress plane. Quasi-static and high strain rate (500 s^{-1}) tensile and compressive tests are shown, highlighting the shape of the yield surface and its expansion with increasing strain rate.

Conclusion and Future Work

This study provided a comprehensive experimental characterization of solid solution-strengthened ferritic ductile iron (SSFDI) under quasi-static and dynamic loading conditions. Tensile, compression, shear, and torsion tests revealed that the material exhibits a non-Von Mises yield surface, with shear and torsional strengths significantly higher than predicted by classical isotropic plasticity. These results indicate that the yield locus is strongly dependent on stress state, highlighting the limitations of conventional models for SSFDI. High strain rate tests up to 500 s^{-1} showed a pronounced strain rate sensitivity, with yield stresses increasing by approximately 45% compared to quasi-static conditions. Despite this strengthening, post-yield hardening remained similar, suggesting that strain rate effects primarily influence the onset of plasticity. A moderate reduction in ductility and the formation of localized deformation bands under dynamic loading were observed, likely promoted by adiabatic heating. The combination of multiaxial and dynamic data indicates that the yield surface expands isotropically with strain rate while maintaining its shape, emphasizing the importance of stress-state and rate-dependent modeling. To capture this behavior, a compressible elastoplastic model was calibrated using an inverse finite element approach. The model successfully reproduces the experimentally observed yield surface and its evolution with strain rate and temperature, providing a robust predictive tool for engineering applications. Overall, the findings offer critical insight into SSFDI behavior, supporting reliable design and numerical simulation of components subjected to complex loading conditions.

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