

Plasticity and fracture of metals under tensile loading at elevated temperatures

Mohammad Sajjad Kiani

Department of Mechanical Engineering, Tehran University, Tehran, Iran

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Abstract

This study provides a comprehensive examination of the plasticity and ductile fracture behavior of high-strength AA7075-T6 aluminum alloy sheets under uniaxial tensile loading over a wide range of strain rates and elevated temperatures. An extensive experimental campaign was carried out, covering quasi-static, intermediate, and high strain rate conditions (from 0.001 s^{-1} to 150 s^{-1}) and temperatures from room temperature ($20\text{ }^{\circ}\text{C}$) to $360\text{ }^{\circ}\text{C}$, which are relevant to hot forming and impact applications. Low- and intermediate-strain-rate tests were conducted using a servo-hydraulic universal testing machine (Instron 8801), while high-strain-rate experiments employed a modified Split Hopkinson Pressure Bar (SHPB) system incorporating a Load Inversion Device (LID) for tensile loading and a custom induction heating setup for fast, uniform temperature control. Full-field deformation and strain measurements were obtained via digital image correlation (DIC) using high-speed cameras and stochastic speckle patterns. Temperature uniformity was monitored and confirmed through infrared thermography and pyrometer feedback. The experimental findings highlighted strong coupled effects of temperature and strain rate on flow stress, strain hardening, and fracture behavior. Flow stress decreased substantially with increasing temperature across all strain rates, while strain rate sensitivity shifted from negligible at lower temperatures to pronounced at higher temperatures (above $\sim 120\text{ }^{\circ}\text{C}$), with significant hardening observed at the highest rates and temperatures. To capture these complex thermo-viscoplastic behaviors, a modified Johnson–Cook constitutive model was first calibrated but proved inadequate for the non-separable interactions. A machine learning-enhanced model was then developed, integrating a neural network with a baseline Swift–Voce hardening law. This data-driven approach achieved superior accuracy in describing the intricate, nonlinear dependencies without relying on predefined functional forms.

Keywords: Ductile fracture, Tensile loading, Elevated temperature, Strain rate effect, Metal plasticity, Machine learning constitutive modeling

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1 Introduction

Understanding and accurately modeling the coupled effects of strain rate and temperature on material behavior have long been central objectives in materials science, driven by practical challenges in industrial processes such as metal forming, machining, crash scenarios, and high-velocity impacts. In this regard, AA7xxx-series aluminum alloys have garnered considerable interest for their application in impact-resistant structures [14]. These alloys typically display limited strain rate sensitivity at room temperature [61], but exhibit pronounced rate dependence at elevated

Email address: msjd.kiani@ut.ac.ir (Mohammad Sajjad Kiani)

temperatures [54]. To capture such nonlinear, interdependent phenomena, various phenomenological constitutive models have been developed, with the Johnson–Cook (JC) framework remaining one of the most prevalent [29]. The physically grounded yet mathematically straightforward nature of these models has facilitated their widespread adoption across diverse applications. Recently, however, data-driven methodologies incorporating machine learning have emerged as robust alternatives, offering exceptional fidelity in replicating intricate material responses [2, 42].

Amid escalating concerns over environmental pollution and global energy shortages, the imperative for lightweight structural solutions has intensified across industries, including automotive, marine, aerospace, and advanced manufacturing [53, 79, 86]. In the automotive sector, enhancing fuel efficiency while curbing emissions poses a persistent technical hurdle [40]. Marine applications demand sustained corrosion resistance [83], whereas aerospace requires an optimal balance of high strength and low weight [72]. Across these domains, there is a universal pursuit of materials that deliver long-term reliability alongside efficient, scalable forming processes [92, 47]. Structural optimization has proven efficacious as a design strategy [76], complemented by the advancement of low-density, high-strength materials that enable lightweight constructs with superior mechanical properties and enhanced formability [89, 15].

Over the course of metallic materials development and engineering integration, a diverse array of aluminum alloys has been engineered to address varied requirements. Notably, alloying aluminum with Zn, Mg, and Cu yields the 7xxx series, renowned for exceptional strength-to-weight ratios and fracture toughness [70, 69]. These alloys merge superior performance with amenable processing attributes. Nonetheless, during manufacturing and service, components from these alloys often encounter multifaceted loading conditions, including high-temperature tensile deformation. Thus, a comprehensive grasp of the hot tensile response in 7xxx-series alloys is indispensable for their deployment in rigorous environments [19, 75, 78]. As precipitation-hardenable materials, they follow a typical aging sequence: SSSS $\rightarrow$ GP zones $\rightarrow$ η' $\rightarrow$ η [71]. Relative to heavily alloyed variants like AA7075 and AA7050, AA7005 contains lower levels of Zn, Mg, and Cu [22], conferring improved weldability and deformability, and facilitating extrusion into thin-walled, complex hollow profiles [8]. Accordingly, AA7005 finds extensive use in load-bearing elements such as frames, cross-members, and civil infrastructure like bridges [37]. However, evolving demands in aerospace and transportation necessitate further enhancements to its mechanical properties.

Extensive research underscores that the high-temperature mechanical behavior of metallic alloys diverges substantially from ambient conditions. For instance, Chen et al. [10] investigated the compressive deformation of extruded AA7005 across 350–550 °C, observing a positive correlation between flow stress and strain rate, alongside a sharp decline in stress with rising temperature. Microstructural attributes were identified as pivotal in dictating macroscopic performance. Duan et al. [13] assessed the impact of equal-channel angular extrusion parameters and annealing on AA7005's tensile properties, revealing that these factors modulate grain size and, consequently, mechanical behavior.

Jiang et al. [27] further elucidated microstructure–property linkages in thixoformed AA7005 components, showing that process parameters and heat treatments influence grain morphology and enable property tailoring. Reports also indicate a shift in AA7075's fracture mode from ductile at moderate tensile temperatures to brittle at higher levels [43], with elongation initially rising then diminishing with temperature. Fu et al. [17] examined laser-directed energy deposited AA7075, pinpointing dislocation and Orowan strengthening as dominant in as-deposited states, transitioning to primarily Orowan post-heat treatment.

As advanced materials advance and their applications expand into harsher regimes, they undergo complex microstructural evolutions under varied service conditions, yielding diverse mechanical responses. Hence, systematic studies of behavior and microstructural mechanisms across deformation modes are vital for expanding their utility.

Lightweight materials are pivotal in contemporary automotive design, aiding fuel economy and environmental sustainability. Aluminum alloys hold a key role due to their advantageous strength-to-weight profiles, though they often suffer from constrained room-temperature formability relative to steels. Warm forming has thus gained traction as a means to augment formability.

The formability of metals is profoundly influenced by stress states, characterized by parameters like stress triaxiality and the Lode angle. Bao and Wierzbicki [4] demonstrated via experiments on 2024-T351 aluminum that stress triaxiality markedly affects ductility. Gao et al. [18] echoed this, noting stress state's role in plasticity and ductile fracture initiation. Zhang et al. [88] extended the framework, emphasizing the Lode parameter—linked to the third deviatoric stress invariant—as crucial for fracture prediction, advocating its integration with triaxiality for holistic stress state depiction.

Temperature and strain rate further modulate formability. Shehata et al. [66] studied Al–Mg alloys from 20–300 °C under uniaxial and biaxial tension at varying rates, finding reduced temperature/rate sensitivity in biaxial modes. Li and Ghosh [41] evaluated warm biaxial forming of AA5754, AA5182, and AA6111-T4 at 200–350 °C, reporting substantial formability gains.

In this study, uniaxial tensile tests were performed across strain rates of $0.001\text{--}110\text{ s}^{-1}$ and temperatures of $20\text{--}360\text{ }^{\circ}\text{C}$. A neural network-based strain-hardening model was formulated to encapsulate rate-temperature coupling, with its efficacy benchmarked against the JC model, highlighting the data-driven approach's superior flexibility and precision.

Literature review

One of the foremost challenges facing the automotive industry is adherence to progressively stringent regulations on fuel efficiency and vehicle safety. Consequently, substantial efforts have been devoted to reducing structural weight by substituting advanced high-strength steels with precipitation-hardenable 7xxx-series aluminum alloys. Among these, AA7075—an Al–Zn–Mg–Cu alloy—stands out for its exceptional mechanical properties, including high specific strength, excellent fracture toughness, and robust resistance to stress corrosion cracking, which have underpinned its widespread adoption in aerospace structures. Nevertheless, its restricted room-temperature formability and elevated processing costs have impeded broader penetration into automotive applications.

To circumvent the formability constraints of AA7075, various elevated-temperature sheet forming processes have been explored as alternatives to conventional cold stamping. Hot stamping with in-die quenching has emerged as a particularly promising technique. In this method, blanks are solution heat-treated above $\sim 480\text{ }^{\circ}\text{C}$ to achieve a supersaturated solid solution (W-temper), rapidly transferred to cooled dies for forming and simultaneous quenching in the soft W-temper state, and subsequently artificially aged to the peak-strength T6 condition via precipitation hardening [31]. Harrison and Luckey [20] validated the industrial viability of this approach by successfully producing an automotive B-pillar from AA7075, demonstrating that hot forming followed by artificial aging yields components with mechanical properties comparable to those of the conventional T6 temper. Complementarily, Ilinich and Luckey [25] employed thermomechanical simulations to predict strain and thickness distributions in hot-stamped B-pillars, underscoring the critical need for accurate stress–strain data for solution-treated AA7075 across temperatures of $200\text{--}480\text{ }^{\circ}\text{C}$ and strain rates of $0.01\text{--}10\text{ s}^{-1}$.

Recent research on aluminum alloys has increasingly emphasized the influence of complex loading on plasticity and fracture, encompassing multiaxial stress states [9, 63, 38, 46], nonlocal damage models [1], strength differential effects and strain-rate sensitivity [21, 49, 30], and nonproportional loading paths [57, 56, 48]. Microstructural phenomena, such as micro-defect evolution [84] and heterogeneity-induced macroscopic variability [90], have also received considerable attention. Concurrently, crystal plasticity models for aluminum have advanced significantly [6, 50, 23, 33, 45, 85, 5], including statistically equivalent representations derived from experimental microstructures [73]. Dislocation- and atomistic-scale simulations have further elucidated fundamental mechanisms [35, 36].

Despite this prolific literature, studies specifically addressing the plasticity and fracture of 7xxx-series alloys in the W-temper remain comparatively scarce. Xiao et al. [80, 82] performed high-temperature uniaxial tensile tests on solution-treated AA7075 using a Gleeble simulator ($300\text{--}450\text{ }^{\circ}\text{C}$; $0.1\text{--}10\text{ s}^{-1}$), proposing a constitutive framework that incorporates dynamic recrystallization, dislocation recovery, grain growth, and damage. Omer et al. [51] characterized the response of AA7075-W via controlled solutionizing, quenching, and tensile testing ($25\text{--}470\text{ }^{\circ}\text{C}$; $0.01\text{--}0.5\text{ s}^{-1}$), employing 3D digital image correlation to extend stress–strain curves beyond necking and fitting an extended Voce hardening law. Supporting investigations relevant to hot stamping have examined natural aging effects on strength and anisotropy [39], process parameter optimization [52], forming limit prediction [77], comparative hot forming strategies and post-form strength [91], and interfacial heat transfer during quenching [44, 81, 82].

From a constitutive modeling standpoint, physically based thermoviscoplastic theories grounded in dislocation mechanics have been extensively developed [87, 16, 68, 74, 3, 34, 12, 62], alongside phenomenological approaches that retain mechanistic inspiration without explicit microstructural resolution [28, 29, 7, 82, 67, 24, 55]. More recently, purely data-driven machine learning frameworks have shown remarkable efficacy in capturing intricate responses absent rigorous physical constraints. For example, Kessler et al. [32] utilized neural networks to model the flow behavior of AA6061 across $300\text{--}550\text{ }^{\circ}\text{C}$ and $10^{-3}\text{--}1\text{ s}^{-1}$. Jenab et al. [26] applied similar techniques to predict rate-dependent tensile response in AA5182-O over $0.001\text{--}1000\text{ s}^{-1}$. Li et al. [42] further demonstrated the versatility of machine learning-based hardening laws for temperature- and rate-dependent behavior in dual-phase steels.

A seminal review of hot workability was provided by Sellars and Tegart [64]. Uniaxial tension and torsion remain the predominant methods for assessing high-temperature ductility [64, 11, 58], though they inherently limit exploration of diverse stress states prevalent in forming operations. To address this, hybrid tests incorporating superimposed axial loads during compression or torsion have been developed to yield more robust fracture criteria for hot processes [65]. Such criteria must explicitly account for temperature and strain rate influences, substantially expanding the required experimental scope. In the present investigation, uniaxial tensile testing is utilized to quantify fracture strains in aluminum alloys across broad temperature and strain rate regimes, revealing a peak in ductility under

certain constant-rate conditions.

Research background

The mechanical behavior of high-strength 7xxx-series aluminum alloys, particularly AA7075, has been the subject of extensive research due to their pivotal role in aerospace structures, automotive lightweighting, hot forming processes, and impact-resistant applications.

Early investigations into dynamic loading highlighted the competing effects of strain rate on strength and ductility. Børvik et al. [14] studied the ballistic perforation resistance of AA7075-T651, combining experiments with numerical simulations to demonstrate enhanced flow stress but diminished ductility at high strain rates. Similarly, Roth et al. [61] examined dynamic perforation in lightweight aluminum-based armor, elucidating the role of elevated strain rates in promoting adiabatic shear localization and ductile fracture. Pandya et al. [54] performed uniaxial tensile tests on AA7075 across wide ranges of strain rates and temperatures, revealing pronounced thermal softening, a shift from negligible to positive strain rate sensitivity above -120°C , and substantial reductions in fracture strain under coupled high-rate/high-temperature conditions.

Foundational viscoplastic constitutive frameworks, such as the phenomenological Johnson–Cook model [28, 29], were originally calibrated on high-rate tensile, torsional, and compressive data for various metals, providing a separable description of strain hardening, strain rate sensitivity, and thermal softening that remains widely employed for aluminum alloys.

Significant efforts have focused on elevating the formability of AA7075 through hot stamping technologies. Harrison and Luckey [20] pioneered the production of an automotive B-pillar from AA7075 sheet via solution heat treatment, rapid transfer, hot forming, and in-die quenching, followed by artificial aging to recover peak strength. Ilinich and Luckey [25] developed thermomechanical finite element models for this process, emphasizing the need for accurate flow stress data in the solutionized (W-temper) state across relevant temperature and rate regimes. Xiao et al. [80, 82] conducted elevated-temperature tensile tests on solution-treated AA7075, incorporating microstructural observations to formulate constitutive equations accounting for dynamic recovery, recrystallization, grain growth, and damage evolution. Omer et al. [51, 52] systematically characterized the constitutive response of AA7075-W, optimizing solutionizing, quenching, and aging protocols to maximize post-form strength. Zheng et al. [91] compared deformation characteristics and post-forming mechanical properties across different elevated-temperature forming strategies for heat-treatable aluminum alloys.

Advanced studies have addressed complex loading paths and fracture mechanisms. Chen et al. [9] and Scales et al. [63] investigated localization and failure in aluminum under combined shear-tension, while Luo et al. [46] developed hybrid experimental-numerical approaches for ductile fracture prediction in extrusions subjected to multiaxial loading.

More recent contributions have explored microstructural evolution and process optimization in AA7075 and related compositions. Ma et al. [47] optimized high-temperature stamping parameters through mechanical testing and formability analysis. Zhou et al. [92] examined microstructure, mechanical properties, and corrosion resistance in recycled AA7075. Tang et al. [70, 69] elucidated precipitation sequences, dynamic softening mechanisms, and their influence on hot flow behavior in Al–Zn–Mg–Cu alloys with varying Zn content.

Parallel advancements in constitutive modeling have shifted toward data-driven paradigms. Li et al. [42] and Roth et al. [42] demonstrated the superiority of neural network-enhanced formulations in capturing intricate temperature- and rate-dependent hardening and fracture responses in metals, outperforming traditional models in non-separable regimes.

Collectively, these studies highlight persistent challenges in accurately describing the strongly coupled thermo-viscoplastic behavior of AA7075 using conventional phenomenological models, while underscoring the potential of hot forming routes and emerging machine learning approaches. The present work builds on this foundation by undertaking a comprehensive experimental characterization of AA7075-T6 across an extensive matrix of strain rates and temperatures, complemented by a hybrid neural network-based constitutive framework to overcome limitations of existing models.

2 Material and specimens

The material examined in the present investigation is a high-strength AA7075-T6 aluminum alloy with a nominal thickness of 2 mm. All test specimens were manufactured using waterjet cutting to minimize thermal and mechanical

damage during preparation. Two distinct uniaxial tensile (UT) specimen geometries were employed, as illustrated in Fig. 1.

- For experiments conducted at low and intermediate strain rates, standard uniaxial tensile specimens with a gauge width of 10 mm and a gauge length of 40 mm were utilized (Fig. 1a).
- To enable testing under high strain rate conditions, a reduced-size uniaxial tensile configuration (D-UT) was adopted, featuring a gauge length of 15 mm and a gauge width of 5 mm (Fig. 1b).

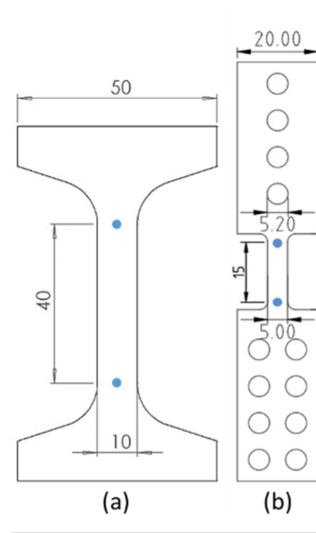


Figure 1: Geometries of the tensile specimens employed for (a) low and intermediate strain rate tests and (b) high strain rate experiments. The locations of the extensometers used for global displacement measurements via digital image correlation (DIC) are indicated by blue markers.

3 Experimental methods

Low strain rate testing setup

Low strain rate tensile experiments were performed using a servo-hydraulic universal testing machine (Instron 8801) operating under displacement-controlled conditions. An actuator velocity of 2.4 mm/min was applied, corresponding to an engineering strain rate of 0.001 s^{-1} . Prior to testing, specimen surfaces were coated with a stochastic black-and-white speckle pattern to enable full-field deformation measurements using digital image correlation (VIC2D, Correlated Solutions). Image acquisition was carried out at a sampling rate of 1 Hz using a 5-megapixel camera (Point Grey GS3-U3-51S5M-C).

Temperature control was achieved using a custom-designed induction heating system regulated by a pyrometer-based feedback loop. Specimens were heated to the desired test temperature at a controlled rate of 30 K/s. The spatial uniformity of the temperature distribution was verified using an infrared thermal imaging camera (FLIR x6801).

Intermediate strain rate testing setup

Tests at intermediate strain rates were conducted on the same hydraulic testing platform (Instron 8801). A crosshead speed of 240 mm/min—corresponding to a loading rate 100 times higher than that used for quasi-static experiments—was selected. For deformation measurements, a high-speed camera (Photron SA-Z) equipped with a 105 mm f/2.8 macro lens was employed to capture images at a frame rate of 200 Hz. Both image acquisition and data recording were synchronized and initiated by the onset of the force signal. Temperature regulation during these experiments relied on the same induction heating system and high-speed infrared camera utilized in the low strain rate tests.

High strain rate testing setup

High strain rate tensile experiments were carried out using a Split Hopkinson Pressure Bar (SHPB) apparatus equipped with a Load Inversion Device (LID) to enable tensile loading. A detailed description of the SHPB system configuration can be found in Ref. [60]. Specimens were secured within the setup using twelve M5 screws to ensure proper alignment and load transfer. The axial force applied to the specimen was determined from strain gauge measurements collected on the output bar at a distance of 430 mm from the specimen–bar interface.

Specimen deformation during high strain rate loading was recorded using the same high-speed camera system employed for intermediate strain rate tests (Photron SA-Z). For these experiments, the camera resolution was reduced to 512×280 pixels, allowing operation at an acquisition rate of 100 kHz. Image capture and mechanical data acquisition were triggered simultaneously upon detection of the incident wave in the input bar.

4 Constitutive modeling

An elasto-plastic constitutive framework was adopted to describe the mechanical response of the AA7075-T6 alloy. The elastic properties, including Young's modulus and Poisson's ratio, are summarized in Table 1. In the absence of detailed information regarding material anisotropy, an isotropic von Mises yield criterion combined with an associated flow rule was selected for simplicity. Accordingly, the yield function can be expressed as:

$$f[\sigma, k] = \bar{\sigma}_{VM} - k = 0 \quad (4.1)$$

The dependence of the plastic deformation behavior on strain rate and temperature is captured through two separate constitutive descriptions: a conventional analytical model of the Johnson–Cook type and a data-driven hardening model based on neural network techniques.

Johnson–Cook-type hardening formulation

Within the Johnson–Cook framework, the material's resistance to plastic flow, denoted by k , is expressed as a product of three independent contributions accounting for the effects of plastic strain, strain rate, and temperature. This multiplicative decomposition enables the individual influence of each variable to be represented explicitly within the constitutive formulation, while collectively describing the overall deformation resistance of the material.

$$[k_{SV}, \dot{\bar{\epsilon}}_p, T] = k_{SV}[\bar{\epsilon}_p] k_{\dot{\bar{\epsilon}}_p}[\dot{\bar{\epsilon}}_p] k_T[T] \quad (4.2)$$

In this formulation, the strain hardening contribution is represented as a weighted superposition of the Swift and Voce hardening laws, where the parameter α governs the relative contribution of each term to the overall hardening response.

$$k_{SV}[\bar{\epsilon}_p] = \alpha k_S[\bar{\epsilon}_p] + (1 - \alpha) k_V[\bar{\epsilon}_p] \quad (4.3)$$

$$k_S[\bar{\epsilon}_p] = A(\epsilon_0 + \bar{\epsilon}_p)^n \quad (4.4)$$

$$k_V[\bar{\epsilon}_p] = k_0 + Q(1 - e^{-\beta \bar{\epsilon}_p}) \quad (4.5)$$

The strain rate and temperature contributions are formulated in accordance with the classical Johnson–Cook expressions, without modification.

$$k_{\dot{\bar{\epsilon}}_p}[\dot{\bar{\epsilon}}_p] = \begin{cases} 1 & \text{for } \frac{\dot{\bar{\epsilon}}_p}{\dot{\epsilon}_0} < \dot{\epsilon}_0 \\ 1 + C \ln \left[\frac{\dot{\bar{\epsilon}}_p}{\dot{\epsilon}_0} \right] & \text{for } \frac{\dot{\bar{\epsilon}}_p}{\dot{\epsilon}_0} \geq \dot{\epsilon}_0 \end{cases} \quad (4.6)$$

$$k_T[T] = \begin{cases} 1 & \text{for } T < T_r \\ 1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m & \text{for } T_r \leq T \leq T_m \end{cases} \quad (4.7)$$

Neural network–based hardening formulation

The hardening model based on neural networks is developed in close accordance with the framework proposed in Ref. [42]. In this approach, the material's resistance to plastic deformation is expressed as the sum of two distinct contributions: a reference strain-hardening component represented by a combined Swift–Voce law, and an additional neural network term that captures the coupled influence of strain rate and temperature on the hardening behavior.

In the present work, the neural network employed to model the hardening behavior is implemented as a fully connected feed-forward architecture comprising three hidden layers, each containing ten neurons. The neural network output serves as a multiplicative scaling factor, which adjusts the reference strain-hardening curve to account for the prevailing strain rate and temperature conditions.

5 Results and discussion

Experimental results

Figure 2a presents the experimentally obtained engineering stress–strain responses from uniaxial tensile tests performed at different loading rates and temperatures. The corresponding true stress–plastic strain curves, evaluated up to the onset of uniform deformation, are displayed in Fig. 2b.

The experimental data reveal a consistent and monotonic reduction in equivalent stress with increasing temperature, independent of the applied strain rate. At temperatures below 60 °C, the influence of strain rate on the mechanical response is found to be negligible. In contrast, a pronounced strain-rate-sensitive hardening behavior emerges at temperatures of 120 °C and above. At the highest investigated temperature of 360 °C, increasing the strain rate from 0.001 s^{-1} to 0.1 s^{-1} results in an increase in yield stress exceeding 90%, highlighting the strong coupling between thermal and rate effects under these conditions.

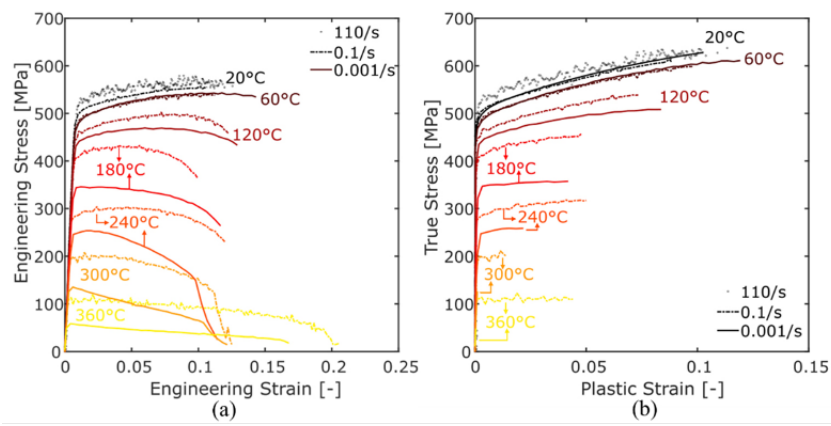


Figure 2: (a) Engineering stress–strain responses obtained from uniaxial tensile tests conducted at different temperatures. Results from low loading speeds are shown using solid lines, intermediate speeds are represented by dashed lines, and high strain rate tests are indicated by dotted curves. (b) Corresponding true stress–plastic strain curves derived from the same experiments at various temperatures. All curves are terminated at the maximum force point, corresponding to the onset of uniform elongation.

Modeling Results

The elastic properties of the material, namely Young’s modulus and Poisson’s ratio, were determined from the engineering stress–strain response of the uniaxial tensile test performed at room temperature. The parameters defining the reference mixed Swift–Voce strain-hardening law were subsequently identified by fitting the true stress–plastic strain curve obtained from the same room-temperature experiment.

An overview of the baseline constitutive parameters is provided in Table 1. The parameters associated with the Johnson–Cook formulation were calibrated using true stress–plastic strain data obtained across the full range of investigated strain rates and temperatures. A detailed listing of the resulting calibrated Johnson–Cook parameters is presented in Table 2.

Calibration of the neural network–based hardening model was carried out using the identical set of true stress–plastic strain curves employed for the Johnson–Cook model. Training of the neural network was performed using a resilient back-propagation (RPROP) algorithm [59]. The training process was executed for a total of 500 epochs and required less than 10 minutes of computation time on a standard desktop computer.

Table 1: Plasticity model parameters for AA7075-T6.

E	ν	ρ				
[GPa]	[-]	[kg/m ³]				
67.6	0.33	2780				
A	ε_0	n	k_0	Q	β	α
[MPa]	[-]	[-]	[MPa]	[MPa]	[-]	[-]
855	0.026	0.15	502	194	10.08	0.5

Table 2: Calibrated parameters of the Johnson–Cook–type hardening model.

C	$\dot{\varepsilon}_0$	m	T_r	T_m
[-]	[$\frac{1}{s}$]	[-]	[°C]	[°C]
0.11	0.001	1.23	20	477

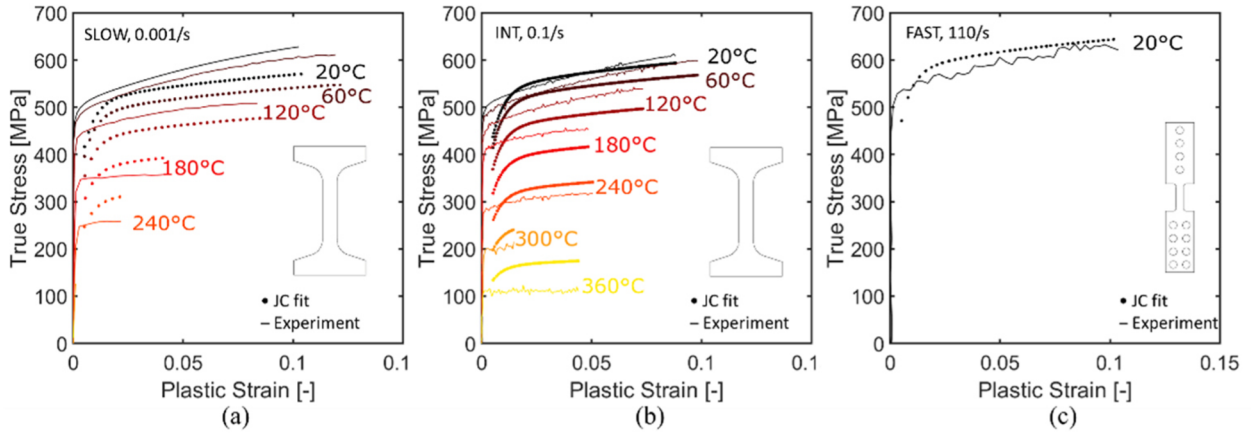


Figure 3: Comparison between the hardening response predicted by the Johnson–Cook model (symbols) and the corresponding experimental curves (solid lines).

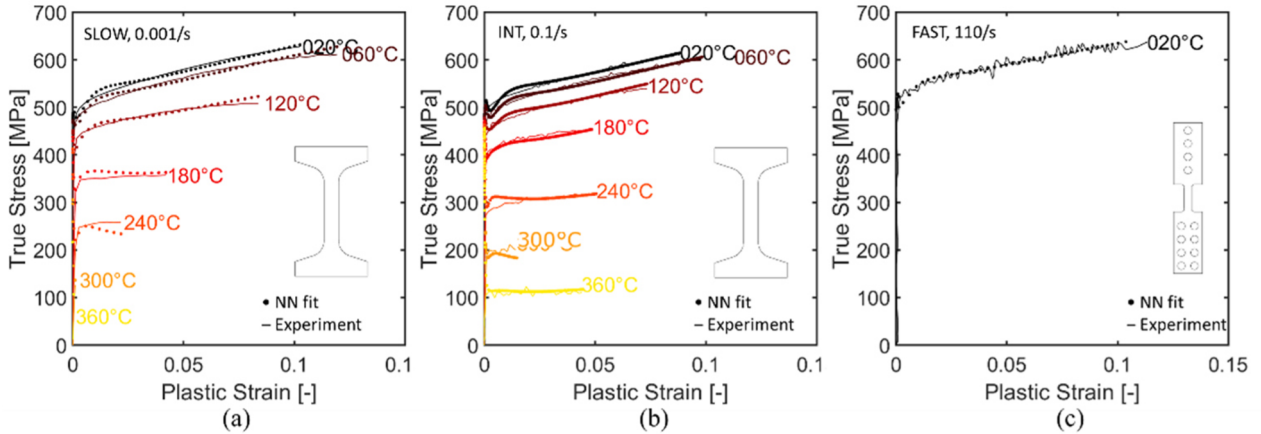


Figure 4: Neural network–based hardening response (symbols) compared with the corresponding experimental stress–strain curves (solid lines). The figure highlights the strong adaptability of the model in accurately representing pronounced strain hardening at lower temperatures as well as more moderate hardening behavior at elevated temperatures.

A direct comparison between the calibrated Johnson–Cook model (Fig. 3) and the neural network–based formulation (Fig. 4) clearly indicates the superior performance of the latter in fitting the experimental data. The predictive

capability of the Johnson–Cook approach is inherently constrained by its multiplicative separation of strain, strain rate, and temperature contributions, which imposes a uniform strain-rate sensitivity across all temperature levels. As a result, this formulation is unable to simultaneously reproduce the negligible strain-rate dependence observed at low temperatures and the pronounced rate sensitivity emerging at temperatures exceeding 120 °C. In contrast, the neural network model operates as a universal function approximator, enabling it to uncover complex and non-linear relationships between the input variables and the resulting material response without imposing restrictive assumptions.

6 Conclusion

This investigation provides a thorough and systematic characterization of the thermo-viscoplastic behavior and ductile fracture response of the high-strength AA7075-T6 aluminum alloy under uniaxial tensile loading conditions. Through an extensive experimental program, the mechanical response was examined across a wide range of strain rates—from quasi-static (0.001 s^{-1}) to dynamic high rates (up to 150 s^{-1})—and temperatures from ambient (20 °C) to elevated levels (up to 360 °C). These conditions are highly relevant to practical engineering applications, including hot forming processes, warm stamping operations, automotive crashworthiness design, and high-velocity impact scenarios where materials experience simultaneous thermal and high-rate mechanical loading.

The experimental results unequivocally demonstrated the strong coupling between temperature and strain rate effects on the alloy’s plastic deformation and fracture characteristics. A consistent thermal softening was observed, with flow stress decreasing significantly as temperature increased across all strain rate regimes. At lower temperatures (below approximately 120 °C), the material exhibited limited strain rate sensitivity, behaving in a manner closer to rate-independent plasticity. In contrast, at elevated temperatures, a pronounced positive strain rate hardening emerged, particularly evident at the highest tested rates, where yield and flow stresses increased substantially. This transitional behavior highlights the inadequacy of constitutive models that assume constant or separable strain rate sensitivity across the temperature spectrum. Furthermore, the evolution of ductility and fracture strains with temperature and rate provided critical insights into failure mechanisms, showing enhanced formability at intermediate temperatures but potential risks of premature fracture under combined high-rate and high-temperature loading.

To accurately describe these complex, non-linear interactions, two constitutive modeling strategies were evaluated. The classical Johnson–Cook model, despite its widespread use and reasonable capture of broad trends, was limited by its multiplicative formulation, which enforces decoupled contributions from strain hardening, strain rate, and thermal effects. This structure proved insufficient for reproducing the observed shift from negligible rate dependence at low temperatures to strong rate hardening at higher temperatures. In response, a hybrid machine learning-enhanced constitutive framework was developed, integrating a physically based Swift–Voce strain-hardening law as a reference curve with a neural network component to flexibly represent the coupled strain rate and temperature dependencies. Trained and validated against the comprehensive experimental dataset, this data-driven model achieved significantly superior predictive accuracy, effectively capturing intricate non-linearities and transitional phenomena without relying on predefined functional forms or empirical assumptions.

The success of the neural network-based approach underscores the growing potential of machine learning techniques in advancing constitutive modeling for advanced metallic materials, especially those displaying complex thermo-mechanical behavior under extreme conditions. By offering greater flexibility and fidelity compared to traditional phenomenological models, this framework provides a more reliable tool for numerical simulations in finite element analysis (FEA) codes, enabling improved predictions of component performance during hot forming, crash events, or ballistic impacts.

In addition to its modeling contributions, this study establishes a valuable experimental database for AA7075-T6 under coupled thermo-mechanical loading, which can serve as a benchmark for future material characterization efforts and model validations in the aluminum alloy community. The developed methodologies—including the high-strain-rate tensile testing with simultaneous induction heating and precise DIC measurements—represent advancements in experimental techniques that can be adopted for other temperature-sensitive alloys.

Looking ahead, several promising extensions emerge from this work. Incorporating damage and fracture criteria (e.g., via continuum damage mechanics or phase-field approaches) into the proposed model would enable full prediction of failure initiation and propagation. Further validation under multi-axial stress states, anisotropic conditions, or cyclic loading would broaden its applicability. Integration with process simulation tools could optimize industrial hot forming parameters, reducing trial-and-error costs and improving part quality.

Overall, the findings of this study significantly advance the understanding of plasticity and fracture in high-performance aluminum alloys under non-isothermal, rate-dependent conditions. By combining rigorous experimental-

tion with innovative data-driven modeling, this research paves the way for more accurate, robust, and efficient design of lightweight structures in automotive, aerospace, and defense applications, ultimately contributing to enhanced safety, performance, and sustainability.

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