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Electroplasticity for Sustainable Metal Forming: A Comparative Energy Assessment

Luigi Benvenuto[1,a*], Ersilia Cozzolino[2,b], Agnese Testa[3,c],
Chiara Mandolfino[1,d], Alessandro Simeone[3,e], Enrico Lertora[1,f],
Luca Settineri[3,g], Antonello Astarita[2,h]

[1]Department of Mechanical Engineering, Polytechnic School of University of Genoa, Via Opera Pia 15, 16145 Genoa, Italy

[2]Department of Chemical, Materials and Industrial Production Engineering, University of Naples Federico II, Piazzale V. Tecchio 80, 80125 Naples, Italy

[3]Department of Management and Production Engineering, Polytechnic of Turin, Corso Duca Degli Abruzzi 24, 10129 Turin, Italy

[a*]luigi.benvenuto@edu.unige.it, [b]ersilia.cozzolino@unina.it, [c]agnese.testa@polito.it,
[d]chiara.mandolfino@unige.it, [e]alessandro.simeone@polito.it, [f]enrico.lertora@unige.it,
[g]luca.settineri@polito.it, [h]antonello.astarita@unina.it

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Abstract. Modern manufacturing increasingly demands energy- and resource-efficient solutions. Conventional metal forming often requires high temperatures to reduce flow stress, resulting in high energy consumption, especially for low-formability alloys. Electrically-Assisted Manufacturing (EAM) has emerged as a promising alternative, leveraging the electroplastic effect, i.e. electricity's direct influence on plastic deformation. Documented benefits include reduced forming forces, improved ductility, and altered fracture modes. Indeed, integrating electroplasticity into manufacturing aligns with Industry 4.0 and decarbonization goals, enabling lower energy consumption, extended tool life, and greater compatibility with renewable energy sources. This study compares conventional tensile testing and electro-assisted tensile testing (EAM) of Ti6Al4V, evaluating both mechanical results and the energy consumption of the testing machine under different conditions. The comparison results highlight the potential of pulsed current to improve material formability while reducing energy consumption, offering a more sustainable approach to manufacturing.

Introduction

Titanium alloys, particularly Ti-6Al-4V (Grade 5), are extensively employed in the aerospace and automotive industries due to their high specific strength, high corrosion resistance and excellent mechanical properties at elevated temperatures [1]. Despite these advantages, their processing remains a significant challenge; Ti-6Al-4V exhibits low ductility and high flow stress at room temperature, often leading to premature failure and high tool wear [2]. Traditionally, these limitations are overcome through warm or hot forming processes. However, conventional heating methods are inherently inefficient, involving significant energy losses, surface oxidation and long cycle times, which conflict with the modern manufacturing goals of decarbonisation and resource efficiency [3-4].

Electrically-Assisted Manufacturing (EAM) has emerged as a promising solution to these challenges. This technology relies on the Electroplastic Effect (EPE), a phenomenon first systematically observed by Troitskii in 1984 [5], where the application of a high-density electric current during deformation leads to a reduction in flow stress and an increase in elongation [6]. While the macroscopic benefits are well-documented, the scientific community has long debated the dominant mechanisms of EPE, broadly categorising them into thermal and athermal effects. Joule heating is the primary thermal contributor, causing thermal softening; however, experimental evidence often shows stress drops that exceed those predicted by temperature increase alone [7].

Magargee et al. [7-8] demonstrated that while Joule heating is a significant factor in Commercially Pure (CP) Titanium, the sensitivity to current density suggests complex thermally activated behaviours.

Further investigations have revealed that electricity can induce microstructural changes comparable to traditional heat treatments but at lower global temperatures. Kim et al. [10] and Hong et al. [11] proved that pulsed current can induce "electrically-induced annealing" and recovery of dislocation density, effectively softening the material during forging or tensile deformation. More recently, groundbreaking research by Zhao et al. [12] in Ti-Al alloys has shown that electroplasticity originates from defect-level reconfigurations, such as enhanced cross-slip and twinning, which prevent the localization of planar slip bands, a mechanism that cannot be rationalized by simple Joule heating.

Despite these advancements in material science, a critical gap remains regarding the industrial sustainability of EAM. Most literature focuses on the metallurgical benefits, while the global energy balance is often overlooked. As highlighted by Ingarao et al. [13] and Liu et al. [14], the transition to a circular economy requires manufacturing processes to act as enablers of energy efficiency. EAM offers a localized heating approach that eliminates the need for large industrial furnaces, potentially reducing the carbon footprint of the forming stage [15].

This study addresses this gap by providing a comparison between conventional tensile testing and Electrically-Assisted (EA) testing of Ti-6Al-4V. The novelty of this work lies in the dual-track analysis: alongside the characterisation of mechanical properties (yield stress, tensile strength, and ductility), a rigorous energy absorption assessment is conducted for both configurations, but also, from a sustainable perspective. Energy consumption was measured during the tensile test of Ti-6Al-4V, either with or without the application of pulsed current, to assess the energy consumption associated with reducing the applied loads while improving material formability. By applying electro-assisted techniques, the required loads for deformation were lowered, enhancing the material's formability. The results offer valuable insights into the energy efficiency of this approach, demonstrating how reducing mechanical forces needed for deformation can lead to significant energy savings while maintaining or even improving material performance.

Materials and Methods

Material Characterisation and Specimen Design.

The material investigated in this study is the Titanium alloy Ti-6Al-4V (Grade 5), supplied in sheet form, 1 mm thick. Two tensile samples were machined from the as-received sheets via milling operations to minimise the alteration of the microstructural properties of the edges. The geometry of the samples was designed in accordance with the EN ISO 6892-1 standard [16]. A rectangular cross-section of 16 mm x 1 mm was selected for the gauge length. A proportionality factor $\mathrm{k} = 9$ was adopted to determine the initial gauge length ($\mathrm{L_0}$) based on the relationship $\mathrm{L_0} = \mathrm{k}\sqrt{\mathrm{S_0}}$, where $\mathrm{S_0}$ is the initial cross-sectional area fixed equal to 16 mm^2.

A tensile test was conducted with a pulsed current, alongside a reference test performed without it. To accommodate the specific requirements of the electrically-assisted (EA) test, the standard geometry was modified by extending the grip sections. This elongation was necessary to ensure sufficient space for both the mechanical clamping of the testing machine and the aluminium electrodes required for current injection. To ensure the safety of the equipment and the accuracy of the electrical measurements, an ad hoc experimental setup was developed, taking into account the need for electrical insulation between the specimen and the metallic grips of the testing machine. In particular, this was achieved by bonding glass-fibre-reinforced epoxy composite tabs onto the specimen heads using a rigid structural adhesive. This configuration ensured that the electrical current flowed exclusively through the gauge length of the specimen, preventing leakage into the testing frame.

Experimental Setup and Electrical Parameters.

Uniaxial tensile tests were conducted using a Galdabini Sun 5 universal testing machine equipped with a 50 kN load cell and a dedicated software interface for data acquisition. All tests were performed under controlled environmental conditions, with an ambient temperature of $T_r = 23 \pm 2\ °C$ and a relative humidity of $RH = 50 \pm 5\%$. The crosshead speed was set to a constant value of $v = 5\ mm/min$. This velocity was selected as a trade-off to maintain a quasi-static strain rate while keeping the total test duration under 5 minutes, thereby mitigating excessive uncontrolled Joule heating during the electrical tests.

A high-power programmable DC power supply (Itech IT-M3900D) was used to apply pulsed current to specimens during the tensile tests.

The IT9000 software controlled the waveform, which in this work was imposed with a maximum current density $J_{theoretical}$ of $20\ A/mm^2$, calculated as the ratio between the imposed current at the top time and the initial cross-section S_0. Fig. 1 shows the trapezoidal waveform, while Table 1 shows the values for the duration of each stage. The pulsed mode was chosen over continuous current to exploit the athermal effects of electroplasticity while limiting the thermal softening component, consistent with recent literature findings on electropulsing-induced plasticity in metals [17]. Based on the duration of each stage of the pulse current, a frequency of 0.17 Hz was fixed for a total number of pulses derived from the end of the tensile test.

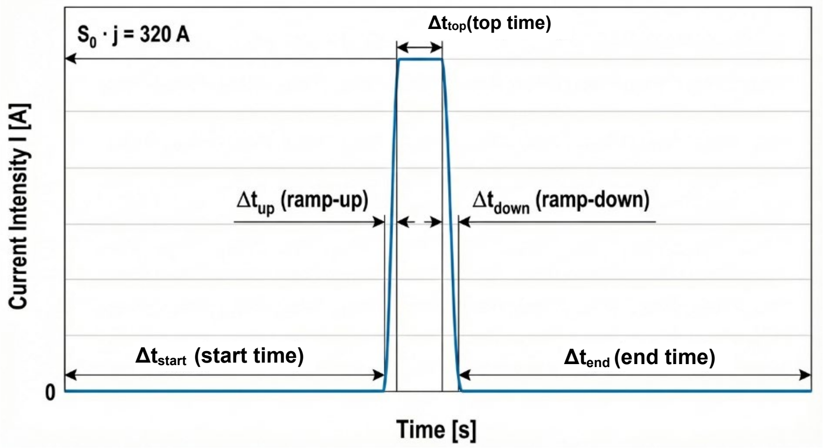

Fig. 1. Schematic representation of the single trapezoidal current pulse waveform applied during the EA tensile tests.

Table 1. Temporal parameters defining the trapezoidal pulse cycle employed in the experimental campaign.

Phase Description	Symbol	Duration [s]
Start time (delay)	Δt_{start}	5.00
Ramp-up time	Δt_{up}	0.03
Peak holding time (Top)	Δt_{top}	0.25
Ramp-down time	Δt_{down}	0.03
End time (delay)	Δt_{end}	0.50
Total pulse period	T	0.31

Most experimental studies reported in the literature present the applied electric current density without accounting for electrical losses, presenting the results considering the theoretical current density and not the effective one. This work aims to fill this gap of knowledge and, to this purpose, the DEWESoft SIRIUS modular data acquisition (DAQ) system, equipped with a DEWESoft DS-CLAMP-150DC current sensor, was employed to measure the actual current flowing through the specimens during the EA tensile test and discuss the results in relation to the effective current density.

Energy Consumption Measurement Framework.

The energy consumption of the universal testing machine was monitored during the tensile test of both samples. To this purpose, a Fluke 435 Series II Power Quality and Energy Analyzer was connected to the power input of the testing machine and the auxiliary equipment. The instrument acquired the instantaneous values of phase voltage, neutral voltage, and ground voltage, as well as the current intensity on both the phase and neutral lines throughout the entire duration of the tests. This setup allowed for the calculation of the specific energy absorption for both the baseline (mechanical work only) and the EA configuration (mechanical work plus electrical energy supplied by the generator), providing the dataset necessary for the comparative energy assessment.

Fig. 2 shows the general overview of the experimental arrangement, showing the universal testing machine interfaced with the high-power programmable DC supply and the energy analyzer (a) and a close-up of the setup during an EA test (b), showing the custom aluminium clamps used for current injection onto the specimen gauge length. The electric current causes visible thermal reddening along the surface of the metal.

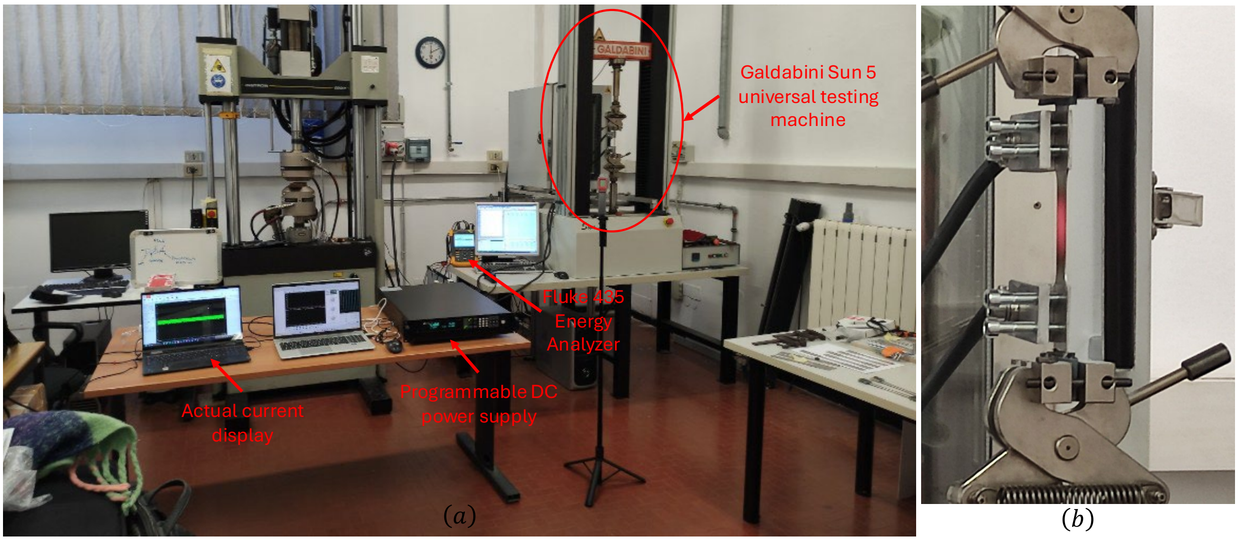

Fig. 2. Experimental setup for Electrically-Assisted (EA) tensile test (a) and detail of the test piece during current passage and consequent temperature increase (b).

Results and Discussions

Mechanical Behaviour and Flow Stress Analysis.

As mentioned in the previous section, two tensile samples were tested: one in a traditional way, as a reference, and another one with the application of a pulsed current. The theoretical current imposed by the current generator is 320 A, thus resulting in a theoretical current density of 20 A/mm^2. The current measurements of the effective current flowing in the specimen during the test, considering the electrical losses, showed an effective current of 290 A, thus resulting in an effective current density of 18 A/mm^2. A total of 35 pulses were applied until the break of the EA test.

Fig. 3 shows the post-fracture view of the samples tested in the reference configuration (a) and with EA (b). The latter highlights the fibreglass-reinforced epoxy resin tabs used for electrical insulation at the grip points. Significant surface oxidation (distinct blue/purple colouring) is evident, particularly in the necking area, providing qualitative evidence of highly localised Joule heating prior to fracture.

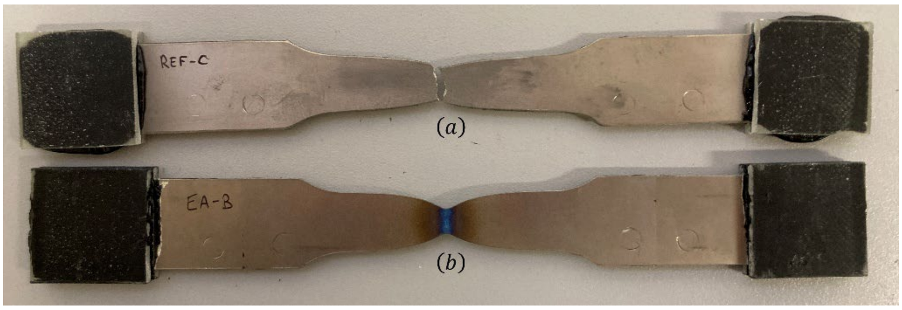

Fig. 3. Post-fracture view of Reference-B and EA-C tested specimens.

The engineering stress-strain curves (Fig. 4) for the reference condition and the electrically-assisted configuration were analysed to quantify the Electroplastic Effect (EPE), while the mechanical properties of the most representative test specimens from the two samples are summarised in Table 2.

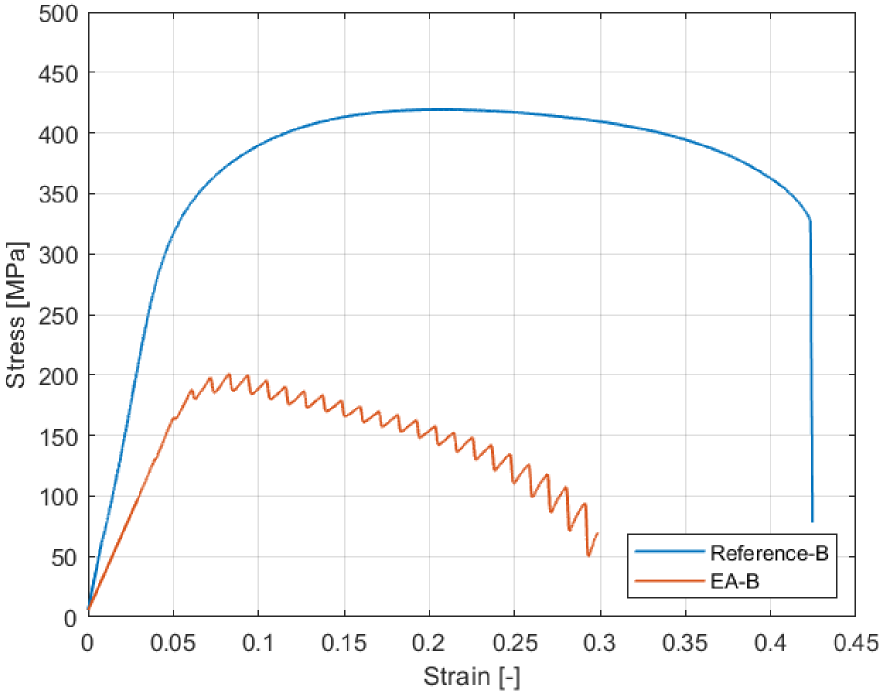

Fig. 4. Stress-Strain curves for Reference-B and EA-B.

Table 2. Summary of mechanical properties for Reference and EA conditions.

Sample ID	Strain @$R_{p0.2}$ [-]	Yield strength $R_{p0.2}$ [MPa]	Strain @R_m [-]	Tensile strength R_m [MPa]	Strain at break [-]
Reference	0.053	326	0.208	419	0.424
EA	0.061	187	0.083	201	0.299
Variation	**+14.4%**	**-42.6%**	**-60.2%**	**-52.0%**	**-29.5%**

The application of an effective pulsed current density of 18 A/mm^2 resulted in a substantial "softening" of the material. As shown in Table 2, the yield strength dropped by approximately 42.6%, while the Ultimate Tensile Strength (UTS) decreased by 52.0%. This behaviour is consistent with the classical theory of electroplasticity described by Conrad [6], where the reduction in flow stress is attributed to the combined action of Joule heating (thermal softening) and the electron wind force aiding dislocation motion.

It is noteworthy that the ratio between Yield Strength and Tensile Strength ($R_{p0.2}/R_m$) increased from 0.77 in the reference state to 0.93 in the EA state. This flattening of the plastic region suggests that the work-hardening capability of the Ti-6Al-4V alloy is significantly inhibited by the electric current. According to Magargee et al. [8], this suppression of strain hardening is typical in Titanium alloys under electric flow, as the rate of dynamic recovery is accelerated by the energy input.

Ductility and Failure Mechanisms.

Contrary to the expectation that EAM enhances formability, the experimental results indicate a 29.5% reduction in elongation to failure for the EA samples compared to the baseline. It is hypothesised that this premature failure is driven by localised Joule heating at the necking region. As the cross-section decreases during necking, the local electrical resistance increases, leading to a spike in current density and temperature [2]. This causes a thermal instability that accelerates failure, overriding the athermal benefits of defect reconfiguration described by Zhao et al. [12].

Comparative Energy Assessment.

The sustainability of the Electrically-Assisted (EA) process was evaluated by comparing the total energy demand of the experimental cell in both reference and EA configurations. The data, summarized in Table 3, account for the electrical energy absorbed by the universal testing machine.

Table 3. Average energy consumption of the testing machine for Reference and EA tests.

Sample ID	Duration [s]	Energy Consumption [Wh]	Energy Consumption [kJ]
Reference	233.7 ± 1.9	1030 ± 7	286.0 ± 2.1
EA	174.7 ± 7.2	307 ± 1	85.1 ± 0.3
Variation	**-25.3%**	**-70.2%**	**-70.2%**

As shown in Table 3, the application of pulsed current resulted in a remarkable 70.2% reduction in mechanical work. This reduction is significant from a machinery perspective: lower forming loads imply reduced tonnage requirements, less elastic deflection of the machine frame, and potentially reduced wear on tooling, extending the service life of the equipment. This reduction is directly linked to the electroplastic softening effect: since the material flow stress is lower, the machine's electric motors perform less mechanical work to maintain the constant crosshead speed of 5 mm/min.

It is important to note that the total energy demand of a universal testing machine includes constant auxiliary loads (control electronics, cooling, sensors). Therefore, the saving on the total machine absorption suggests a much higher percentage of saving on the net mechanical work performed. When scaling this technology to industrial presses, where the forming work represents a larger share of the total energy consumption, the benefits of EA-induced softening would be even more pronounced, leading to significant reductions in the factory's carbon footprint and operational costs.

Conclusion

The present study investigated the electro-mechanical response and the energy efficiency of Ti-6Al-4V titanium alloy under pulsed Electrically-Assisted Manufacturing (EAM) conditions. By integrating mechanical testing with a dual-source energy assessment (machine tool grid absorption and generator pulse energy), the following conclusions can be drawn:

- **Mechanical Performance and Softening:** the application of a theoretical 20 A/mm^2 pulsed current induced a significant reduction in flow stress, with a decrease in Yield Strength and Tensile Strength of approximately 42.6% and 52.0%, respectively. This confirms the effectiveness of the electroplastic effect in reducing the force required for deformation.
- **Ductility and Localized Effects:** a reduction in elongation to failure (-29.5%) was observed in EA specimens. This is attributed to localized Joule heating at the necking region, where the reduced cross-section causes a current density spike, leading to thermal instability and premature fracture.
- **Machine Energy Efficiency:** the analysis of the testing machine's grid absorption revealed a direct sustainability benefit. The EA configuration required 70.2% less electrical energy (approx. 200 kJ saving) compared to the reference cold tests. This proves that the reduction

in material flow stress translates into a measurable decrease in the energy demand of the machine’s drive system.
- **Total Energy Balance:** while the process requires additional electrical input for pulse generation, the low duty cycle (approx. 5.3%) ensures that this consumption remains a small fraction of the total energy balance. The energy saved by the machine tool, combined with the potential for shorter process chains and the elimination of furnace pre-heating, positions EAM as a highly sustainable alternative to conventional hot forming for low-formability alloys.

Future work will focus on optimizing the pulse parameters and the duty cycle to mitigate localized overheating, aiming to maximize ductility without compromising the significant energy savings achieved.

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