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On the Effect of Electric-Pulsed Treatments on the Formability and Sustainability of Titanium Alloy Reshaping

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Abstract. Electroplasticity in sheet metal forming is a relatively recent method that involves applying an electric current to metal sheets during or before the forming process. Existing research on Electro-Assisted (EA) forming primarily focused on material characterization; few studies have investigated the effect of electropulsing on loads, power, and energy consumption during sheet metal forming, and no studies have explored the reshaping of previously formed titanium sheets after the Electro-pulsed treatment (EPT). This research aims to bridge some of these gaps of knowledge by applying two different electropulsing treatments, varying in current density, to square Ti6Al4V specimens prior to shaping and reshaping. performed using dies and counter dies having different geometries. Load, power, and energy consumption data were measured to assess the benefits of EPT compared to an untreated specimen serving as a reference. The findings suggest that EPT can significantly reduce the energy consumption and forces required for both shaping and reshaping of titanium components, extending their useful life and reducing the need for remelting. The study highlights the potential of EPT as a sustainable solution for reducing the environmental impact of titanium sheet disposal and recycling, improving material efficiency, and optimizing industrial forming processes.

Introduction

In the pursuit of net-zero emissions by 2050, a growing focus is being placed on the reshaping and forming of metal alloys like titanium, which is widely used in aerospace, automotive, medical, and industrial sectors due to its exceptional properties, including a high strength-to-weight ratio, corrosion resistance, and biocompatibility. Among the various objectives is achieving carbon neutrality by 2050, with a key focus on reducing the environmental impact of the end-of-life of components made from stamped sheets. This goal emphasizes the need for sustainable practices throughout the lifecycle of these materials, from production to disposal and recycling. Reshaping is increasingly seen as a method to reduce the environmental impact at the end of life of these components, offering a way to extend their usefulness and reduce waste [1].

From a sustainability perspective, recycling and forging titanium are energy-intensive processes, although they are more environmentally friendly than producing virgin titanium. The traditional recycling method for titanium involves melting scrap material and casting it into ingots or reusable forms. Due to titanium's high melting point of 1668°C, this process requires substantial energy, approximately 361 megajoules (MJ) per kilogram. While conventional recycling produces high-purity recycled titanium, it is energy-intensive and has high environmental costs [2][3].

Moreover, traditional sheet metal forming methods as well as heat treatment performed by using traditional furnaces, are very energy-intensive, thus highlighting the need for more sustainable, energy-efficient manufacturing practices [4][5][6]. As a result, there is an increasing demand to reevaluate and redesign conventional processes to reduce their environmental impact [7].

Electroplasticity in sheet metal forming is a relatively recent method that involves applying an electric current to metal sheets during or before the forming process to reduce the yield strength and make them easier to shape with lower loads [8]. This process enhances material formability, reducing energy consumption, forces required, and tool wear. It allows for easier deformation at lower temperatures, improving the efficiency and quality of processes like stamping, deep drawing, and bending [9]. Thus, electropulsing has been demonstrated to alter the grain structure, reduce internal stresses, and facilitate a more uniform material response during forming processes, offering a potential alternative to traditional pre-treatment methods [10] [8].

Despite existing studies in the literature on Electro-Assisted (EA) tensile tests, which primarily focus on material characterization, there is a lack of research investigating the effect of electropulsing before sheet metal forming of Ti6Al4V on loads, power, and energy consumption. Additionally, no studies have explored the reshaping of sheets previously formed after undergoing Electro-Pulsed Treatment (EPT). This highlights the need for further investigation into the potential benefits of EPT in these processes.

This study aims to address existing gaps in understanding the effects of EPT on the shaping and reshaping of Ti6Al4V alloy. Specifically, two different EPTs, differing in current density, were applied to square specimens (0.6 mm thick) prior to shaping and subsequent reshaping. To evaluate the impact of EPT on both processes, dies and counter-dies with various geometries were used, ensuring that the study focused on the effects of EPT independently of the final shape. Loads, power, and energy consumption were measured during the forming process to quantitatively assess the benefits of EPT. A specimen was also formed through shaping and reshaping without treatment, serving as a reference.

The main objective of this research is to explore the impact of EPT on material performance during stamping, providing valuable insights into how such treatments can optimize industrial forming processes. The main findings of the work demonstrate that EPT can serve as a solution to the end-of-life of titanium sheets, improving their environmental impact by extending their useful life, as well as that of the tools, for the production of other components, rather than resorting to their end-of-life after initial use or remelting. This approach aims to enhance sustainability by enabling the reshaping of titanium components, thus reducing material waste and energy consumption associated with their disposal and recycling.

Materials and Methods

In this work, the effectiveness of the EPT process on the formability of titanium sheets was tested. To this purpose, the response in terms of load, power, and energy consumption of stamping twice, using different shape dies and counter dies, was investigated and discussed.

Fig. 1 illustrates the experimental setup adopted to perform the EPT (Step I) and the consequent stamping process (Step II), either including shaping and subsequent reshaping of sheets. In particular, firstly the EPT was performed on two 50×50 mm^2 cold-rolled Ti6Al4V sheets (Fig. 1c), having a thickness of 0.6 mm, by means of the current generator Itech IT-M3900D (Fig. 1a). The IT9000 software was used to set the operational parameters of the generator to perform the EPTs of this work: for all of them, the pulsed mode was chosen over continuous current as the pulsed current is more effective than continuous current in enhancing formability, according to recent literature findings on electropulsing-induced plasticity in metals [11]. Aluminum clamps (Fig. 1b), machined from an AA2024 block, were used to hold the specimens during the EPT. Most experimental studies reported in the literature present the applied electric current density without accounting for losses. To address this limitation, a DEWESoft DS-CLAMP-150DC current sensor (Fig. 1d), connected to a DEWESoft SIRIUS modular data acquisition (DAQ) system, was employed to consider the effective current flowing through the specimens during the EPT in the analysis of the results. Temperature was also monitored during all the EPTs over time by means of an Optris IR infrared thermal camera.

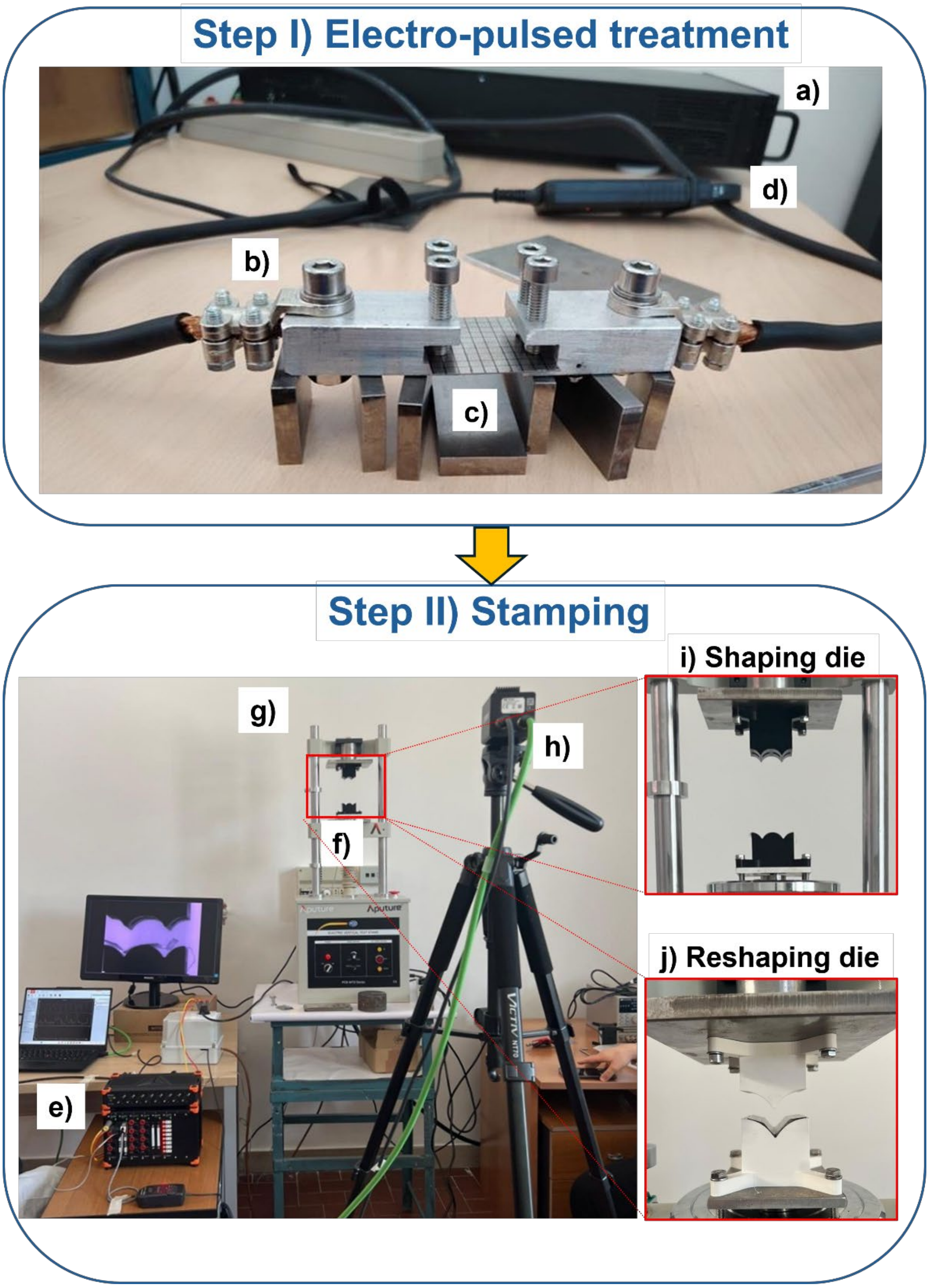

Fig. 1. Experimental setup adopted to perform the Electro-pulsed treatment (EPT) and the consequent double stamping process (shaping and reshaping)

Table 1 contains the main inputs of the process parameters imposed by the current generator to perform two EPTs, indicated as EPT1 and EPT2, differing in the theoretical current intensity, I_{theor}, and the theoretical current density, J_{theor}. The theoretical current density is given as follows:

$$J_{theoretical} = I_{theoretical}/S \qquad (1)$$

where S is the cross-section of the specimens, which is equal to 30 mm^2.

A specimen indicated as "base" was not treated by the EPT but formed by stamping as a reference for the EPT samples. For each test of the experimental plan (Table 1), three samples were treated and processed in the same way, ensuring repeatability and consistency of the results.

Table 1. Experimental plan of the EPT

Test	S (mm^2)	I_{theor} (A)	J_{theor} (A/mm^2)	N	f (Hz)	ES=SS (s)	TT (s)
Base	30	-	-	-	-	-	-
EPT1	30	300	10	40	0.18	0.03	0.5
EPT2	30	600	20	40	0.18	0.03	0.5

As mentioned above, a pulsed current was applied to the EPT samples, selecting a total of 40 pulses, indicated in Table 1 as N. Fig. 2 is a schematic representation of the applied pulse, showing either the theoretical and effective current flowing through the specimens. It can also be observed that each pulse consists of the following main time stages:

- Start time (SS): the ramp-up period to reach the maximum current value.
- Total time (TT): the duration for which the maximum current is maintained.
- End slew (ES): the ramp-down period from the maximum current value to zero.

In this work, the pulse frequency f was fixed at 0.18 Hz for both the EPTs.

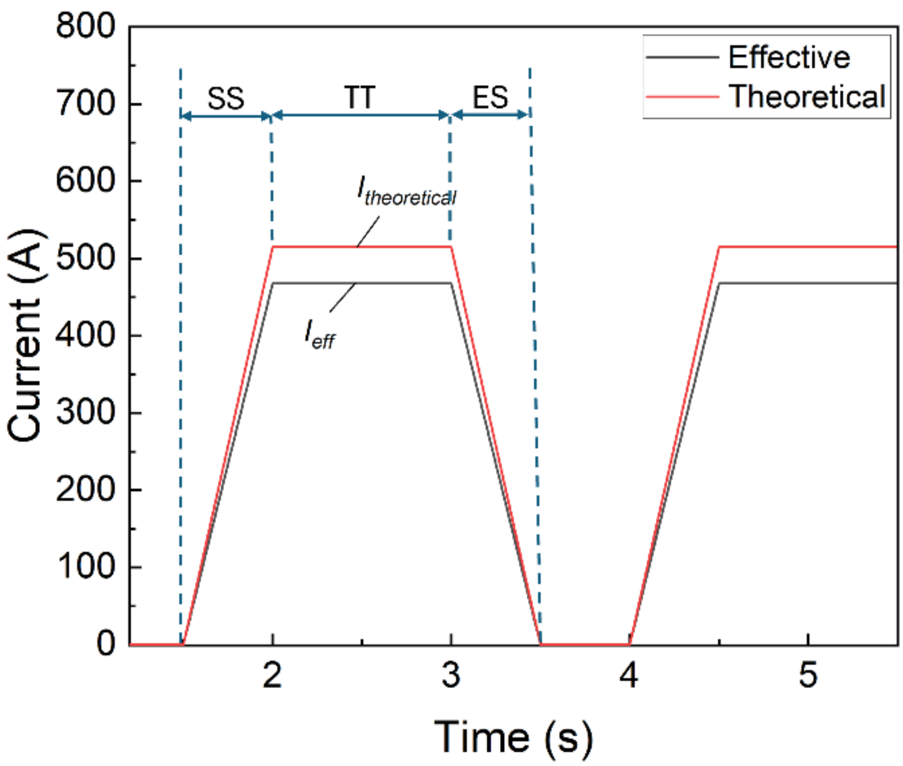

Fig. 2. Schematization of the time stages of each electric pulse

At the bottom of Fig. 1, the setup adopted to perform the stamping of the titanium sheets, either those treated by EPT and the reference one – the base material – is presented. Two different dies and counter dies, having different shapes, have been printed in ABS by Fused Filament Fabrication (FFF) and used during the stamping to test the response in terms of loads, power and energy consumption in imposing the first shape to the material, indicated as shaping (Fig. 1i), and the second one, indicated as reshaping (Fig. 1j). The main dimensions of both the shaping and reshaping dies are the following:

- The total width and depth of each die are 50.00 mm.
- For the shaping die, the central feature measures 25.00 mm, with a height of 42.79 mm, including an additional top section of 10.00 mm. The radii and specific contours within the die are designed to optimize the shaping process.

- The reshaping die has a central feature of 35.57 mm in height, with an overall height of 49.50 mm and an additional top section of 10.00 mm. The radii at the bottom of the reshaping die are 27.87 mm, facilitating the reshaping process. These precise dimensions are crucial for ensuring the proper fit and function of the dies in the electro-assisted forming and reshaping processes.

The PCE Instruments PCE-MTS500 stand (Fig. 1g) was adopted to perform the stamping process, with the die and counter-die securely fixed in place. The Futek 400 Button Load Cell was used, placed under the lower die in pre-compression (Fig. 1f), to measure the force during the stamping process. Moreover, the high-speed DS CAM 1100 M (Fig. 1h) was utilized to capture frame-by-frame images throughout the stamping process, which were then correlated with the force measurements for a comprehensive analysis of the results. Finally, the power of either shaping and reshaping of each sample was measured by means of the DEWESoft SIRIUS modular data acquisition (DAQ) system (Fig. 1e), equipped with a current sensor and two tension cables, which were connected to the monophase with neutral electrical system of the stand.

A sampling period Δt equal to $0.02\ s$ was selected and, based on the active power , p_{active}, measurements, the total energy consumption was calculated as the sum of energy consumption for shaping, E_{shap}, and that for reshaping, E_{reshap}, the same titanium sheet, as follows:

$$E_{TOT} = E_{shap} + E_{reshap} = \int_0^{T_{shaping}} p_{active}(t) \cdot dt + \int_0^{T_{reshaping}} p_{active}(t) \cdot dt \approx \sum_{i=0.02}^{T_{shaping}} P_{active,i} \cdot \Delta t + \sum_{i=0.02}^{T_{reshaping}} P_{active,i} \cdot \Delta t \quad (2)$$

$T_{shaping}$ and $T_{reshaping}$ are the duration of the shaping and reshaping processes performed at the same speed, fixed at 1.8 mm/s. To standardize all tests, the stamping process was defined as starting when the counter-die first contacts the sheet, with the sheet already positioned on the die.

Results and Discussion

In this section, the main results obtained by the EPT and the consequent stamping process are presented and discussed. As mentioned in the previous section, during the EPT, the current effectively flowing into the specimens was measured by using a current sensor connected to the current generator cables connected to the clamps holding the samples. Table 2 contains the effective current intensity I_{eff} and the corresponding current density J_{eff} applied to the specimens.

In this regard, a current loss of approximately 8% was observed when imposing both a theoretical current intensity of 300 A and 600 A. As a result, a 10% reduction in the effective current density was identified.

Table 2. Main results of the EPT monitoring

Test	S **(mm²)**	I_{theor} **(A)**	J_{theor} **(A/mm²)**	I_{eff} **(A)**	J_{eff} **(A/mm²)**
EPT1	30	300	10	275	9
EPT2	30	600	20	550	18

As mentioned in the previous section, the temperature was monitored during the EPTs and then analyzed by means of the Optis PIX Connect software. The maximum temperature reached during the EPT1 was around 100°C, while the maximum temperature reached during the EPT2 was around 250 °C. Fig. 3 and Fig. 4 show the load trend over time during the shaping and reshaping, respectively, of all the investigated sheets.

The base material - stamped without any prior EPT - showed a steadily increasing load over time during both the shaping and reshaping processes. This trend indicates that the material experienced significant resistance to deformation, requiring progressively higher forces to continue deforming as the process progresses. The force increased relatively sharply, particularly in the later stages of both the shaping and reshaping processes, reflecting the greater resistance of the material to plastic deformation without the assistance of pulsed current prior to the forming process.

For EPT1 (J_{eff}=9 A/mm^2), the trend showed a moderate reduction in force compared to the base material. The load increased more gradually over time, indicating that the material is more easily deformable due to the electroplastic effect at this lower current density. Thus, the load required to achieve deformation was lower than that of the base material, and the rate of increase in force slowed down. This suggests that the pulsed current reduced the material's flow stress and improved formability, although to a lesser degree than in EPT2.

The EPT2 (J_{eff}=18 A/mm^2) showed the most pronounced reduction in force among the three conditions. The load curve for EPT2 rose more slowly compared to both the base material and EPT1, indicating the most significant reduction in material resistance due to the higher current density. The force required to continue deforming the material is much lower throughout the process, with a notably slower increase in load. These findings suggest that the higher current density provides a stronger electroplastic effect, making the material more easily deformable and requiring less force to achieve the desired shape.

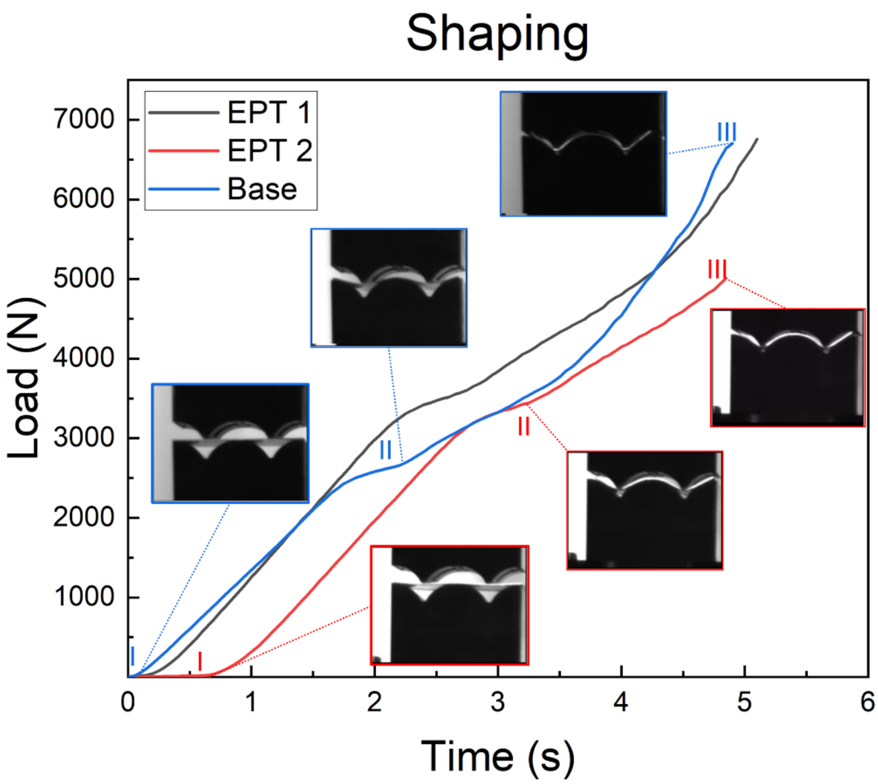

Fig. 3. Load over time during the shaping of titanium sheets

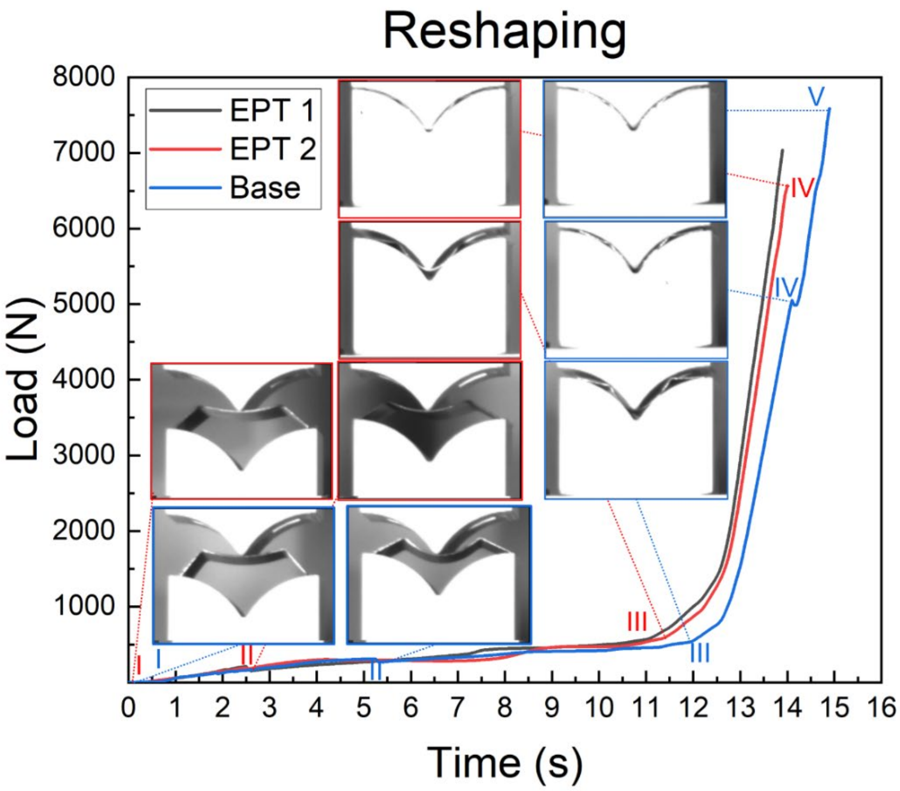

Fig. 4. Load over time during the reshaping of titanium sheets

As mentioned in the previous section, a high-speed camera was used during either shaping and reshaping of all the investigated sheets. The most representative frames, corresponding to specific stage of material deformation, are highlighted in Fig. 3 and Fig. 4. These stages are labeled with numbers and correspond to specific moments in the load vs. time curves.

In particular, for the shaping process (Fig. 3), the following three points were labeled:

- I; at this stage, the base material (blue curve) required a higher load to start deforming, with the camera showing localized resistance to deformation. For EPT1 (J_{eff}=9 A/mm^2), the load resulted in lower values, indicating reduced resistance, and the camera shows more uniform deformation. EPT2 (J_{eff}=18 A/mm^2) required the lowest load and displayed the most uniform and smooth deformation, reflecting the most effective reduction in resistance due to the higher current density.
- II; as deformation progresses, the base material required increasingly higher loads, with the camera showing localized resistance. In EPT1, the load increases more gradually, with the camera revealing more uniform deformation and reduced localized resistance due to the electroplastic effect. EPT2 required the lowest load, with a slower increase in force and more even deformation, as the higher current density facilitates smoother plastic flow with minimal resistance.
- III; at this stage, the base material required generally the highest load, with the camera showing significant localized plasticity as it reached its yield point. EPT1 required less force, with the camera showing more uniform deformation and fewer areas of strain concentration. EPT2 showed the lowest load and the most uniform deformation, with minimal strain localization, indicating that the higher current density facilitates substantial deformation with minimal force.

After the shaping, the sheets were reshaped using another couple of FFFed die-counter dies to perform the reshaping process. Four labeled points were considered for the EPT samples, and five for the base material (Fig. 4). In particular:

- I; at this stage, the base material required significantly higher force, with the camera showing localized strain, indicating resistance to reshaping. For EPT1, the force is lower, and the camera shows more uniform deformation with reduced strain, suggesting the electroplastic effect is easing reshaping. EPT2 required the lowest force, with the camera showing the most uniform reshaping and minimal resistance, reflecting the most effective reduction in material resistance.
- II; as reshaping continues, the base material required a significantly higher force, with localized strain visible in the camera frame. EPT1 showed a more gradual increase in load, with the material deforming more evenly and reduced strain localization. EPT2 required the least force, with the camera showing uniform reshaping and no strain localization, indicating that the higher current density greatly reduces material resistance during reshaping.
- III; the base material required significantly higher forces to continue reshaping, with localized strain visible in the camera frames, indicating resistance to deformation. EPT1 requiref less force with more uniform deformation, showing reduced strain localization due to the electroplastic effect. EPT2 required the lowest force, with uniform reshaping and minimal resistance, reflecting the most effective reduction in material resistance due to the higher current density.
- IV; this stage is the final one for the EPT samples, while the base material reached its maximum deformation and highest force.
- V; this stage is the final one for the base material, and it can be observed that the material required more force to maintain its shape, with visible strain localization.

Table 3 contains the main results of the load and power monitoring during the stamping process. In particular, $F_{max, shap}$ and $F_{max, reshap}$ are the maximum forces occurring during shaping and reshaping, respectively, as a result of the load monitoring performed by using the button load cell described in the previous section. Similarly, $P_{max, shap}$, and $P_{max, reshap}$ are the maximum power measured during shaping and reshaping, respectively, as a result of the power monitoring.

E_{tot} is the total energy consumption calculated as the sum of energy for shaping and for reshaping, as indicated by Eq. 2. For all these response variables, the standard deviation was calculated, as shown in Table 3. Fig. 5 depicts the main outputs of the load measurements (Fig. 5a) and the energy consumption calculations (Fig. 5b).

Table 3. Main results of the monitoring of the stamping process

Test	$F_{max, shap}$ (N)	$F_{max, shap}$, dev std	$F_{max, reshap}$ (N)	$F_{max, reshap}$, dev std	$P_{max, shap}$ (W)	$P_{max, shap}$, dev std	$P_{max, reshap}$ (W)	$P_{max, reshap}$, dev std	E_{shap} (J)	E_{shap}, dev std	E_{reshap} (J)	E_{reshap}, dev std	E_{tot} (J)	E_{tot}, dev std
Base	6756	285	7581	256	333	8	405	24	967	30	1540	47	2507	56
EPT1	6703	223	7037	246	255	19	342	32	643	50	1340	52	1983	72
EPT2	5009	200	6570	231	256	15	307	29	656	34	1279	54	1935	64

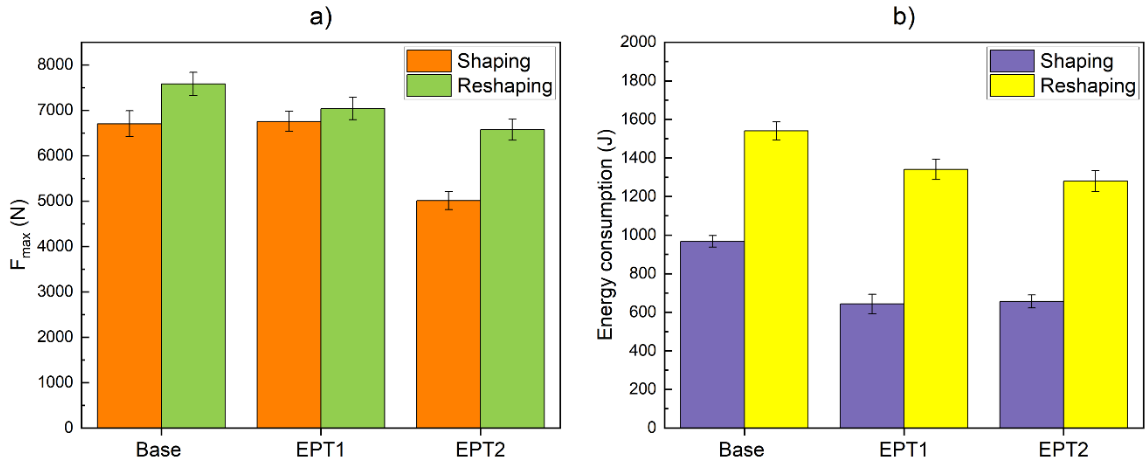

Fig. 5. Main results of the a) load measurements and b) energy consumption calculation of shaping and reshaping of titanium sheets investigated in this work

Concerning the force analysis, the base material required the highest final force at both the shaping and reshaping stages, indicating significant resistance to deformation throughout the entire process. EPT2 (J_{eff}=18 A/mm^2) showed the largest decrease in maximum force (-25.86 %) in the shaping phase, and a significant decrease in the reshaping phase as well (-13.34%), indicating that higher current density leads to the greatest reduction in material resistance, making reshaping easier and requiring less force at the final stage of both shaping and reshaping processes.

Concerning the power measurement, the base material required the highest power to maintain the deformation throughout the process, with noticeable decreases in power in the EPT conditions. In EPT1 and EPT2, both the shaping and reshaping phases showed significant reductions in power compared to the base material (about 24% less).

Regarding the energy consumption calculations, in both shaping and reshaping phases, EPT1 and EPT2 required less energy than the base material. In particular, EPT1 showed a 33% reduction in energy consumption for shaping, while EPT2 showed a 32% reduction, reflecting a more efficient deformation. These findings indicate that the short EPTs help to reduce the energy required to perform the subsequent forming process, likely due to lower resistance to deformation, even without achieving high temperatures over extended periods, as supported by recent literature, as confirmed by the recent literature [10].

During reshaping, EPT1 and EPT2 resulted in 12.9% and 16.9% reductions in energy consumption, respectively, confirming that higher current densities applied during the EPT significantly improve energy efficiency of the consequent forming process. The total energy consumption required for the entire process, considering shaping and reshaping, is also lower in both EPT1 and EPT2, with EPT2 using the least energy overall, confirming that higher current densities lead to more energy-efficient stamping processes.

Moreover, the standard deviations associated with both maximum forces, maximum power and total energy consumption (Table 3) are consistently limited across all investigated conditions, indicating good repeatability and stability of the experimental procedure. The relative scatter remains low compared to the corresponding mean values, and no significant increase in variability is observed between shaping and reshaping stages. Moreover, the differences measured among Base, EPT1 and EPT2 conditions are generally larger than the respective standard deviations, suggesting that the observed trends are representative of actual process and material effects rather than experimental noise.

Finally, it is paramount to underline that, for the sake of brevity, only the frames of one EPT specimen and the base material specimen have been presented for both shaping and reshaping processes (Fig. 3 and Fig. 4). This was possible because the curves for the specimens subjected to EPT followed the same trend, though with different force values due to the varying current densities, and were distinct from the base material. Additionally, it is important to highlight that the different geometry of the die and counter die used for reshaping likely influenced the load curve's shape, as it had to account for the initial sheet position, which was already formed and not flat as in the shaping process.

A limitation of this study is the use of small, simple geometries (50×50 mm²), which may limit the direct applicability of the results to larger, more complex geometries typically encountered in industrial settings. While the choice of small samples was necessary to control experimental variables and focus on the fundamental effects of EPT on Ti6Al4V sheets, it is important to recognize that real-world applications often involve larger, more intricate geometries. Future work will seek to address this limitation by extending the investigations to larger-scale specimens, which will more accurately represent industrial conditions. Additionally, simulations and modeling studies will be undertaken to predict the performance of EPT under a broader range of geometries and operational conditions. These efforts will help bridge the gap between fundamental research and practical industrial applications, improving the transferability of the findings from this work, particularly in alignment with current industrial priorities focused on energy efficiency and the sustainable reuse of high-value alloys.

Conclusions

This work investigates the effects of electropulsing on cold-rolled Ti6Al4V specimens performed prior to the stamping process, either shaping and reshaping, on load response, power consumption, and energy consumption, which were experimentally monitored. The main conclusions that can be drawn are the following:

- The base material showed the highest load values and a steep increase in force, indicating significant resistance to deformation compared to the material electrically treated by EPT prior the stamping process.
- Selecting a higher current density during the EPT, the lowest load values and the slowest increase in force were reached during either shaping and reshaping, indicating the most significant reduction in resistance, improving material formability the most.
- Applying a higher current density during the EPT resulted in the most significant energy savings and lower force requirements, making it beneficial for more efficient forming processes.

Thus, based on the findings of this work, using EPT with varying current densities can optimize the subsequent forming processes, obtaining improvements in material formability and energy efficiency for both shaping and reshaping stages. These results contribute to ongoing research focused on reducing environmental impact, as they suggest the potential for reshaping materials that have already been formed into different shapes. This approach could play a key role in minimizing the environmental footprint of components made from stamped sheets at the end of their lifecycle, aligning with goals for reusability and remanufacturing in the context of a 2050 sustainability vision.

Future developments will focus on comparative cradle-to-grave Life Cycle Assessment (LCA) of the forming of titanium sheets, comparing the scenario including the remelting of titanium to obtain another product having a different final shape, and the other scenario where this objective has been reached as shown in this work, without remelting of titanium but using the EPT prior or hopefully during the forming process.

On the other hand, the results obtained in this work suggest the relevance of continuing to do research on the electroplasticity, including either mechanical characterization and sustainability analysis, to better highlight its potentialities in minimizing the environmental impact in comparison with traditional long-duration and energy-intensive furnace treatments. In this regard, future developments should focus on studying the effects of a wide range of top time, frequency, and current density on both forming, shaping, and reshaping processes to fully understand and optimize the potential of electropulsing in traditional industrial manufacturing.

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