

Environmental Impact Assessment of Ti6Al4V Chips Recycling Using Shear Assisted Processing and Extrusion (ShAPE)

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Abstract. Titanium alloys combine strength, low weight, and corrosion resistance, making them vital in high-performance industries; yet machining generates substantial chips that is difficult to recycle via conventional remelting due to contamination and high energy requirements, reducing material sustainability. Solid-state recycling methods, like Shear Assisted Processing and Extrusion (ShAPE), provide a promising alternative by consolidating chips below the melting point while preserving alloy chemistry. This study assesses the environmental performance of ShAPE across a system boundary spanning degreasing through consolidation and extrusion. Impacts were quantified using Cumulative Energy Demand (CED), Global Warming Potential, Environmental Footprint, Average Dissipation Rate (ADR), and Lost Potential Value (LPV), with ADR and LPV applied for the first time to solid-state recycling of scrap from discrete manufacturing. Scenario analyses addressed variations in torque, argon consumption, and electricity mix. Energy demand and CO₂-eq for the ShAPE process were estimated at 279.51-567.75 MJ and 17.22-32.35 kg per kg of wire, respectively, with sensitivity analysis showing that variations in torque constitute the dominant determinant of these environmental outcomes. While energy demand is comparable to, or moderately lower than, that of traditional wire fabrication only under low- and baseline-torque conditions, ShAPE substantially reduces the resource dissipation and lost material values, with its overall environmental impacts further decreasing by 45.45% when powered with greener electricity. These results highlight ShAPE as a viable route for circular titanium production, preserving material value & reducing dependence on primary extraction.

Introduction

Titanium and its alloys, particularly Ti6Al4V, play a central role in high-performance engineering sectors due to their exceptional strength-to-weight ratio, corrosion resistance, and biocompatibility. These properties make the alloy indispensable in aerospace structures, medical implants, and energy applications, where material performance directly influences system efficiency and safety [1], [2]. However, the strategic importance of Ti6Al4V is accompanied by a substantial environmental burden. Primary titanium production remains one of the most energy-intensive and carbon-intensive metallurgical processes in industrial use today, largely because it relies on the multistage Kroll process, high-temperature chlorination, and extensive vacuum metallurgy [3]. As global demand for titanium continues to rise, driven by lightweighting policies, expansion of aerospace manufacturing, and increasing adoption of additively manufactured components, the pressure on titanium supply chains and associated environmental impacts intensify accordingly. These trends highlight the urgency of improving circularity and developing efficient recycling strategies capable of reducing reliance on primary titanium while maintaining the alloy's stringent performance requirements. Machining operations used to fabricate Ti6Al4V components generate substantial quantities of chips, often representing 50-90% of the original billet mass depending on part geometry and manufacturing route [4]. Despite their high intrinsic material value, these chips constitute a challenging scrap stream due to their heterogeneous morphology, high surface-area-to-volume ratio, and susceptibility to oxidation and contamination during machining and handling. Conventional recycling practices for titanium, primarily based on remelting technologies such as vacuum induction melting and vacuum

arc remelting, are poorly suited to this form of scrap. Fine chips exhibit elevated reactivity at high temperatures, leading to burning losses, increased formation of interstitial contaminants, and compromised melt quality. As a result, chips are commonly downgraded to lower-grade feedstocks or blended with clean bulk scrap to dilute impurities, reducing their overall economic and environmental utility [5]. Moreover, remelting routes require substantial thermal energy input and complex vacuum processing to ensure alloy integrity, further diminishing the sustainability benefits typically associated with recycling. These limitations underscore the need for alternative recycling pathways tailored specifically to the traits and constraints of machining chips. In recent years, solid-state recycling technologies have emerged as promising alternatives to conventional remelting for the valorization of machining chips. These processes consolidate metallic scrap below the melting point, hence mitigating oxidation-driven losses and preserving valuable alloy chemistry. Unlike melt-based processes, solid-state methods do not remove pre-existing oxides or surface contaminants. The chemical composition of the incoming scrap therefore plays a critical role in determining the feasibility and final quality of the recycled product. In practice, this necessitates careful selection or segregation of scrap to ensure that oxygen and other interstitial elements remain within specification limits required by the target application. Approaches such as hot pressing, powder metallurgy, and severe plastic deformation have demonstrated the potential to convert discontinuous chips feedstocks into fully dense, structurally sound products [6], [7]. Among the emerging techniques, Shear Assisted Processing and Extrusion (ShAPE), developed at the Pacific Northwest National Laboratory (PNNL), offers a promising route for the conversion of Ti6Al4V machining chips into wire feedstock, which can subsequently be used in downstream processes such as wire-based additive manufacturing [8].

Although recent advances have demonstrated the technical feasibility of solid-state consolidation techniques, their environmental burden remains largely unexplored. The existing research on ShAPE, for instance, has predominantly focused on process mechanics, microstructural evolution, and mechanical performance. Comparable attention has not been given to quantifying the energy requirements, emissions, and resource savings associated with this type of melt-free recycling routes. Life cycle assessment (LCA) studies on titanium recycling have historically emphasized conventional remelting pathways, with limited consideration of chip-specific valorization strategies or emerging solid-state techniques. As a result, there is little evidence-based understanding of how processes like ShAPE perform in relation to established recycling routes, nor of the conditions under which they offer environmental advantages. This gap in the literature hinders informed decision-making regarding the integration of solid-state recycling technologies into titanium supply chains and limits the potential for data-driven evaluation of their role in circular material strategies.

The present study aims to address the knowledge gap in the environmental evaluation of solid-state recycling of Ti6Al4V machining chips via the ShAPE process developed at PNNL, USA. The study further incorporates a comparative assessment with conventional remelting-based recycling routes, allowing quantification of the relative environmental performance of the solid-state approach. By explicitly linking process characteristics, scrap selection, and operational parameters to environmental outcomes, this work provides a systematic and evidence-based evaluation of chip-based valorization strategies, offering insights into the sustainability potential and process design considerations for emerging solid-state recycling technologies in titanium supply chains.

Materials and Methods

The environmental performance of Ti6Al4V chips recycling via the ShAPE process was evaluated in accordance with ISO 14040/44 standards. The LCA was performed using the SimaPro v10.1 software environment, and background data were sourced from the Ecoinvent v3.9 database (cut-off system model). All foreground processes were modelled using primary experimental data from this study. The goal of the study was to quantify energy consumption, material use, and environmental impact associated with converting machining chips into wire feedstock, and to compare the performance of the ShAPE process with conventional remelting-based recycling routes. The functional unit was defined as 1 kg of consolidated Ti6Al4V wire, providing a consistent basis for comparison across recycling pathways, with the system boundary encompassing washing, drying,

and consolidation/extrusion in the ShAPE process, as illustrated in Figure 1. Sorting of chips was not considered, based on the assumption that chips selection procedures are equivalent to those applied in traditional recycling. In the current industrial practice (Reference), titanium chip are briquetted and incorporated in limited proportions into a blend with titanium sponge and master alloys. This feed is assembled into a mechanically stable consumable electrode by welding the sponge pieces under argon shielding, with chips briquettes embedded within the structure. The electrode is then remelted in vacuum arc remelting to produce an ingot, which is subsequently processed via conventional thermomechanical steps into wire. A broad range of LCA methods was applied to capture the environmental performance of the ShAPE process from multiple perspectives, including the Environmental Footprint 3.1, Cumulative Energy Demand (CED), IPCC Global Warming Potential (GWP, 20-year horizon), and Mineral Resource Dissipation (MRD). To the best of the authors' knowledge, MRD has not previously been applied to any solid-state recycling techniques, providing an additional perspective on resource use in titanium scrap valorization. Due to the lack of publicly available industrial-scale life cycle inventory (LCI) data, the analysis relies on laboratory-scale process parameters and operational conditions reported by the process developers in literature [8], [9], which are used to estimate energy consumption, material inputs, and waste generation associated with chips consolidation and extrusion, as detailed in the following section.

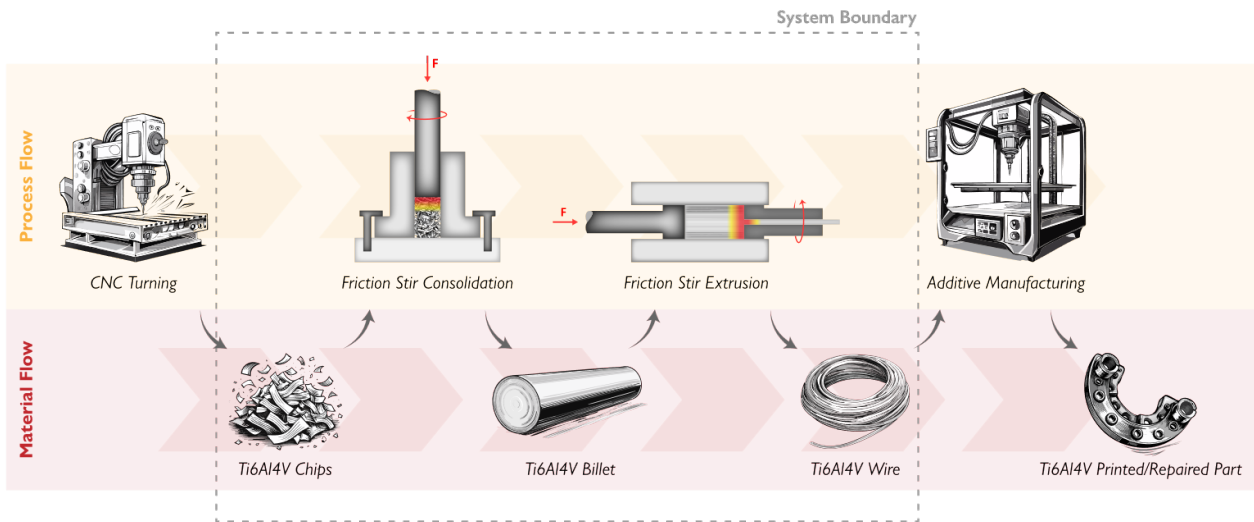


Fig. 1. Material and process flow of the ShAPE solid-state recycling route.

Analytical basis for Specific Energy Consumption (SEC) estimation

The Specific Energy Consumption (SEC) for the lab scale Friction Stir Extrusion (FSE) was determined through an empirical analysis of the total electrical power input relative to the mass flow rate (\dot{m}) using the process parameters reported in [8]. The total specific energy consumption, SEC_{total} , is defined by the energy balance that includes the specific mechanical energy input (SEC_{ME}), the equipment's electrical efficiency (η_{eq}), and the auxiliary power specific consumption (SEC_{aux}). Using the billet diameter ($D_{billet} = 0.019$ m), ram velocity ($V_{ram} = 0.02$ m/min $\approx 3.333 \times 10^{-4}$ m/s), and the density of Ti6Al4V, the billet cross-sectional area ($A_{billet} \approx 2.835 \times 10^{-4}$ m²) allowed for the calculation:

$$\dot{m} = A_{billet} \cdot V_{ram} \cdot \rho \approx 4.19 \times 10^{-4} \text{ kg/s} \quad (1)$$

The total mechanical power input (P_{total}) delivered to the material is the sum of the rotational power (P_{torque}) and the axial thrust power (P_{ram}). The axial power, $P_{ram} = F_{ram} \cdot V_{ram} = 90 \times 10^3$ N $\cdot 3.333 \times 10^{-4}$ m/s ≈ 30 W, was calculated but noted as negligible compared to the rotational power. The rotational power, $P_{torque} = M \cdot \omega$, utilizes the tool's angular velocity ($\omega = 2\pi N/60$, with $N = 236$ RPM, yielding $\omega \approx 24.71$ rad/s). It is worth mentioning that the experimental torque (M) was unavailable and was therefore estimated to define a robust sensitivity range reflecting uncertainty in the effective

friction coefficient. Upper and lower bounds of 400 Nm and 100 Nm, with a baseline of 200Nm, were selected as reasonable limits based on values in the literature for friction-based processing [9],[10].

$$SEC_{ME} = \frac{P_{total}}{\dot{m}} \quad (2)$$

The lower bound for the SEC_{ME} was calculated to be 5.90 MJ/kg, derived from the minimum estimated total mechanical power input of $P_{total, low} = 2.47$ kW. Conversely, the upper bound for the SEC_{SEM} was determined by the maximum estimated power input, $P_{total, high} = 9.91$ kW, resulting in a value of 23.68 MJ/kg. The SEC_{total} integrates the SEC_{ME} range with the uncertainty in η_{eq} and SEC_{aux} . The SEC_{aux} accounts for the constant power draw of the lab setup's ancillary systems ($P_{aux} \in [550, 1250]$ W), and is calculated as $SEC_{aux} = P_{aux} / \dot{m}$, yielding a range of 1.31 to 2.99 MJ/kg.

$$SEC_{total} = \left(\frac{SEC_{ME}}{\eta_{eq}} \right) + SEC_{aux} \quad (3)$$

The sensitivity analysis provided the bounding SEC_{total} values: 8.26 MJ/kg (using $SEC_{ME, low}$, $\eta_{eq, high} = 0.85$, and $SEC_{aux, low}$) to 34.6 MJ/kg ($SEC_{ME, high}$, $\eta_{eq, low} = 0.75$, and $SEC_{aux, high}$). To provide a thermodynamic context, the Specific Energy Retained ($SEC_{retained}$) in the material was quantified as the minimum theoretical energy required to heat the Ti6Al4V sample from ambient temperature to the extrusion temperature ($T_{ext} \approx 980^\circ\text{C}$). Utilizing an estimated average specific heat capacity of Ti6Al4V ($\overline{C_p} \approx 600$ J/kg $^\circ\text{K}$) over the temperature rise ($\Delta T = 955$ $^\circ\text{K}$):

$$SEC_{retained} = \overline{C_p} \cdot \Delta T \approx 0.57 \text{ MJ/kg} \quad (4)$$

The thermal efficiency (η_{th}), defined as the ratio of retained energy to input mechanical energy ($SEC_{retained}/SEC_{ME}$), was calculated to be between 1.7% and 4.8%. This result emphasizes that the large SEC_{ME} is necessary not for the net heating of the titanium, but primarily to provide the high mechanical power needed to overcome the temperature-dependent flow stress (28-35 MPa at 1000 $^\circ\text{C}$, and 52-59 MPa at 950 $^\circ\text{C}$ at the strain rate of 0.1/s [11]) and to compensate for massive continuous heat loss ($P_{loss} \approx P_{total} - P_{retained}$) to the surrounding tooling and machine structure, which is typical for FSE on materials with high processing temperatures [12]. The specific argon consumption was estimated to quantify the inert-gas auxiliary load required for processing reactive titanium alloys at elevated temperatures. In the absence of measured flow data, literature values for inert-gas shielding in high-temperature solid-state titanium processing were used. A conservative argon flow rate of 4 l/min was assumed to maintain a protective atmosphere around the friction tool and heated workpiece. The total argon consumption was determined by multiplying this flow rate with the total estimated run time, accounting for both the active extrusion and the necessary gas shielding during tool plunge, dwell, and initial cooling (7.5 minutes total). The total volume of 30 l was then normalized by the mass of the material extruded (0.188 kg) to yield the specific consumption (0.16 Nm³/kg-Ti).

The energy and material consumption for the prior Friction Stir Consolidation (FSC) step was estimated for the billet. Since the process description was derived from a lab-scale, multi-charge batch method [9], the Specific Energy Consumption (SEC_{FSC}) is governed by 3 primary factors: mechanical work (E_{ME}), fixed auxiliary overhead (E_{aux}), and pre-heating ($E_{preheat}$). The total electrical energy required for the consolidation of 1 billet was normalized by the final consolidated billet mass (m_{billet}).

$$SEC_{FSC} = \frac{1}{m_{billet}} \left[\frac{E_{ME}}{\eta_{eq}} + E_{aux} + E_{preheat} \right] \quad (5)$$

The billet mass was determined from the process parameters: $m_{billet} = 3 \text{ charges} \times 0.016 \text{ kg/charge} = 0.048 \text{ kg}$. The total time the machine and auxiliary systems were running was calculated to be 600 seconds, including pre-compaction, 3 consolidation cycles (at 60 s each), setup, and a final cooling period. The mechanical energy applied is derived from the rotating tool's power integrated over the active consolidation time ($t_{active} = 180$ s). In the absence of direct torque measurements, a sensitivity analysis was performed based on comparable friction stir processes using a $\varnothing 19$ mm tool & 450 RPM:

$$E_{ME} = (M \cdot \omega) \cdot t_{active} \quad (6)$$

Where M is the rotational torque and ω is the angular velocity (47.12 rad/s). The torque sensitivity analysis utilized a range of 100 to 400 Nm for the rotational torque, which consequently translated to a mechanical power range of 4.71 to 18.85 kW. The axial ramming power was included but deemed negligible (≈ 1.1 W). The final mechanical energy value was corrected by an assumed machine efficiency $\eta_{eq} \in [0.75, 0.85]$. The auxiliary energy, which covers the fixed power draw of the machine's control system, cooling unit, and motors over the entire 600 s run time, was calculated by assuming a standard auxiliary power draw of 1000 W according to [13], resulting in a total E_{aux} 600kJ; this yields a significant fixed specific energy overhead of 12.5 MJ/kg that noticeably influences the final SEC_{FSC} value due to the disproportionately small billet mass (0.048 kg). The energy required to pre-heat the chips to 200°C was calculated based on the billet mass, the specific heat capacity of titanium, and a heater electrical efficiency ($\eta_{oven} \approx 0.6$ [14]): $E_{preheat} = 9.24$ kJ. Thus, the calculated SEC_{FSC} based on the sensitivity range for torque is [33.49, 106.95] MJ/kg. During the FSC, argon gas was supplied locally to the chip feed region and tool-material interaction zone via an external nozzle positioned adjacent to the rotating tool. The argon flow was applied continuously throughout the FSC to minimize chips oxidation at high temperatures. The process was conducted in ambient atmosphere; no sealed or fully enclosed chamber was used. The argon consumption was estimated using a flow rate of 4 l/min over the total 10 min machine run time, yielding a total volume 40 l, which, when normalized by the billet mass of 0.048 kg results in a specific argon consumption of 0.833 Nm³/kg.

It is worth noting that a unified torque sensitivity range of 100-400 Nm was assumed for both FSE and FSC to reflect the balance between their distinct mechanical demands. In FSE, high torque is required to overcome the flow stress of a dense billet and maintain continuous material flow under substantial extrusion pressure. In contrast, although FSC involves lower initial resistance due to the loose packing of chips, this is offset by two factors: (i) a 90% higher rotational speed (450 vs. 236 RPM), which proportionally rises the power demand, and (ii) the scroll-patterned tool face geometry, designed to enhance material transport and induce intense shear deformation. The combined effect of increased rotational speed and tool-induced shear compensates for the lower chip packing resistance, thus justifying the adoption of a similar torque range for both processes. A sensitivity analysis was performed to evaluate how variations in inert-gas usage influence the environmental performance of the ShAPE. Since the process developer reported that higher argon flow rates during the FSC and FSE stages help reduce oxidation and improve wire quality, the total argon consumption in these steps was scaled using a dimensionless Specific Argon Consumption Coefficient (SACC). The actual argon demand for consolidation and extrusion was multiplied by SACC to reflect different operating conditions and quality targets. The adjusted argon consumption is calculated as:

$$Ar_{sensitivity} = SACC \cdot Ar_{actual}, \quad 1 \leq SACC \leq 2 \quad (7)$$

Although FSE is often performed directly on cold-briquetted chips, an intermediate FSC step was intentionally introduced in this work. FSC enables enhanced inter-chip bonding, oxide layer disruption, and densification compared to conventional briquetting, which is particularly critical for Ti6Al4V chips. This pre-consolidation results in a more homogeneous feedstock, improving process stability during FSE and reducing the risk of defects such as incomplete bonding. While FSC introduces an additional energy input, it contributes to improved material integrity and can reduce extrusion forces and process variability during FSE, supporting a system-level optimization rather than minimizing energy at a single process step. The LCI of the ShAPE recycling process is summarized in Table 1.

Table 1. Life Cycle Inventory of the ShAPE process (values in the ‘Quantity’ column are reported per 1kg of material processed).

Step	Input	Quantity	Remark
CNC Turning	Electricity & auxiliary	[15]	Turning was modeled using the Ecoinvent process ‘Chromium steel removed by turning, primarily roughing’, adjusted for the specific cutting energy of Ti6Al4V (0.89-1.27 J/mm ³ [16], [17]).
	Electricity	1.70 kWh	The washing step was modelled using the Ecoinvent process ‘Degreasing, metal part in alkaline bath’. Drying was based on [18], assuming a mid vacuum oven (53l) with 40-70% efficiency [19]. No solvent and heat recovery were assumed.
Degreasing & Drying	Auxiliary	[15]	
Briquetting	Electricity	0.40 kWh	The parameter was adopted from the specifications of an industrial briquetting machine, based on data reported in [20].
Friction Stir Consolidation	Electricity	9.30 kWh (low torque) 15.07 kWh (baseline) 29.70 kWh (high torque)	The range of reported electricity consumption reflects the dependence of energy requirements on the different torque values applied during the process calculations..
	Argon	0.83 Nm ³	
Friction Stir Extrusion	Electricity	2.29 kWh (low torque) 4.25 kWh (baseline) 9.61 kWh (high torque)	The range of reported electricity consumption reflects the dependence of energy requirements on the different torque values applied during the process calculations.
	Argon	0.16 Nm ³	
Waste Treatme	-	5-10%	Ti6Al4V waste generated during the ShAPE is assumed unsuitable for reuse and is instead sent to downstream ferrotitanium production, for which environmental credits are included.

Results and Discussion

Figure 2 presents the normalized impacts of the ShAPE process for the low- and high-torque boundary conditions, which span the energy demand estimates described earlier. Under all torque conditions, the ShAPE route exhibits substantially lower impacts than conventional Ti6Al4V wire manufacturing when the latter is modeled without scrap incorporation. However, this comparative advantage diminishes once a more realistic Reference scenario with 60% scrap integration [21] is considered. In this case, the ShAPE process achieves environmental performance comparable to traditional wire fabrication only under the low- and baseline-torque conditions; at the high-torque extreme, its relative environmental performance substantially degrades, exhibiting a noticeable increase in some impact categories. The impacts reported for ShAPE in Figure 2 assume a SACC of 1. Since higher SACC values reduce oxidation during FSC and FSE, as experimentally demonstrated in [8], but require proportionally more argon, rising SACC is expected to worsen the overall impacts.

The high normalized impacts for the Reference at a scrap-to-sponge (SS) ratio of 0% primarily arise from the titanium sponge production via the Kroll process. This route is dominated by energy-intensive chlorination, magnesio-thermic reduction, distillation, and Mg recovery steps, collectively resulting in great environmental burdens. One exception is the slightly higher impact of the ShAPE in the ‘Ionising radiation’ category relative to the Reference. This difference is attributable to the contrasting electricity mix profiles between the region where the ShAPE was developed and the regions supplying titanium sponge in the Reference. The LCA assumes sponge in the Reference to be sourced from China (42.5%) and Japan (24.5%), with the remaining 33% attributed to regions with impact profiles similar to Chinese production. According to the International Energy Agency, the contribution of nuclear power to the electricity supply in the United States, China, and Japan is 17.8%, 4.6%, and 9.5%, respectively. The higher nuclear share in the U.S. grid, where ShAPE recycling route was developed, thereby explains the comparatively higher contribution to the ‘Ionising radiation’.

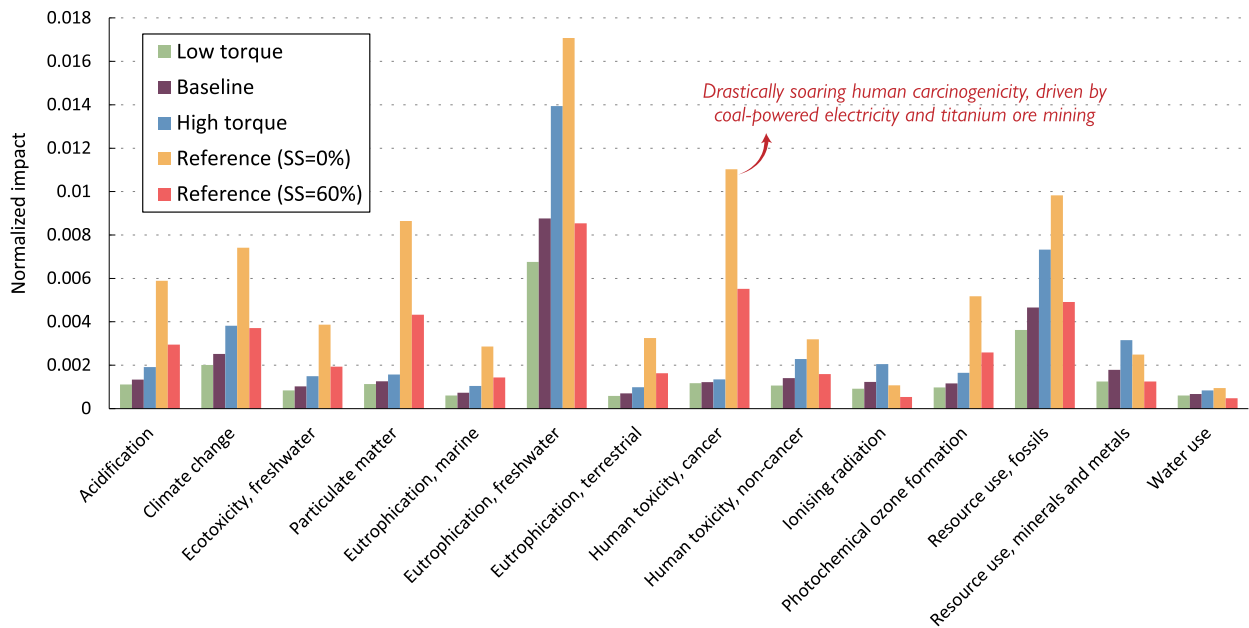


Fig. 2. Normalized impact results of the ShAPE process (for both torque extremes) compared to the Reference for producing 1 kg of wire, assessed using the Environmental Footprint method. The impacts shown for the ShAPE, at all torque conditions, correspond to the actual argon consumption with the lowest specific argon consumption coefficient. The values labeled as ‘SS’ in the Reference scenario represent the fraction of titanium scrap incorporated into the consumable electrode used in conventional vacuum arc remelting.

The CED and CO₂-eq emissions associated with the ShAPE process per intermediate product for producing 1 kg of Ti6Al4V wire are presented in Figure 3, including the torque-based sensitivity ranges derived from the calculations described earlier for both the FSC and FSE stages. Under the SACC = 1, the process was found to require 279.51-567.75 MJ of cumulative energy and to emit 17.22-32.35 kg CO₂-eq per kg of wire, depending on the torque demand during consolidation and extrusion. When compared to traditional wire fabrication, assuming a 60% scrap input typical of U.S. vacuum arc remelting [21], the ShAPE route exhibits a variation of -25.34% to +51.64% in CED and -47.69% to -1.75% in CO₂-eq relative to the Reference. These findings indicate that, under the discussed process parameter combinations, the ShAPE route can become highly energy intensive, with energy requirements that surpass those of traditional remelting-based wire production [22]. It is important to note, however, that the present comparison is based on laboratory-scale operational characteristics, including batch-mode processing. Noticeable impact improvements are expected as the process transitions to pilot scale, where higher throughput and improved thermal management can reduce per-unit impacts. The sensitivity analysis further reveals that variations in the torque needed to overcome materials flow at chips interfaces have a great influence on both consolidation and

extrusion performance. Among all process stages, FSC contributes the largest share to both CED and CO₂-eq, followed by the FSE step, reflecting their dominant roles in the process energy balance.

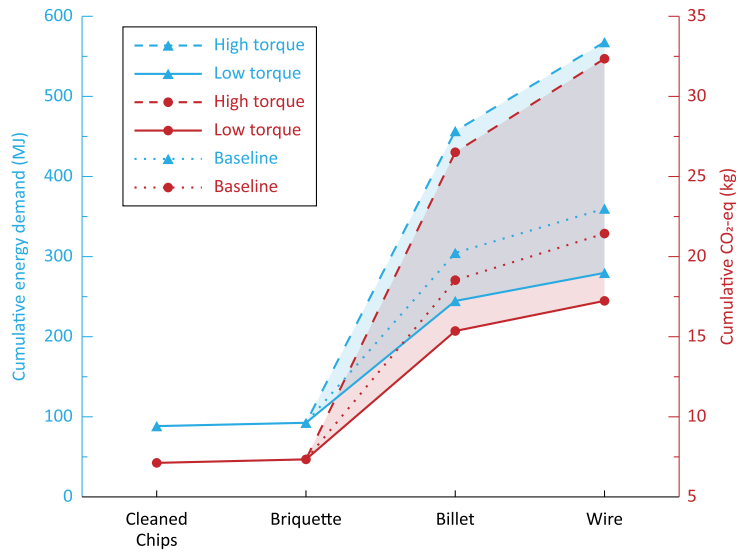


Fig. 3. Cumulative energy demand and CO₂-eq emissions of the ShAPE route, respecting the material/process flow shown in Figure 1. The values reported assume that both the consolidation and extrusion operate at the lowest specific argon consumption coefficient.

Figure 4 illustrates the relative variation in CED and CO₂-eq for the ShAPE process as a function of the SACC across the two torque extremes. The results clearly show that torque variation exerts a substantially greater influence on the impacts than changes in SACC. This is particularly evident in cases where doubling the torque requirement (Baseline→High) produces a considerably larger impact shift than increasing SACC from 1 to 2. Under the examined process conditions, the ShAPE provides only marginal CED advantages over traditional wire fabrication, and only when operating at the lower torque boundary when considering the average value of the SACC. In the ShAPE route, electricity is the sole energy carrier across all process steps, whereas the Reference scenario includes both electrical and thermal energy inputs at various stages of the titanium value chain. This difference in energy mix explains the divergence between the CED and CO₂-eq observed decreasing trends.

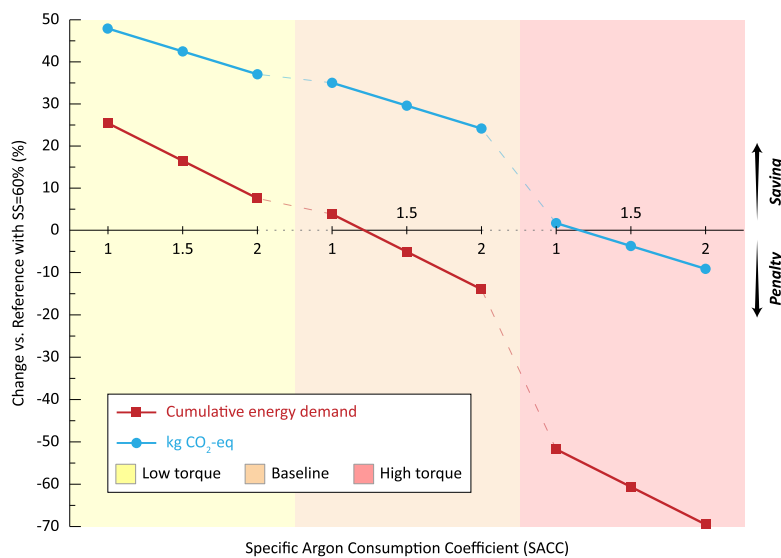


Fig. 4. Cumulative energy demand and CO₂-eq variation of the ShAPE process for producing 1 kg of Ti6Al4V wire relative to the traditional wire fabrication (Reference), shown as a function of torque change and the specific argon consumption coefficient (SACC).

Although the ShAPE recycling process does not substantially reduce energy demand compared to conventional wire fabrication, its inherent characteristic of eliminating primary titanium sponge consumption leads to significant improvements in other critical environmental indicators, namely the Average Dissipation Rate (ADR) and the Lost Potential Value (LPV). The ADR quantifies the rate at which a material's inherent utility or economic potential is irreversibly dissipated over its lifecycle, reflecting the depletion of critical resources due to consumption or dispersion. The LPV measures the unrealized value of a material when it is not effectively recovered or recycled, representing the potential economic or functional utility loss when a material exits the circular supply chain [23]. The ShAPE process enables reductions of up to approximately 12 kg Fe-eq in ADR and 69 USD in LPV per 1 kg of wire produced, relative to traditional remelting-based fabrication (SS=60%) as shown in Figure 5. These results highlight the process's ability to preserve material value and resource potential, providing measurable benefits for resource efficiency and circularity in titanium production. In a complementary scenario analysis, the ShAPE was assessed under an alternative electricity supply configuration with a more balanced distribution of fossil and non-fossil energy sources, represented by the hypothetical 'Region B' defined in Table 2. Under the low-torque condition and the highest SACC value, situating the ShAPE process in 'Region B', whose electricity mix contains 43% more green energy than that of the United States (average mix), reduces the overall impact by around 45.45%, underscoring the substantial influence of regional electricity composition on the process's environmental performance. Compared to conventional wire fabrication, the adoption of a greener electricity mix yields an overall impact reduction of 55.9% (Figure 6).

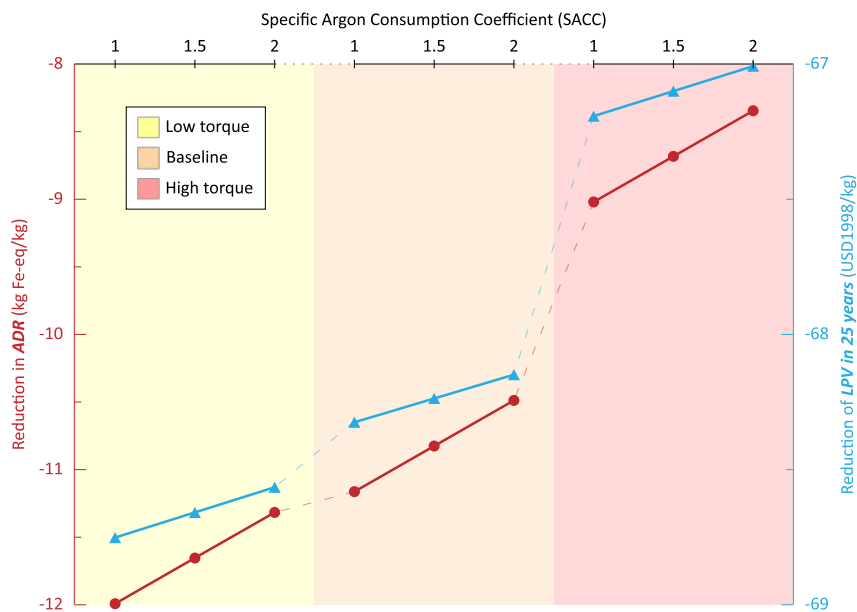


Fig. 5. Reduction in Average Dissipation Rate (ADR) and Lost Potential Value (LPV), relative to traditional wire fabrication (SS = 60%), as a function of torque extremes and SACC, evaluated using the methodology described in [23].

Table 2. Electricity supply profile of the United States, where the ShAPE process was developed, compared to 'Region B', a hypothetical region with a higher share of renewable electricity in the energy mix.

Region	Non-renewable (%)		Renewable (%)		
	Fossil	Nuclear	Wind, Solar, Geothermal	Water	Biomass
United States (average mix)	63	25	7	3	2
<i>Total</i>	88		12		
B	32	13	25	13	17
<i>Total</i>	45		55		

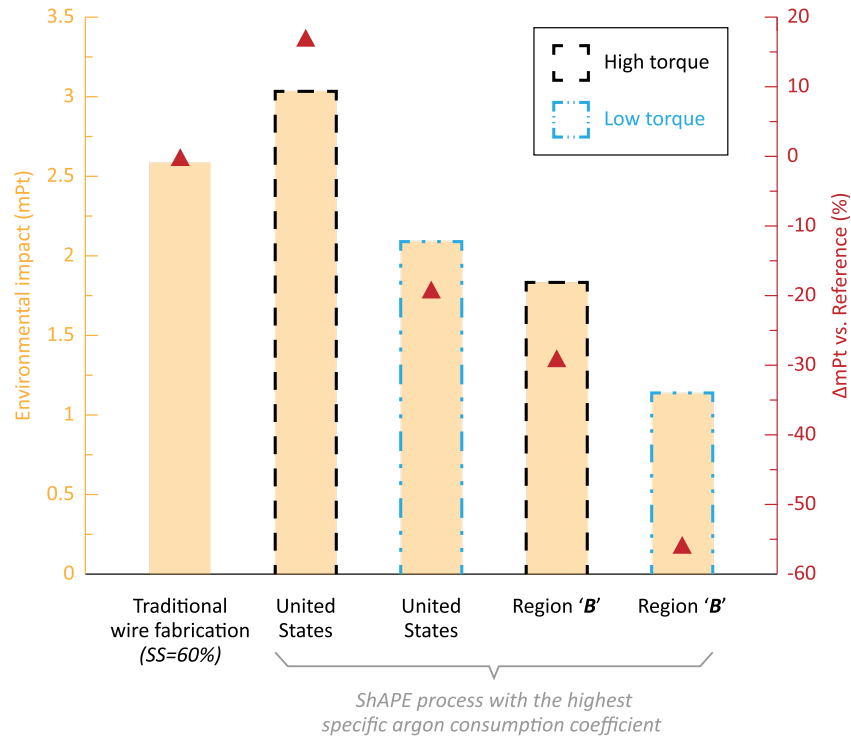


Fig. 6. Comparison of the overall environmental impact of the ShAPE process operated in two regions with different electricity mixes versus traditional manufacturing (Reference scenario, SS=60%) for the production of 1 kg of Ti6Al4V wire.

Conclusion

This study presents an environmental impact assessment of solid-state recycling of Ti6Al4V machining chips via Shear Assisted Processing and Extrusion (ShAPE), using 1 kg of wire as the functional unit and a system boundary including washing and drying, and consolidation/extrusion. Impacts were evaluated with multiple metrics; Environmental Footprint, Cumulative Energy Demand (CED), Global Warming Potential, Average Dissipation Rate (ADR), and Lost Potential Value (LPV), under varying torque conditions, argon consumption, and alternative electricity mixes. The ShAPE requires 279.51-567.75 MJ of CED and emits 17.22-32.35 kg CO₂-eq per kg of wire, with torque needs in consolidation/extrusion governing energy demand and emissions. Low- and baseline-torque conditions yield environmental performance comparable to the Reference, while high-torque extremes substantially elevates some impact categories. Sensitivity analysis indicates torque has a greater influence than argon use. Although energy demand is not consistently reduced, ShAPE improves resource efficiency by eliminating primary titanium sponge input, lowering ADR by approximately 12 kg Fe-eq and LPV by 69 USD per kg of wire. A greener electricity mix further reduces overall impacts by 45.45%, or 55.9% relative to traditional wire fabrication. Limitations to the study include reliance on a lab-scale experimental setup-based life cycle inventory and batch-mode operation, which may overestimate per-unit impacts. Overall, ShAPE recycling offers a promising route for circular titanium manufacturing, preserving material value, reducing primary extraction, and supporting sustainable production. Optimizing process parameters and scaling up, particularly with low-carbon electricity, could further enhance its environmental performance.

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