Orthogonal cutting of Wire and Arc Additive Manufactured parts

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Abstract
This work aimed to evaluate whether the established scientific knowledge for machining homogeneous and isotropic materials remains valid for machining additively manufactured parts. The machinability of thin-walled structures produced through two different variants of wire and arc additive manufacturing (WAAM) was studied, namely conventional MIG deposition and the innovative hot forging variant (HF-WAAM). Cutting operations were carried out varying the undeformed chip thickness (UCT) and the cutting speed, using a tool rake angle of 25°. A systematic comparison was made between the existing theoretical principles and the obtained practical results of the orthogonal cutting process, where the relation between the material properties (hardness, grain size, yield strength) and important machining outcomes (cutting forces, specific cutting energy, friction, shear stress, chip formation and surface roughness) is addressed. Additionally, high-speed camera records were used to evaluate the generated shear angle and chip formation process during the experimental tests. The machinability indicators shown that, through the appropriate selection of the cutting parameters, machining forces and energy consumption can be reduced up to 12%, when machining the mechanical improved additive manufactured material. Therefore, it has been confirmed the feasibility of machining such materials following the traditional machining principles, without compromising the surface quality requirements.

Keywords HSLA steel · Orthogonal cutting · WAAM · Hot Forging Wire and Arc Additive Manufacturing (HF-WAAM) · Chip formation

1 Introduction
Towards following the new paradigms of industry, the need for mass customization, combined with higher productivity and efficiency levels, led to the rise of additive manufacturing (AM) [1]. AM is the process of joining materials to make objects from three-dimensional (3D) model data, created layer-by-layer, with versatility and cost-effectively. New AM techniques are being developed to respond as a viable alternative in various industries, namely aerospace [2, 3], automotive [4] and rapid tooling industry [4–6], to produce complex near-net-shaped components [7]. Current advantages over traditional manufacturing processes are the high potential for process automation, the reduced amount of total production time, flexibility, costs and less material waste, as well as the benefit in design freedom. In addition, a wide range of materials can be processed by these technologies.

Powder bed fusion (PBF) [8] and directed energy deposition (DED) are the most used AM techniques. In DED processes, focused thermal energy is applied to, simultaneously, melt and deposit the material into the surface, where it solidifies. Different types of primary heat sources can be used: arc plasma, electron beam or laser combined with powder or wire used as feedstock material.

Wire and arc additive manufacturing is a DED process, emerged as a promising technology for producing large and medium-complexity steel components [9, 10], as it allows rapid manufacturing of large metallic parts with a high deposition rate, low equipment cost and eco-friendly approachability.

However, there are still some concerns regarding metal components produced by WAAM and consequently their implementation in the industry. The main challenges related to this technology involve poor geometric accuracy
and surface finish, which require post-processing operations [1, 7, 9, 11]. Duarte et al. [12] developed a new variant of WAAM, known as HF-WAAM that can improve the quality of the manufactured parts, by homogenizing (and refining) the grain structure, increasing the ductility, reducing the levels of residual stress and porosities, as well as improving the waviness and the geometrical accuracy of the component. This new process variant consists of the in situ appliance of pressure at high temperatures, with a given frequency and force, immediately after the material is deposited. Several alternative methods were also described as an attempt to correct some WAAM process limitations, mainly focused on controlling the temperatures involved during the process. Approaches like optimization of interpass temperature [13–15], use of different deposition strategies [16], adaptation of the hot wire method [17], active interlayer cooling/heating, interpass cold rolling and preheating of the substrate were reported to improve the mechanical properties and dimensional accuracy of the as-build parts, as well as to reduce the need for post-processing operations like machining and heat treatments [10].

A significant impact on the machinability may occur due to microstructural and local mechanical differences, where the anisotropy and the microstructural heterogeneity are two of the most challenging features regarding the AM parts [18]. Regarding the good weldability and ductility exhibited by HSLA steels, one of the major concerns during machining this type of steel is the development of a build-up edge (BUE). When slot milling WAAM parts, Lopes et al. [19] observed top milling burrs on the periphery of grooves, due to material plastic flow when compressed and related to high ductility of the workpiece material, and exit burrs at the end of machined grooves, generated when the workpiece material was pressed and deformed, instead of sheared at the exit of the tool. However, they found that the gradient on the mechanical properties of as-built parts did not yield significant differences on the milling process responses.

The study of the phenomenological response of the material is essential to understand the principles of chip formation. Some early studies regarding the chip formation process were based on simplified assumptions, namely the shear plane card model proposed by Pijspanen, considered as a solid logical explanation of the chip formation process with experimentally acceptable results [20]. Regardless of the machining operation to be performed, numerous factors are considered to have a major influence on the generated chips, namely the material properties (anisotropy, homogeneity, grain size and mechanical strength), cutting parameters, cooling/lubrication conditions and the tool material and geometry. The orthogonal cutting approach is the most appropriate method to understand the fundamental cutting mechanisms, especially when the cutting behaviour of the workpiece material is yet unknown. When the chip formation process is captured in situ it provides information about the specific material removal mechanisms and their correlation with the cutting conditions. As commonly referred in the literature [21–23], the correct prediction, modelling and monitoring of the cutting forces signals are the main focus of various researchers. Analysing the cutting forces allows to determine the specific cutting energy involved, one important factor regarding an adequate selection of cutting parameters.

Therefore, the objective of this paper is to exhaustively investigate and compare, through a detailed and systematically approach, the eight main features of machinability study, where a scientific correlation is established between the material properties and cutting parameters, providing an interesting database regarding machining WAAM components and the HF-WAAM variant.

### 2 Experimental procedure

The experimental procedure comprised two steps. First, the production and characterization of the WAAM samples were conducted. Then, the analysis of the chip formation and the orthogonal cutting phenomenological study was performed. Figure 1 illustrates the experimental procedure, describing the techniques employed for their characterization, which are further detailed in the following sections.

#### 2.1 HSLA steel samples manufactured through WAAM

Two different thin-walled structures were manufactured using a custom-built GMAW-WAAM machine [24]. A zigzag strategy was used, where the deposition direction was inverted at the end of each layer. The length of the thin-walled structures was set to 180 mm and the final height to 100 mm. In addition, an 8 mm contact tip to work distance (CTWD) was kept constant between the welding torch and the substrate/previously deposited layer, as well as an interlayer deposition time of one minute. Commercial Argon (99.999%) was used as shielding gas, using a constant flow rate of 15 L/min. A 1.2-mm-diameter consumable solid wire was used as feedstock material, namely ER110S-G from LINCOLN ELECTRIC [25], equivalent to HSLA steel.

Equal low heat input values (221 J/mm) were used to manufacture both samples, however, through distinctive variations of the WAAM process. The first sample was produced with conventional WAAM, while the second sample was produced with the HF-WAAM variant.
This new variant comprises the use of a hammer placed inside the gas nozzle, which is actuated by a pneumatic cylinder that can operate at different frequencies. The hammer is placed at 10 mm from the arc welding centre and travels along with the torch. The hammer activation consists of giving it cyclic vertical movement, and it is activated while the material is still being deposited, so that it is forged while it is at high temperatures (from 800 to 900 °C), similar to hot forging process. The deposition parameters employed during the samples production are summarized in Table 1.

| Table 1 WAAM process parameters used to produce the thin-walled structures (conventional WAAM and HF-WAAM) |
|---------------------------------------------------|
| **Welding mode** | **Gas metal arc welding—continuous mode (DC +)** |
| **Current [A]** | 95 |
| **Voltage [V]** | 21 |
| **Travel speed [mm/min]** | 540 |
| **Wire feed speed [m/min]** | 3 |
| **Contact tip to work distance [mm]** | 8 |
| **Shielding gas** | Argon 99.99% |
| **Gas flow rate [l/min]** | 15 |
| **Heat Input [J/mm]** | 221 |
| **Forging frequency (HF-WAAM) [Hz]** | 8 |

2.2 Orthogonal cutting experiments

Orthogonal cutting operations were conducted on an ALBA TYPE-2S mechanical shaper machine, providing relative linear motion between the workpiece and a single-point cutting tool. The cutting tool used was a 16 × 16 × 80 mm high-speed steel (HSS) tool, crafted to a rake angle of 25° and a clearance angle of 5°. Due to the fundamental features of the orthogonal cutting, some simplifications were considered; namely, the tool edge effects were neglected, and the ideal case of a perfectly sharpened tool with zero tool edge radius was adopted. Furthermore, due to the small length of the experimental tests, tool wear was not considered significant regarding the acquired experimental results, as verified by preliminary tests.

To evaluate the influence of the gradient of hardness presented along the built-up direction, both thin-walled structures were divided and cut into three different regions of interest with similar mechanical behaviour: base, centre and top, as represented in Fig. 2. The dimensions of each sample were set to 50 mm in length and 20 mm in height.

Moreover, to ensure a constant width across the sample and to avoid undesirable vibration during the machining processes, grinding operations were performed to remove the waviness on both sides of each sample, ensuring a constant wall width of 3 mm. For the orthogonal cutting model,
the cutting depth corresponds to the width of the sample, whereas the undeformed (uncut) chip thickness represents the distance below the original work surface where the cutting edge of the tool is positioned, as represented in Fig. 3.

Regarding the operational recommendations for shaping operations, the sample machining was conducted in the stable cutting stage of the machine, to avoid variations in the cutting speed during the experiment. The different cutting
parameters selected for the experiments are summarized in Table 2.

A design of the parameters combinations was employed, namely distinctive values of cutting speed and undeformed chip thickness, in the three distinctive zones (base, centre and top) of each thin-walled structure (WAAM and HF-WAAM). To ensure a reference comparison for the additively manufactured WAAM material, experiments were conducted on low-carbon steel samples. Thus, 3 replicates of 56 tests were conducted under dry condition and in a stationary cutting regime, i.e. with a constant cutting speed during the complete operation. The components of the cutting force were acquired for each test, using a Kistler 9257B dynamometer together with a Kistler LabAmp 5165A charge amplifier and data acquisition, at a sample rate of 10 kHz. The chip formation process was recorded using a Photron FASTCAM AX50 high-speed camera system comprising 10,000 fps at 384×384 pixels resolution. To reach the appropriate level of magnification, the camera was equipped with a Nikon AF NIKKOR 28–80 mm macro lens. The required levels of lighting were ensured by two 100 W rectified LED floodlights from V-TAC. The shaping performance was evaluated throughout the analysis of the different output variables based on the existing theoretical models from the orthogonal cutting literature. These variables include cutting force, specific cutting energy, friction coefficient and angle, shear angle and shear stress. The overall experimental apparatus is shown in Fig. 4.

### 2.3 Characterization techniques

Different characterization techniques were employed to evaluate the properties of the produced thin-walled structures. To evaluate the waviness, the profile for each section was acquired through a scanner and further processed with DraftSight 2020 software. The methodology used for the waviness measurements was the same as presented in [26]. The common way to quantify the surface quality is according to the equation (TWW – EWW) / 2, where TWW refers to the total wall width and EWW refers to the effective wall width, as depicted in Fig. 5; the final waviness was calculated through the average value measured on five equally spaced sections.

For microstructure characterization, each sample was mounted in epoxy resin, polished and etched with Nital (3%...
solution). A Leica DMI 5000 M inverted optical microscope was used to observe the microstructure. For microhardness measurements, a Mitutoyo HM-112 Vickers microhardness testing machine was used, a 0.5 mm distance was used between measurements, and a load of 0.5 kg was applied during 10 s for each indentation.

To evaluate the mechanical properties of the samples, particularly the material yield strength, uniaxial compression tests were conducted. For that purpose, a Shimadzu auto-graph test machine, equipped with a 10 kN load cell, was used to perform three replicates for each testing condition (base, centre and top of WAAM and HF-WAAM samples), at a displacement rate of 1 mm/min.

Electrical conductivity measurements were taken to evaluate the material variations along with the deposited layers. A commercial Jandel™ linear four-point probe was used together with a Keithley 2182A digital nano voltmeter, according to the conditions described in [28].

As for the machined surfaces, the surface quality analysis was performed through the surface roughness parameter, Ra, following the ISO 4287 standard for the assessment of surface texture in machining operations [29], using a Mahr MarSurf PS 10 mobile roughness measuring instrument. The roughness measurements were taken, for each experiment, in five equally spaced sections of the machined surface. The presented results are the calculated average of the acquired values.

For each shaping operation, the generated chip was gathered and analysed regarding the morphology, thickness and curvature radius. Five different measurements of thickness were taken via image analysis software, and the chip compression ratio was calculated. Morphology observations were carried out on a Leica DMI 5000 M Inverted Microscope. For the chip curvature radius assessment, a scaled image of each chip was analysed using CAD software Solidworks. Five measurements were taken using a superimposed arc in the middle area of each chip curvature. The radius was subsequently computed and the result given by the calculated average.
3 Results and discussion

3.1 WAAM parts characterization

Evaluating the low-alloy thin-walled steel structures manufactured through WAAM and HF-WAAM (Fig. 2), is noticeable the superior spattering presented on the hot-forged component, evident for the higher number of droplets (of molten metal) marked in the side wall. The waviness measurements, acquired through the profile of both samples, have revealed higher surface waviness for the HF-WAAM sample (1210 ± 25 μm), when compared to WAAM structure (977 ± 63 μm). Such observation was slightly unexpected, running against the predictions presented by Duarte et al. [12], where deforming the as-deposited layers at high temperature could result in improved waviness and surface roughness of the produced components.

The isometric micrographs from the centre areas of both samples, presented in Fig. 6, show a homogeneous microstructure, independent from the samples direction. The material is heat treatable and consequently sensible to thermal cycling effects. Considering the cooling rate as one of the main factors to delineate the grain growth process, the relative higher cooling rates of the WAAM deposition process may be responsible for promoting the formation of smaller prior austenite grains that during the cooling process are transformed by solid-state transformations into polygonal ferrite (Fig. 6 details) with a homogeneous structure, i.e. without a significant preferential orientation. The most significant microstructural difference observed between samples was the smaller grain size of the hot-forged sample.

As depicted in Fig. 7, both thin-walled structures revealed uneven microstructures along the building direction,

![Microstructure of conventional WAAM samples and HF-WAAM samples, through the build-up direction](image-url)
changing the grain size across the height, as a consequence of the effect of the different thermal behaviour (cooling rates, substrate effect) experienced by the material during the deposition process. Moreover, the larger grain size is commonly observed on the centre zones of the samples, which results from two different heat effects: the increased difficulty in sinking the heat through the underlying layers, which are progressively warmer; and the repetitive thermal effects caused by the deposition of the overlying layers that causes a temper heat treatment effect. Furthermore, at the bottom of the sample, most of the heat is dissipated through the cold substrate, which increases the material cooling rate when compared to the upper layers and therefore forms finer microstructure. In the last layers, the material is subject to less thermal reheating cycles, not allowing the grain to coalesce as occurred in the middle of the sample.

As supported by Duarte et al. [12], the hot forging WAAM variant can generate a microstructure refinement, promoting grain size reduction and so improving the mechanical properties. Similar results were reported by Hönnige et al. [30] when peening a WAAM deposited Ti-6Al-4 V wall. From Figs. 6 and 7, it is clear the hot forging effects on the microstructure of the HF-WAAM sample, particularly on the smaller grain size of the material.

The hardness measurements registered for the areas of interest of the cutting experiments are shown in Fig. 8. For WAAM samples, the hardness was in the 220–260 HV range, while for HF-WAAM samples higher hardness values were measured, namely 240–300 HV. The low-carbon steel, as expected, registered lower hardness values (160–180 HV range).

Both WAAM and HF-WAAM structures revealed identical hardness profiles along the height, decreasing from the base to the centre and increasing from the centre to the top, being in good agreement with the aforementioned changes in grain size, following the Hall–Petch equation. The grain size has a direct impact on the hardness levels, since the grain boundaries act as a mechanical barrier to dislocations propagation, validating the acquired data for the superior hardness of the HF-WAAM structures. The higher hardness on the HF-WAAM sample is generated by the hot forging effects when the material is at the range of hot working temperatures, promoting the grain refinement effect on the material.

The hot forging effects have revealed major mechanical improvements regarding the yield strength, when subjected to uniaxial compression tests. As depicted in Fig. 9, the yield stress has revealed a very similar profile as the hardness measurements, due to the microstructural changes developed across the height. For the conventional WAAM specimens, the measured yield stress range is in accordance with the values presented in [31].

The electric conductivity measurements revealed no main differences between samples, and the results were in the 5–6% IACS amplitude, as shown in Fig. 10. The variation experienced during the tests can be assigned to microstructural differences within the same zone. However, it is more evident in the base zone of the HF-WAAM structure. It is possible to conclude that despite the microstructural variations observed along the sample height, the electrical conductivity remains almost constant. Moreover, the hot forging does not significantly affect the
material electrical conductivity. Although this technique can identify microstructural changes [32], the grain size variations are observed in each sample, and during the comparison between the conventional WAAM and the HF-WAAM, they are within the same order of magnitude, and therefore, the electrical conductivity of the material is not affected.

3.2 Cutting force and specific cutting energy

In an orthogonal cutting operation, the total cutting force $F$ can be decomposed into two components: $F_c$, the cutting force acting in the direction of the tool movement; and $F_p$, the feed force acting perpendicularly to the cutting force (Fig. 3). Both components produce deflection in the workpiece and the cutting tool. The influence of cutting speed and undeformed chip thickness on the cutting force is depicted in Fig. 11. No major influence of the cutting speed is observed on the cutting force results, as expected. Moreover, increasing the undeformed chip thickness, the cutting force increases, due to the higher amount of material removed during the cut. Such observations are shared in both WAAM, HF-WAAM and low-carbon steel samples. As commonly referred in the literature [33–35], there is no straightforward formula to calculate how machinability is dependent on the hardness of the material. However, the literature refers to the fact that cutting force tends to increase with increasing hardness. Such evidence was not completely observed in this work, as the increased hardness of the HF-WAAM samples (when compared to conventional WAAM and low-carbon steel) has revealed different trends. As would be expected, the cutting force tends to increase with increasing UCT in all samples, and its behaviour was similar in all cases. The measured cutting force values were lower for WAAM samples, on the base (except for lower values of UCT when cutting at lower speed) and centre areas. With respect to the base area, the cutting force for the WAAM samples ranged from being 14% lower ($v = 5$ m/min; $h = 0.3$ mm) to 14% higher ($v = 7$ m/min; $h = 0.6$ mm) than for the similar area on HF-WAAM samples. Regarding the centre area, the cutting force values for WAAM samples were up to 10% lower. On the top area the cutting force was lower for the HF-WAAM samples (up to 12%). Nevertheless, the results are in accordance with the literature [36, 37] since the low influence of the mechanical properties and cutting speed on the cutting force is documented.

![Fig. 9](image)

**Fig. 9** Compression tests results for each region of interest

![Fig. 10](image)

**Fig. 10** Electrical conductivity test results of the samples: a) conventional WAAM; b) HF-WAAM
Figure 12 depicts the comparison of WAAM, HF-WAAM and low-carbon steel experimental results for specific cutting energy (SCE). It is possible to notice that the SCE values, regardless of the cutting parameters and sample type/area of interest, remained within the anticipated range of 1.68 to 2.28 GJ/m³, in accordance with most steel alloys [38–40]. Therefore, it is possible to confirm that neither the mechanical properties (hardness and yield strength) nor the cutting speed have largely changed the SCE values for the employed cutting conditions. The increase in the undeformed chip thickness tends to decrease the SCE according to the typical power tendency (SCE = C·h⁻ᵐ). The models obtained for the low-carbon steel samples presented an expected exponent for steel alloys (within 0.252 and 0.358) as the WAAM samples machined using a lower cutting speed. However, with increased cutting speed, the uncut chip thickness influence diminished, as the power exponent decreased to a range between 0.035 and 0.122. The same occurs for HF-WAAM samples, regardless the used cutting speed, which can indicate that the UCT is not the only variable to consider for the mathematical expression for SCE.

The SCE can also be used as an indicator of the tool wear during the machining operation [40]. Thus, the observed consistent behaviour can sustain the tool integrity throughout the experimental work.

3.3 Shear angle and shear stress

The shear angle is fundamental in chip formation, as increasing the shear angle allows to decrease strain, machining forces and power requirements. In fact, compared to the cutting force results, the measured shear angle showed inverse behaviour. Analysing the differences between WAAM and HF-WAAM, WAAM samples presented higher values for lower cutting speed, with the exception of the top area. The range of shear angle was within 29.1° and 33.7°. It should be noted that WAAM samples showed a very similar behaviour to low-carbon steel when the cutting speed was higher (Fig. 13).

The experimental values were compared to the theoretic models, namely the geometrical relationship of orthogonal cutting, based on the cutting ratio or chip thickness ratio, the Lee–Shaffer maximum shear stress principle (MSSP) and the Merchant’s minimum energy principle (MEP). As shown in Fig. 14, the MSSP is the model that better predicts the experimental shear angle for most of the experimental tests.
Similar conclusions were found by Silva et al. [41] performing orthogonal cutting on AISI 1045 medium-carbon steel and Berezvai et al. [42], when studying the shear angle variation during orthogonal cutting of aluminium, in a stationary cutting regime and without build-up edge (BUE) formation.

The geometrical relationship of the orthogonal cutting model presented the worst prediction on the shear angle, which would be expected, since the chip thickness measurements are greatly operator influenced. Also, as predicted, the MEP has overestimated the values for the shear angle; however, the MEP prediction was the most uniform through the cutting experiments.

Regarding the cutting parameters, both cutting speed and undeformed chip thickness have shown no major influence on the shear angle. However, the value range is similar to that observed by Varga [43] when simulating, through finite element analysis, the cutting process on AISI-1045 steel. Choi [44] have reached similar conclusions in a study on the shear angle variation in orthogonal cutting, attesting the independence of the shear angle from the undeformed chip thickness. In addition, the shear angle experimental values are more consistent throughout the height when machining HF-WAAM.

Figure 15 shows the shear stress levels required to allow the chip formation process to occur. Examining the WAAM and HF-WAAM tests, it can be noted that the generated shear stress is close to the material tensile strength (range from 769 to 942 MPa), as should be expected. Moreover, it is also possible to emphasize the similarity behaviour between the WAAM and HF-WAAM samples, when using different combinations of cutting parameters. Despite the known differences in the mechanical properties of the additively manufactured material, the effects on the shear stresses, apparently, only arises when machining at the higher speed ($v = 7$ m/min). However, the generated shear stress levels for the low-carbon steel shows almost an equal behaviour as for WAAM-produced samples, revealing an apparent independent relation of the shear stress from the UCT. However, for the HF-WAAM, such relation is less noted when cutting at the higher speed.

### 3.4 Friction coefficient

Figure 16 depicts the calculated friction coefficient, $\mu$, for the different experiments. The cutting speed produced minor effects on the friction, which may show that the material did not undergo severe thermal-softening effects, as described by Okida et al. [45], when machining alloy steel. Machining WAAM and HF-WAAM material has reduced the generated friction levels up to 17%, comparatively to the low-carbon
Fig. 14 Shear angle comparison between experimental, chip ratio measurements, MSSP and MEP models: a) $v = 5$ m/min, $h = 0.3$ mm; b) $v = 5$ m/min, $h = 0.6$ mm; c) $v = 7$ m/min, $h = 0.3$ mm; and d) $v = 7$ m/min, $h = 0.6$ mm
Fig. 15 Experimental results for shear stress on the base, centre and top of each sample and low-carbon steel: a) WAAM (v = 5 m/min); b) HF-WAAM (v = 5 m/min); c) WAAM (v = 7 m/min); and d) HF-WAAM (v = 7 m/min)

Fig. 16 Experimental friction coefficient, µ on the base, centre and top of each sample and low-carbon steel: a) WAAM (v = 5 m/min); b) HF-WAAM (v = 5 m/min); c) WAAM (v = 7 m/min); and d) HF-WAAM (v = 7 m/min)
steel, probably due to the refinement effect of the microstructure. Additionally, for the WAAM and HF-WAAM components, the friction coefficient was, for all experiments, in conformity with the 0.5–0.8 range described in the literature [46] for static friction on steel-on-steel contact, considering dry conditions. However, the friction coefficient was described by the constant friction coefficient of Coulomb, \( \mu = \frac{F_f}{F_N} \). Still, the values of the friction coefficient experimentally measured in orthogonal cutting tests are usually much higher than those used analytically on metal cutting, due to only be considered the static friction effect. The models typically assume \( \mu = 0.5 \), whereas experimentally obtained values can be up to 2 [47]. A direct relationship is theoretically established between the friction coefficient and the friction angle, being the processed values being constrained in the 34.2° to 35.5° range.

### 3.5 Surface roughness

When machining functional components, the surface quality must respect defined specifications. The surface roughness results for each material, cutting speed, WAAM manufacture process and area of interest are depicted in Fig. 17. From the experimental measurements, it was possible to confirm that all the results were in accordance with the recommended values of Ra for shaping operations, within the 0.4–25 µm range [48]. Machining additive manufactured HSLA steel components has revealed lower roughness values compared to machining low-carbon steel (1.2–10.9 µm range), despite the improved hardness. The average surface roughness values were lower within the range 5% to 90% for WAAM samples and from 7 to 84% for HF-WAAM samples. This is a general result of the lower plastic deformation that harder (and brittle) materials sustain on the machined surface, comparatively to softer materials.

The most uniform and better surface roughness levels were reached when machining at a higher cutting speed, most likely due to the decreasing tendency for BUE formation and increased thermal-softening effects that reduces the adhered material in the rake surface of the tool. However, the higher surface roughness results were reached at higher UCT, probably due to vibrations generated by the greater amount of material removed. Similar conclusions were reported when machining additive manufactured titanium alloy [49].

### 3.6 Chip observations

The generated chips were collected, and the morphology was analysed for different samples and areas of interest, as shown in the macroscopic images of Fig. 18. No pronounced difference was observed in terms of cutting speed. However, the effect of different UCT on the chip thickness and curvature radius is notorious. As described in the literature [50–52], the chip curvature radius tends to decrease with increased shear angle and with decreased UCT. It is clarified that an increase in the shear angle reduces the temperature in the primary shear zone (due to less plastic deformation) and, therefore, increases the friction levels, generating lower curvature in the chip. Following the chip radius measurements presented in Fig. 18 (for different UCT) and the previously shown shear angle/friction results, it is possible to confirm that such relations were witnessed for almost all the cutting conditions, being more evident on the top zone of the samples.

Also, from Fig. 18, it is possible to recognize that all the cutting operations have generated continuous chips without side-flow tendency. Such chip geometry is in accordance with the obtained surface finish results.
The chip thickness ratio (CTR) is an important machining feature that is used to evaluate the efficiency of the chip formation process, through the degree of plastic deformation generated during the machining operation [53]. It is known from the literature that higher CTR values are desirable, since are followed by higher shear angles and, therefore, less cutting forces, promoting a better cutting operation. As shown in Fig. 19, regarding the WAAM samples, the higher CTR was obtained when cutting the centre zone of the samples, at higher cutting speed and UCT \((v = 7 \text{ m/min}, h = 0.6 \text{ mm})\). Following the HF-WAAM samples, the CTR values become more homogeneous, revealing a more consistent cutting operation. Comparing to WAAM, the CTR values of the HF-WAAM samples were improved when machining the base (up to 38\%) and the centre zone (up to 28\%) of the structures.

### Table 1: Computed chip thickness ratio (CTR) on base, centre and top of each WAAM, HF-WAAM and low-carbon steel sample

|          | Base | Centre | Top |
|----------|------|--------|-----|
| WAAM     |      |        |     |
| \( r \)  | 5.71 ± 0.23 | 7.81 ± 0.21 | 7.91 ± 0.21 |
| HF-WAAM  |      |        |     |
| \( r \)  | 3.56 ± 0.15 | 6.31 ± 0.27 | 3.27 ± 0.02 |
| Low-carbon steel | | | |
| \( r \)  | 5.56 ± 0.12 | 6.12 ± 0.14 |   |

\( r \) – chip thickness radius [mm]
Following the low-carbon steel, higher CTR values were registered comparing to HF-WAAM and WAAM samples. Such results are generally in accordance with the cutting force measurements and the superior mechanical properties observed for the additively manufactured material. However, no substantial differences were observed for the CTR values of the low-carbon steel chips, for the employed cutting conditions.

Figures 20, 21 and 22 depict the microscopic images of the generated chips corresponding to the base area of each sample (conventional WAAM, HF-WAAM and low-carbon steel) when cutting with UCT of 0.6 mm and cutting speed of 7 m/min.

From Fig. 20, regarding the originated chip from the WAAM cutting test, it is possible to point out several details. First, it is relatively easy to identify the primary and secondary shear zones. Originated at the shear plane, the primary shear zone is created by the tool compressive forces during tool penetration into the sample, represented by an elongated effect on the material grains. The secondary shear zone is created between the tool rake surface and the chip, where the friction effects lead to additional plastic deformation, rearranging the material in a parallel direction to the tool rake surface. During the cutting operation, the hardness of the sample acts as an opposite force to the cutting tool movement. Therefore, while the adjacent side to the tool is smooth, a sawtooth-like profile, composed by serrations, is generated in the opposite side of the chip, probably due to thermal-softening effects and uneven strain distribution during the cutting operation (Fig. 20a). Observing one serration in detail, it is possible to detect the material reorientation...
(plastic deformation) when subjected to the compressive forces on the shear plane, describing a vortex-style shape (Fig. 20b).

Figure 21 depicts the originated chip from the HF-WAAM sample. It is also possible to identify the primary and secondary shear zones. However, it is possible to notice more dense and linear shear zones, due to the grain refinement effect created by the hot forging effect on the material. Additionally, the improved mechanical properties of such samples may have had an impact on the created serrations. As described in the literature [53], the number of chip segments per unit length is directly related with the microstructure of the material, from which the number of serrations is associated to the ductility of the material. Through the observation of Fig. 21, it is possible to recognize such phenomenon through the existing differences in the number and magnitude of the serrations presented in the HF-WAAM chips, an indicator of the influence of the different physical and mechanical properties of such samples.

As shown in Fig. 22, regarding the generated chips from low-carbon steel samples, the primary and secondary shear zones can also be identified, being notable the flattened effect on the grains and, consequently, a parallel displacement of the shear planes, originated during the chip formation process. Such observation supports the ideal shear card model proposed by Pijspanen, based on the overlapping shear planes [20].

Finally, it is possible to observe the material behaviour when subjected to the shear deformation. Comparing with the conventional WAAM and HF-WAAM samples, where the effect of the refined microstructure is noted, it is possible to observe larger and unequal serrations on the isotropic low-carbon steel chips. As previously stated, such characteristics are a strong indicator of uneven shear strain distribution during the cutting operation.

### 4 Conclusions

Orthogonal cutting operations were performed on thin-walled steel structures manufactured through WAAM and HF-WAAM, as well as on isotropic low-carbon steel. A systematic comparative study was conducted between the physical and mechanical properties of the samples, and the corresponding major machining results. Tables 3 and 4 depict the summary comparison between the different samples for material and machining results, respectively.

Therefore, the following conclusions can be drawn:

- The thin-walled steel structures, manufactured through the HF-WAAM variant, exhibited superior surface waviness (nearly 28%), comparatively to the WAAM samples, against the expected results described in the literature.
- The microstructure observed within all the samples presented local isotropy. Smaller grain size and refinement effect on the material were noticeable in the HF-WAAM samples.
- The hot forging effects have revealed major mechanical improvements, regarding hardness and yield strength, being in good agreement with the observed microstructural changes.
- The cutting force (Fc), the consumed power (Nm) and specific cutting energy (SCE) were up to 12% lower when machining additive manufactured material, when compared to low-carbon steel parts. Additionally, a 14% reduction was obtained when machining the HF-WAAM, comparatively to the WAAM samples.
- High-speed camera records were used to evaluate the generated shear angle. In all cases, MSSP was the the-
Theoretical model that better predicted the experimental shear angle results, which range (29.1°-33.7°) was the expected for alloy steel. The geometrical relationship of the orthogonal cutting model presented the worst prediction on the shear angle.

- Machining WAAM and HF-WAAM material has decreased the generated friction levels up to 17%, comparatively to the low-carbon steel, possibly due to the microstructure refinement effect and smaller size. However, the friction coefficient was, for all experiments, in conformity with the ideal range (0.5–0.8) described in the literature.

- The machined surface presented lower roughness on additive manufactured parts, compared to the low-carbon steel, reaching improvement levels within the range 5% to 90% for WAAM samples and from 7 to 84% for HF-WAAM samples, despite the superior hardness. The most uniform and better surface roughness levels were reached when machining at a higher cutting speed.

- Following the HF-WAAM samples, the CTR values presented by the hot-forged material were improved in the base (38%) and centre zones (28%), compared to WAAM generated chips. Higher CTR values were registered for low-carbon steel, an effect of the inferior mechanical properties of the samples.

- Continuous chips were obtained for all experiments. No pronounced difference was observed in terms of cutting speed. However, the effect of different UCT on the chip thickness and curvature radius was notorious.

- Machining HF-WAAM has proved to be advantageous as it was shown that using appropriate cutting parameters it is possible to machine improved mechanical properties of the samples.

Table 3 Material comparison summary table

| Comparison criteria (Material) | WAAM | HF-WAAM | Low-carbon Steel (reference) |
|-------------------------------|------|---------|-------------------------------|
| Surface waviness, [μm]        | 997  | 1210    | ---                           |
| Grain size                    | Lower| Lower (Refined)| Reference                   |
| Hardness, [HV]                | 220 – 260 | 240–300 | 160 – 180 (reference)         |
| + (38 – 45) %                 |       | + (50 – 67) % |                       |
| Yield stress, [MPa]           | 507 – 556 | 646 – 751 | ---                           |
| + (27–35) %                   |       |       |                               |
| Electric conductivity, [% IACS] | 5–6  | 5–6     | ---                           |

Table 4 Machinability comparison summary table

| Comparison criteria (Orthogonal cutting) | WAAM | HF-WAAM | Low-carbon Steel (Reference) |
|-----------------------------------------|------|---------|-------------------------------|
| Cutting Force [N]                       | Base | −3%     | −12%                          | 1697 – 3133 |
|                                         | Centre| −5%     | −1%                           |
|                                         | Top  | 0%      | −9%                           |
| Consumed Power [W]                      | Base | −3%     | −12%                          | 167.2 – 331.6 |
|                                         | Centre| −5%     | −1%                           |
|                                         | Top  | 0%      | −9%                           |
| SCE [GJ/m³]                             | Base | −3%     | −12%                          | 1.58 – 2.23 |
|                                         | Centre| −5%     | −1%                           |
|                                         | Top  | 0%      | −9%                           |
| Shear Angle [°]                         | Base | 0%      | −8%                           | 28.82 – 33.69 |
|                                         | Centre| −4%     | −4%                           |
|                                         | Top  | −3%     | −5%                           |
| Shear Stress [MPa]                      | Base | +3%     | −9%                           | 586.2 – 844.2 |
|                                         | Centre| +2%     | +2%                           |
|                                         | Top  | +7%     | −2%                           |
| Friction Coefficient                    | Base | +15%    | −17%                          | 0.73 – 0.85 |
|                                         | Centre| −11%    | −17%                          |
|                                         | Top  | −16%    | −16%                          |
| Surface Roughness [μm]                  | Base | −57%    | −84%                          | 11.44 – 15.96 |
|                                         | Centre| −77%    | −59%                          |
|                                         | Top  | −52%    | −65%                          |

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material with lower cutting forces and less energy consumption, without compromising the surface quality requirements.

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Declarations

Ethics approval The authors declare that the present study is original, without any kind of plagiarism and/or inappropriate data manipulation/falsification form, and has not been divided in several parts. The authors also declare that the work reported in this paper has not been published previously, and is not under consideration for publication elsewhere, in English or in any other language.

Consent to participate Not applicable.

Consent for publication The authors declare that they consent the publication of the work reported in this paper.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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