Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Evaluating and comparing secondary machining characteristics of wrought and additive manufactured 316L stainless steel

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A R T I C L E I N F O

Article history:
Available online xxxx

Keywords:
Stainless steel
Secondary machining
Wrought
Additive manufacturing
Threading
Tool wear

A B S T R A C T

This paper is based on evaluating, analysing and comparing the secondary machining characteristics of wrought and additive manufactured 316L Stainless Steel. This paper is an attempt to determine the process efficiency and evaluate the machinability factors which effect the service life. Stainless steel is a historic iron carbon alloy reputed for its high corrosive resistance and extensive application base. Threading, tapping, reaming and knurling are the most common secondary machining operations after a primary machining operation to achieve a required surface finish and form. As threading plays a significant role in fastening two components together. Threading is selected as a secondary machining operation in this paper. The research methodology consists of conducting threading operation on a hollow cylinder of 50 mm diameter using a lathe. Threads are cut into the workpiece using variable cutting parameters such as spindle speed; 90 and 180 rpm and coolant condition; on/off. Thread pitch which is also the feed rate (1 mm/rev) and Depth of Cut (0.3 mm) remains constant for all the trails. Statistical data are collected and analysed by qualitative and quantitative evaluation. The outputs under consideration to evaluate the machinability includes the cutting forces, thread profile accuracy (pitch) and tool wear. It has been observed that the cutting force and the tool wear was predominantly high for SLM compared to wrought. The paper concludes to convey the point that wrought components has better machinability characteristics than additive manufactured stainless steel.

1. Introduction

Steel is defined as an Iron-Carbon alloy containing varying amounts of carbon from 0.008 to 2.1 %. The variation of carbon concentrations and addition of alloying elements varies the properties of steel drastically [1]. Steels exist in various phases depending on the eutectoid temperature. The physical properties exhibited by steel depend on the phases present after the phase transformation. The phases present in steel after heat treatment can be manipulated by the addition of alloying elements. The alloying elements shift the phase diagram depending on their weightage. Depending on the microstructural phase, steel are classified as Austenitic Stainless Steel, Ferritic Stainless Steel, Duplex Stainless Steel and Martensitic Stainless Steel [2]. Austenitic Stainless Steel (316L) is a popular choice in design applications because of its high corrosive resistance. The potential areas of application are petroleum, chemical, biomaterial and automobile industries. The stainless-steel parts are produced by conventional methods like casting, forging, or extrusion. Due to the high chromium content, machining is a drawback but new technology such as additive manufacturing has solved the issue to an extent in certain application involving complex shapes and monolithic structures [3]. There are a lot of unknowns especially on the fatigue and creep characteristics of additive manufactured components. Though for production of complex parts, they need to be machined or welded, which may cause inter-granular corrosion affecting the mechanical properties of the part [4]. Hence, various new advanced manufacturing technologies are developed. These processes make production of complex parts easier, without affecting the mechanical properties of the material [5,6]. Additive Manufacturing (AM) technologies can be processed using various scientific processes and methods. Such as different layer-wise production processes like 3-D printing, stereolithography, Selective Laser Melting (SLM) and Electron Beam Melting (EBM).

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https://doi.org/10.1016/j.matpr.2023.05.404
2214-7853/

Please cite this article as: A. Polishetty, J. Nomani and G. Littlefair, Evaluating and comparing secondary machining characteristics of wrought and additive manufactured 316L stainless steel, Materials Today: Proceedings, https://doi.org/10.1016/j.matpr.2023.05.404

Selective Laser Melting (SLM) is a type of AM technique, which involves layer by layer manufacturing using a micrometer sized particle powder and laser beam as source of heat to melt and bind the powder [7,8]. The specimen manufactured is free from the fabrication of materials. A complete 3D model of the specimen is made using CAD software. The model is then divided in various layers of micrometer thickness with the help of a customized AM software [9]. In SLM, the laser performs an essential operation of scanning of the thin layer of the powder which are deposited on the base of the chamber. The process of material forming goes in the same direction as laser beam scanning. Sequentially, elongated lines of molten powder are filled in every cross-section of the part. The quality of the specimen manufactured by SLM method will depend on the layer thickness, powder size, power of the laser beam, scanning speed, hutching, the orientation and build-direction [7]. Hence, SLM manufacturing process is parameter sensitive process. SLM manufactured specimens of 316 stainless steel show high tensile, compression, hardness, and part density as compared to wrought or cast materials, this is because the parts are subjected to high cooling rates during manufacturing process which results for a short grain microstructure.

This paper attempts to explore the research gap which exists especially regards to secondary machining of additive manufactured stainless steel. There are very few research works conducted regards to secondary machining of additive manufactured components. There are research articles talking about hybrid Additive Manufacturing (AM) which is a combination the AM and physical machining. Research work carried out by Michael P. Sealy, Gurucharan Madireddy et.al conveys that hybrid AM has become a game changer for designers especially for components utilising the concept of Design for Additive Manufacturing (DfAM) [10]. Ugur M. Dilberoglu, Bahar Gharehpapagh et.al talk about the current trends and opportunities regards to hybrid additive manufacturing [11]. Ashwin Polishetty et.al have carried out research on secondary machining characteristics of Additive Manufactured Titanium where the research involved single set up CNC machine tapping of an internal thread in a drilled hole [12].

2. Materials and methods

The chemical composition of the material used was determined using optical spectrometry. The elemental distribution of each material is tabulated under Table 1. The bulk hardness of SLM and wrought 316L was evaluated using Rockwell C scale and found to be 12 Rc and 18 Rc respectively. The threading trials were conducted on a Tos Trencin SN40C conventional lathe machine. A customised tool holder attached to the Kistler dynamometer type 9272 was mounted to the tool post. The dynamometer records the cutting forces during the process. Kistler amplifier 5070A was used for data acquisition purposes. Wrought and SLM 316L cylindrical hollow cylindrical workpiece (as shown in Fig. 1) of size 50 mm in diameter and 50 mm in length is used in this research. Fig. 1 shows as print SLM 316L ready to be machined. External threads are machined on the workpiece using variable machining conditions such as spindle speed and coolant use, as shown in Table 2. The thread pitch, which is also the feed rate and Depth of Cut (DoC) remain constant throughout the machining which are 1.0 mm/rev and 0.3 mm, respectively. Coolant (6 % soluble oil and water) was used for all the trials. The cutting inserts that are utilized for this machining process are ISCAR 16ERM AG60 ic808 with TiAlN PVD coating. The tool and dyno set up for the threading operation is shown in Fig. 2. Each trial run used a fresh cutting edge to ensure zero reference for the tool wear analysis. To ensure tight fit and no relative motion during the threading process, a snap fit tool is designed so that the workpiece can be mounted in the lathe machine. To understand the doubling effect of cutting parameter on the machining outputs, the spindle speed was selected in the ratio of 1:2. The surface of the workpiece is lightly machined to remove any oxidation layer to ensure minimal effect of surface properties influencing the outcomes. Post machining, the cutting inserts were subjected to tool wear analysis using an optical microscope. The thread profile generated is inspected and checked for thread profile accuracy using a stylus-based surface profilometer (Taylor Hobson Form Talysurf 50 machine) as shown in Fig. 3. Threads being a form of repeated pattern/texture on the surface over a pre-defined length, the peak and troughs generated when the stylus move over the thread was used to check for wave amplitude/height and measure thread pitch.

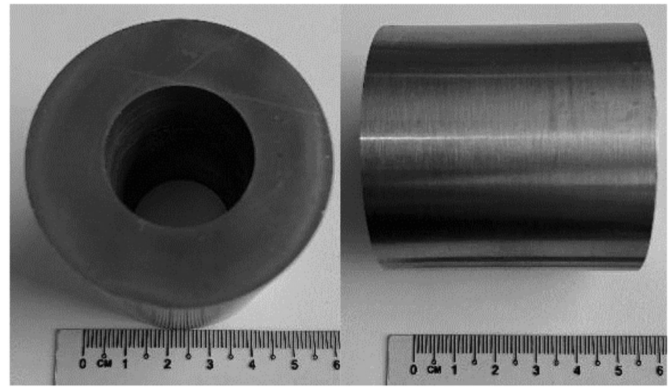

Fig. 1. As Print SLM 316 L hollow cylinder.

Theoretically, thread pitch (1.0 mm/rev) is equal to the feed rate but in practise this is not the case. As pitch measurements from surface profilometer graphs were roughly around 0.75 mm. Due to the limited material resource, a randomly selected trial (D1 and D2) was repeated twice to ensure reproducibility of the results. The variation observed between the results were within the acceptable limit around 1 %. The thread profile obtained using the Talysurf surface profilometer is shown in Fig. 5.

3. Results and discussion

In this section, all data and results obtained from the experimental works in this project are analysed and discussed. All new findings or results that align with previous done research will be correlated and compared. The threaded workpiece was finish machined and slotted for separating each trial to make the threading process easier is shown in Fig. 4.

Table 1
Chemical composition of SLM and wrought Stainless Steel 316.

Material	Fe	Cr	Ni	Mo	Mn	Si
SLM 316L	65.1	17.4	11.8	3.3	1.4	0.9
Wrought 316L	68.6	17.6	9.4	2.5	1.3	0.5

Table 2
Machining plan for wrought and additive manufactured AISI stainless steel 316L.

Material	Diameter (mm)	Trial	Pitch (mm/rev)	Spindle Speed (m/min)	Spindle Speed, n (rpm)	Depth of Cut (mm)	Coolant
Wrought	50	A1	1.0	15	90	0.3	ON
Wrought	50	B1	1.0	15	90	0.3	OFF
Wrought	50	C1	1.0	30	180	0.3	ON
Wrought	50	D1	1.0	30	180	0.3	OFF
SLM	50	A2	1.0	15	90	0.3	ON
SLM	50	B2	1.0	15	90	0.3	OFF
SLM	50	C2	1.0	30	180	0.3	ON
SLM	50	D2	1.0	30	180	0.3	OFF

Fig. 2. Lathe and dyno set up for the threading operation.

Fig. 3. Taylor Hobson Form Talysurf 50 and thread profile evaluation set up.

3.1. Cutting force analysis

The mean value obtained for feed and tangential force are shown in Fig. 6 and Fig. 7 respectively. The radial force was not taken into consideration as it has a negligible effect on the threading process. Taking into consideration the axis defined as per the dynamometer, it is assumed that the feed force is acting towards the spindle and parallel to the spindle axis and tangential force is acting upwards normal to the workpiece. The cutting force was analysed against three distinct factors-type of material, coolant condition and spindle speed respectively. It can be seen in Fig. 6 and Fig. 7 that the feed force and tangential force for each trial was higher for SLM than wrought. This significantly confirms the trends as suggested by earlier research on machining SLM and wrought materials. Usually for a turning operation, tangential force is higher than feed force. Contrary, for a profile cut such as threading where the feed is equal to the pitch of the thread, it is proven to be opposite. Machinability point of view it is difficult and tough to cut SLM because of its process defects- microstructural phase consistency, non-uniform solidification rate, unmelt pool spots, stress

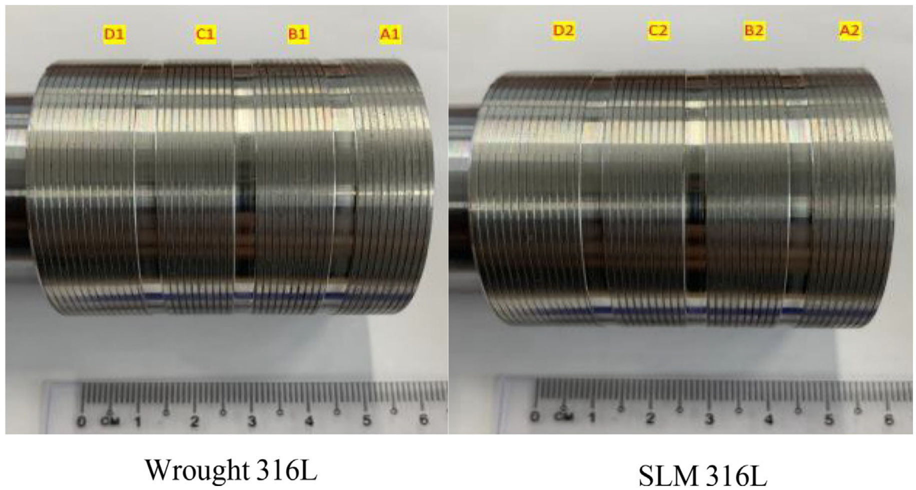

Fig. 4. Post machining-threaded workpiece for wrought and SLM316L.

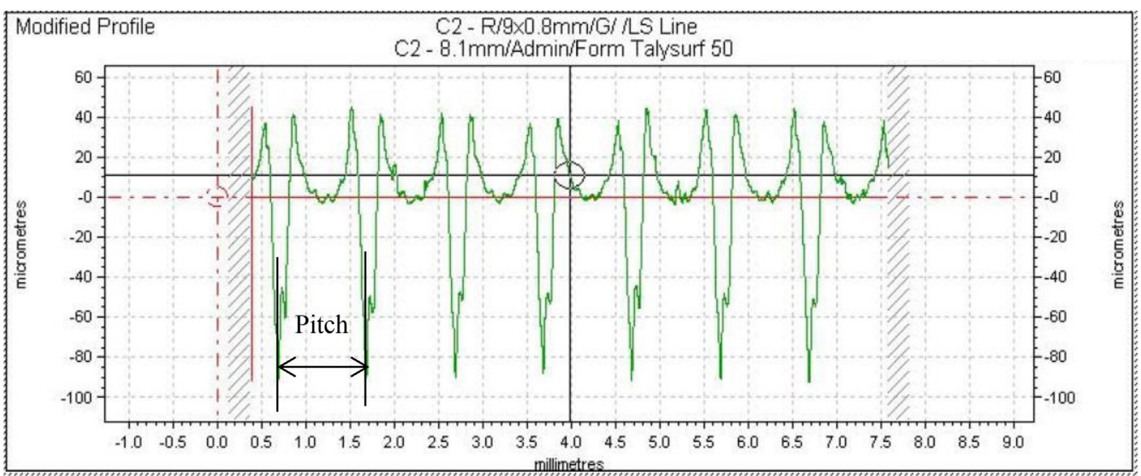

Fig. 5. Pitch measurement for sample: SLM 316L, 180 rpm, Coolant ON.

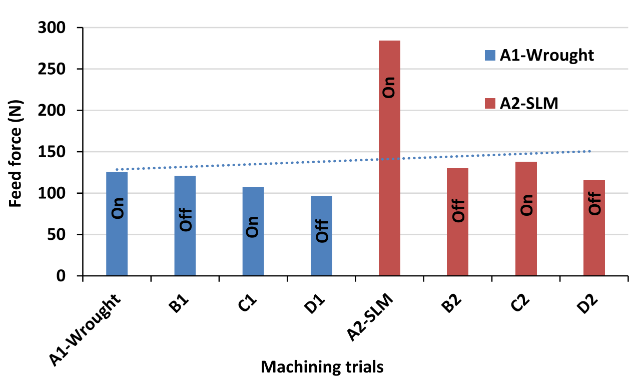

Fig. 6. Feed force variations.

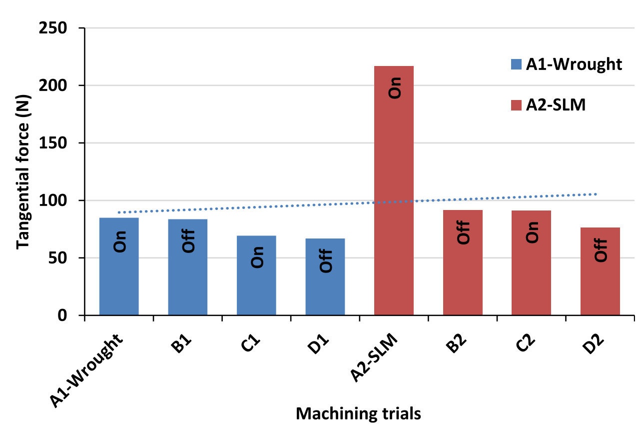

Fig. 7. Tangential force variations.

concentration and overall high hardness. In addition, it is observed for both feed and tangential force, the presence of coolant during machining results in the majority trials especially SLM experiencing a higher cutting force. The probable reason can be the phase hardening due to strain induced transformation which is common in SLM materials born out of rapid fluctuations in thermal gradients and residual stress levels.

3.2. Tool wear analysis

The data obtained from evaluation of tool wear, primarily flank wear for each trial is shown in Fig. 8. The trend line points towards an upwards slope indicating an increment in flank wear after each trial. It should be noted that the initial condition of the tool wear

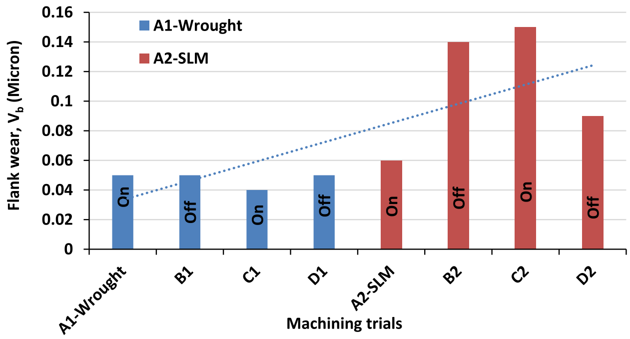

Fig. 8. Flank wear variations.

was set to zero microns as new cutting edge/insert was used at the start of each trial. Because of the high hardness of SLM compared to wrought, SLM experienced a high tool wear. The influence of coolant on tool wear was clear with most of the trials with coolant on condition having less tool wear except one trial C2 (SLM).

The tool wear data obtained to understand the effect of doubling up the spindle speed was not conclusive because of its random nature. A corroboration can be established between the

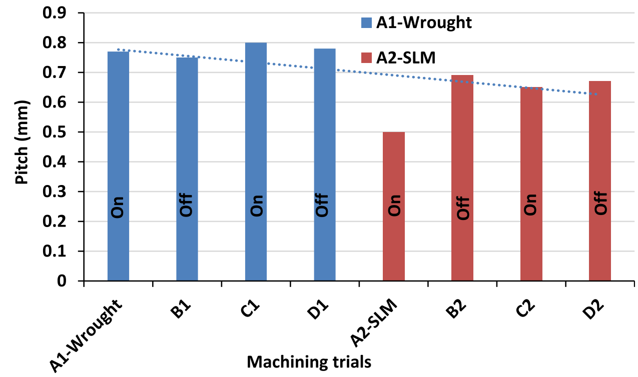

Fig. 10. Thread pitch variations.

current research and previous research work done by the authors on tool wear, chipping and BUE for SLM titanium and Al-6XN super austenitic stainless steel. Alabdullah et al. conducted a study of tool wear to evaluate the machinability of super austenitic stainless steel, AL-6XN alloy and found that chipping-based tool wear was high [13]. Also, chipping based tool wear especially around the flank region of the cutting tool was stated to be one of the reasons

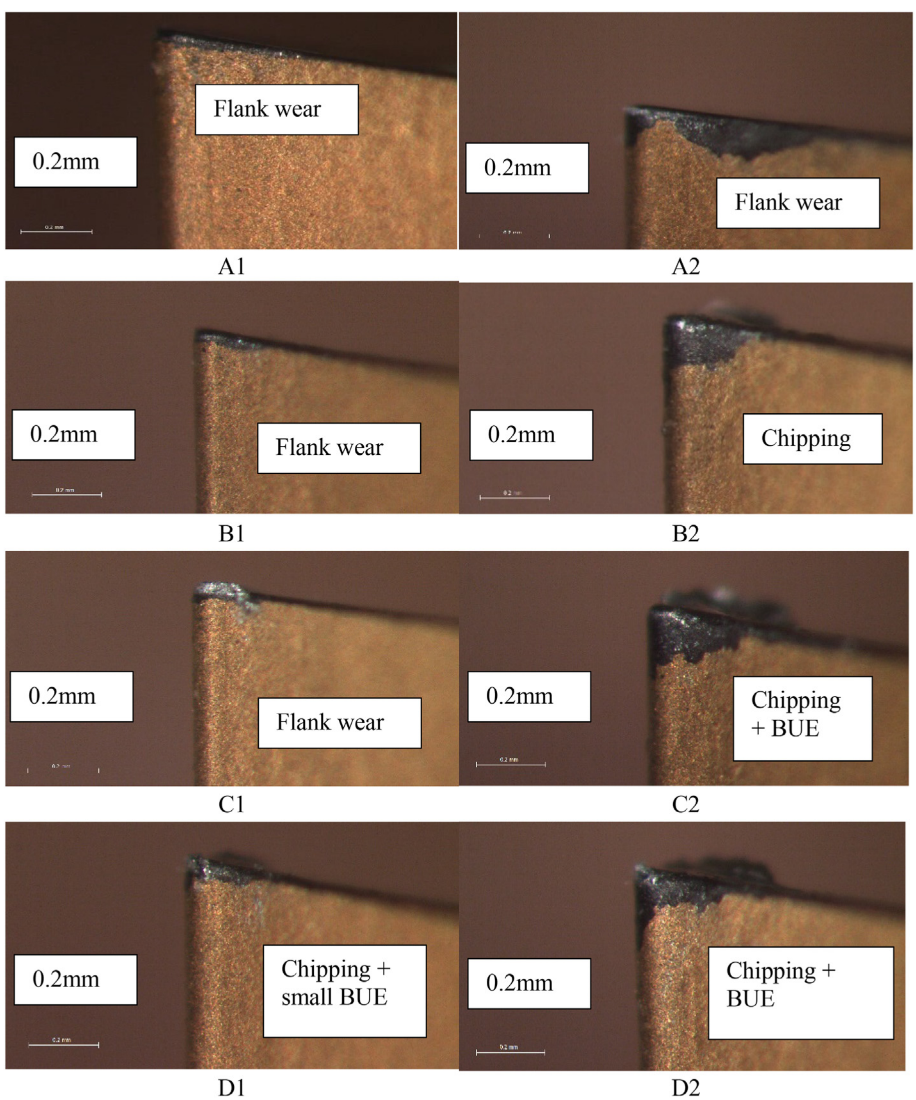

Fig. 9. Types and cause of tool wear.

for higher cutting forces in SLM 316L. Machining the stainless-steel alloy with a chipping wear-resistant cutting edge raised the cutting forces. Instead of one straight and defect free cutting edge, the chipping wear resulted in the creation of separations/loss of material in the cutting edges. These weakened cutting edges worked together to machine the alloy, resulting in a longer tool-chip contact duration on the rake face of the cutting insert, resulting in higher force values.

According to Kalpakjian and Schmid, the addition of 2 % molybdenum to the 316L alloy as an alloying element increases strength but leads to increase in feed force during machining [14]. Molybdenum is found at a higher concentration in the SLM 316L, up to 3.3 %. Fig. 9 shows the pictorial representation of the cutting edge subjected to chipping and abrasion and built-up edge (BUE) wear around the flank region for each trial. The magnified images of cutting edge in C2, D1 and D2 show signs of BUE. There is a negligible amount of tool wear in A1 whereas in rest of the trials, flank wear and chipping can be commonly observed. From trial C2, it is evident that BUE had a positive effect by strengthening the cutting edge leading to lower cutting force. Contrary, the BUE and chipping was also the reason for high flank wear for trial C2.

3.3. Thread profile accuracy

In this section, the thread profile data for each trial obtained from the graphs generated using surface profilometer is analysed and discussed. Thread pitch was taken as the factor defining the thread profile accuracy or dimensional accuracy in machinability terms.

According to the definition, a thread pitch can be calculated by measuring the difference in length between a point on a thread and corresponding point on the immediate or next thread. Fig. 10 shows the pitch variations for each trial. It is observed that all SLM 316L trials have an uneven pitch compared to wrought 316L. Also, wrought 316L has more uniform thread profile where the pitch is around 0.75 mm for all trials. It can be said that the presence of coolant and variable spindle speed especially for SLM has a certain effect on the thread profile. The effect of coolant/spindle speed was negligible in wrought 316 as it produced consistent threads irrespective of coolant condition. Some of the trends observed in thread profile accuracy can again be attributed to the process defects in SLM as threading itself is almost radially creating a thin curved wall of a minimal depth (1 mm) around the workpiece circumference. Intrinsic material properties like bulk hardness, ductility, and consistent microstructural phase for a machining sensitive material like SLM is going to influence the threading process. The other likely reason can be the tool deflection during the threading process.

4. Conclusions

Considering the results obtained, the paper concludes that it is easier and less problematic to machine threads on a wrought material compared to SLM. The research conducted is an attempt to evaluate and compare the machinability of wrought and SLM 316 stainless steel from a secondary machining point of view. Due to its stabilised microstructural phase, material properties, less process defects, wrought has an added advantage in terms of machinability compared to SLM. The cutting force predominantly high for SLM compared to wrought. The presence of coolant has not eased the process anticipating lower cutting force instead the forces were high suggesting a possibility of hardening due to strain induced transformation. The tool wear primarily flank wear was high for SLM compared to wrought. The type of wear most seen in all the trials was chipping, BUE and flank wear. Chipping resulted in the creation of separations/loss of material in the cutting edges and the weakened edge led to increase in the cutting force. Regarding the thread profile accuracy, wrought material has shown more consistency in pitch almost 0.75 mm in most cases. The probable reason for inconsistency in a pitch can be attributed to the tool deflection during the threading process. It is evident that machining SLM material particularly for a dimension and profile sensitive process like threading is problematic and intricate.

CRediT authorship contribution statement

Ashwin Polishetty: . **Junior Nomani:** Formal analysis, Investigation, Supervision, Writing – review & editing. **Guy Littlefair:** Project administration, Resources.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

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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