Experimental Investigation on End Milling Behavior of Additively and Conventionally Manufactured 18Ni300 Maraging Steel

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Abstract: Additive manufacturing has made it possible to design and print complex geometric components that could not be achieved with traditional manufacturing methods. With the current limitations in optimizing the surface topography of printed parts, efficient cutting process parameters are essential for optimal post-processing of additively manufactured components. This experimental study investigated the relationship of end milling parameters with surface quality in view of varying metallurgical conditions with respect to manufacturing methods, besides specifically investigating build orientation and sample condition (aging heat treatment) effects on the machinability of additively manufactured 18Ni300 maraging steel. Key findings reveal that surface roughness is significantly influenced by feed rate, depth of cut, and cutting speed, with marked differences between additively and conventionally manufactured specimens. Additively manufactured components displayed lower surface quality at a 90-degree build orientation, while the best surface finish was achieved on directly aged conventional specimens at 0.089 µm, compared to 0.476 µm in as-printed AM samples. Aging heat treatment also impacted surface characteristics, as observed through optical microscopy, with aged samples showing prominent feed lines. Additionally, pre-existing defects in additively manufactured specimens suggest potential impacts on surface integrity and performance. These findings highlight the importance of optimizing milling parameters for maraging steel, especially for additive manufacturing, to enhance surface quality across varying build orientations and heat treatment conditions.Moreover, machining characteristics are affected owing to the anisotropy induced in AM-produced components.

Keywords: Additive manufacturing, Build orientation, 18Ni300 maraging steel, Aging heat treatment, End milling

B. S. Babu et al. (eds.), *Proceedings of International Conference on Advanced Materials, Manufacturing and Sustainable Development (ICAMMSD-2024)*, Advances in Engineering Research 257,
https://doi.org/10.2991/978-94-6463-662-8_42

1. Introduction

Additive manufacturing has transitioned from prototyping to functional part production over the past decades. Investigations have focused on processing several conventional metallic alloys through AM technology, including 18Ni300 grade maraging steel[1]. Maraging steels are favored for their strength, toughness and corrosion resistance in demanding applications [2]. Besides, their excellent weldability characteristic favorstheir ease of printing- a key factor sought primarily during AM materials' selection [3].

Despite the ongoing research aimed at optimizing process parameters in additive manufacturing, the properties achieved continue to be constrained and are generally inferior when compared to those of components produced through conventional manufacturing methods[4].Surface roughness in metallic additive manufacturing (AM) is often influenced by process parameters, such as laser power, scan speed, and layer thickness[5]. In light of our attempts to optimize these parameters, AM parts commonly exhibit inherent surface irregularities due to various factors like powder particle size, layer-by-layer construction, and thermal gradients [6]. These rough surfaces can negatively impact mechanical performance, fatigue life, and functional properties, necessitating post-processing techniques like machining, polishing, or chemical treatment to achieve the desired finish. Therefore, while process optimization can reduce surface roughness to an extent, post-processing remains essential to meet the stringent requirements for high-performance metallic components [7].

End milling is a widely used machining process in which a rotating cutting tool, known as an end mill, is used to remove material from a workpiece[8]. Unlike other milling processes, end milling can be employed to create intricate shapes and complex features with fine precision for high-value applications.While significant effortshave been made to optimize AM parameters in an effort to improve surface quality, traditional subtractive processes still remain crucial for precision industries[9]. Consequently, there has been a significant growth in the post processing of AM metallic parts, especially over the past decade.

The paper is organized as follows: Section II deals with the existent literature work. Section III describes the methodology of the experimental work, Section IV explores the results and analysis and finally, Section V presents the conclusions.

2. Literature Work

The ongoing research on 18Ni300 maraging steel has been focused on improving the surface finish through end milling operation and hence highlights the importance of cutting parameters in optimizing surface quality. Duro et al.[10] attempted to optimize the end milling process parameters of AM 18Ni300 maraging steel for high-value applications. They noted a significant improvement in surface integrity both in terms of surface finish and residual stresses and compared the machinability of additively manufactured material with its conventionally manufactured counterpart. Oliveira et al.[11]evaluated how build orientation in Laser Powder Bed Fusion (LPBF) manufacturing, combined with post-process aging (480 °C for 3 hours) and milling at different cutting speeds and feed per tooth, impacted the surface condition of maraging steel samples. Statistical analysis of roughness and residual stress showed that mechanical anisotropy and layer arrangement in the LPBF process influenced the samples' surface finish and stress profiles. Fortunato et al.[12] investigated to explore the optimal manufacturing process for producing high-quality 18Ni(300) molds using a combination of additive and subtractive methods. Key variables in their research study included build direction and post-build heat treatment for the SLM process, and cutting speed for the end milling process.

Aging heat treatment is a critical process in enhancing the mechanical properties of both conventional and additively manufactured 18Ni300 maraging steel[13]. The precipitation-hardening steel, known for its exceptional strength and toughness, undergoes a transformation when subjected to controlled heat treatment. The aging process involves heating the material to a specific temperature, allowing the formation of intermetallic precipitates, particularly nickel-rich phases, which strengthen the steel's microstructure[14]. In the context of additive manufacturing, where the microstructure can vary due to the layer-by-layer fabrication method, aging heat treatment plays a pivotal role in homogenizing the properties and improving the overall performance of 18Ni300 maraging steel components[15][16]. Kempen et al.[17] reported the presence of austenite content in directly aged samples owing to the transformation of martensite to austenite during aging. In contrast, samples subjected to solution treatment before aging did not have significant austenite content as the remaining austenite after printing changed to martensite by virtue of homogenization. Conde et. al[18] found increased austenite content for directly aged L-PBF samples in comparison with samples subjected to solution treatment before aging. Traditional maraging steels are generally subjected to solution treatment as an intermediate step; in an attempt to prepare the material for aging through homogenization[19], thereby achieving uniform alloying elements distribution- though with some traces of reverted austenite at more than optimum heat treatment temperatures or time[20].

Among the various attempts in the literature to reduce surface roughness with concurrent improvement of strength and ductility is Hot Isostatic Pressing (HIPing). But such investigationson AM materials were shown to have an insignificant effect in mitigating surface defects or improving surface roughness[21][22] and hence surface machining was still recommended to be performed after HIPing processes[23]. Song et al.[24] reported a drastic reduction in defects when LPBF 18Ni300 maraging steel samples were subjected to HIP and HIP+Aging heat treatment. Yet, upon examining the samples through Micro-CT technique, they emphasized the presence of (majorly) spherical pores along with some lack-of-fusion defects, especially near the sample surface.

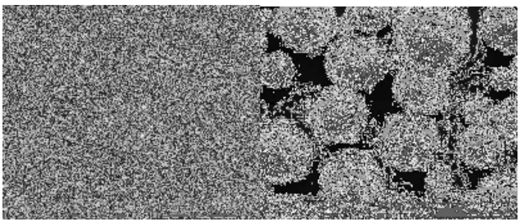
Although there are some research investigations in the existent literature, the machinability and post-processing of AM 18Ni300 maraging steel is still limited and hence needs further exploration.Accordingly, this experimental investigation aims to evaluate the variation of surface roughness of AM-built components with build orientation, sample condition and cutting process parameters, besides comparing their behavior with the conventional 18Ni300 maraging steel.

The work in this paper has been analyzed through two techniques: 1) Analyzing the variation of surface roughness with build orientation, sample heat treatment condition and milling process parameters, and 2) Surface defects analysis through optical microscopic technique. ANOVA technique has been used to analyze the surface roughness variation whereas Light Optical Microscopy (LOM)was utilized to examine the surface defects.

3. Methodology

3.1 Fabrication and Characterization of SLM Specimens

A Dual-laser STLR-400 Metal 3D Printer was utilized to fabricate SLM specimens in a nitrogen atmosphere with the 18Ni300 powder, analyzed via TESCAN Compact SEM (Figure 1). The manufacturer-recommended printing parameters were applied: 250W laser power, 850 mm/s scanning speed, 0.1 mm hatch distance, 100°C platform temperature, 50 µm layer thickness, and a 67° rotational stripe-pattern scan strategy. Machining specimens (32x32x11 mm) were printed in three orientations: 0°, 45°, and 90° (Figure 2). Additional supports for the 45° specimens were removed via wire-EDM. The 0°, 45°, and 90° specimens required 220, 608, and 640 layers, respectively. Density, measured via Archimedes' principle, was approximately 8.065 g/cm³.



(a) **(b)**

Fig. 1. SEM Micrograph of AM 18Ni300 powder (a) low magnification (b) high magnification

3.2 Preparation and Treatment of CM and AM Specimens

A conventionally manufactured (CM) maraging steel plate (200x120x8 mm, 40 HRC) was procured, and 32x32x8 mm specimens were cut using a Wire-EDM machine, essentially matching the size of the additively manufactured (AM) specimens. Both CM and AM specimens were face milled using a 44 mm diameter cutting tool with four inserts, with a 0.35 mm depth of cut for surface leveling in preparation for Design of Experiments (DoE) cutting trials. The specimens were divided into two groups: the "untreated group," which underwent end milling in their as-printed (ASP) or as-cast (ASC) states, and the "heat-treated group," which received direct aging treatment (DAT). DAT was performed on both AM and CM specimens (DAT-AM and DAT-CM) by heating at 480°C for 3 hours in a Yatherm Scientific muffle furnace, followed by air quenching.

3.3 Milling experimental setup and measurement techniques

End milling operations were carried out on a CNC Vertical Milling Center (LMW JV 55), as shown in Figure 3(a). Square, coated Ø6 mm end mills with 4 flutes were sourced from Onyx Toolings LLP. All the experimental trials were conducted in dry/no lubrication condition. The channel dimensions for each milling trial were set to 6x15 mm as shown in Figure 3(b).

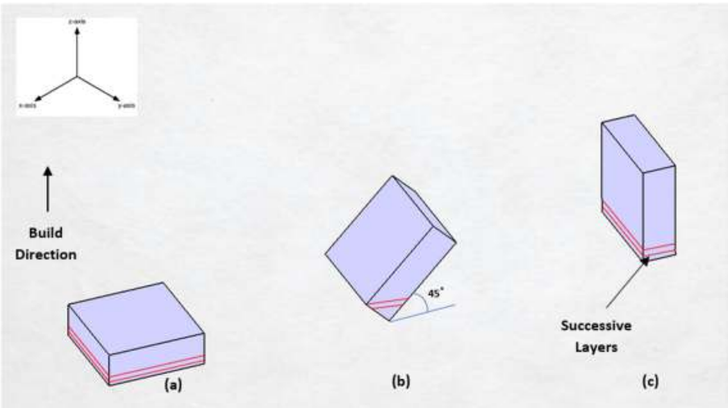


Fig. 2. Illustration of the building process and layers arrangement of **(a)** 0 deg, **(b)** 45 deg and **(c)** 90 degree, during additive manufacturing

Table 1 presents the cutting parameters selected for the experimental study, including cutting speed, feed per tooth, and depth of cut, all varied at three levels.

Table 1. Cutting parameters: Factors and Levels

S. No.	Factors	Levels		
		L1	L2	L3
1.	F1: Cutting Speed (m/min)	50	75	100
2.	F2: Feed per Tooth (mm/tooth)	0.01	0.02	0.03
3.	F3: Depth of Cut (mm)	0.1	0.25	0.4

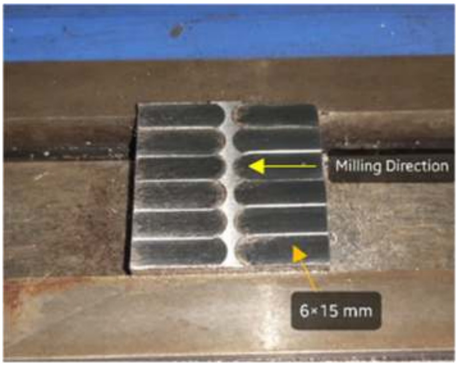
A Taguchi L9 orthogonal array experimental design, as described by Montgomery[25] was conducted for both conventionally manufactured (CM) and additively manufactured (AM) specimens. The AM specimens were tested at three different orientations: 0-degree, 45-degree, and 90-degree. For each orientation, two repetitions of the experiment were performed, ensuring the reliability of the results. The detailed experimental setup, including the specific levels and factors used, is displayed in Table 2. The data obtained from these experiments were analyzed using the Analysis of Variance (ANOVA) technique. This analysis was conducted using Minitab statistical software to determine the significance of the factors affecting the milling performance of the specimens.

SJ210 Mitutoyo surface roughness tester was utilized to measure surface roughness, with a cut-off parameter and sampling length of 0.8mm and 4mm respectively.Measurements are taken at two central locations in the milling channel, aligned with the feed direction, and are later averaged. An Olympus BX53M Optical Microscope (OM) was used to inspect the machined specimens for surface defects.

Table 2. Taguchi L9 orthogonal array

Taguchi Array No.	Cutting Speed (F_1)	Feed Rate (F_2)	Depth of Cut (F_3)
1	50	0.01	0.1
2	50	0.02	0.25
3	50	0.03	0.4
4	75	0.01	0.25
5	75	0.02	0.4
6	75	0.03	0.1
7	100	0.01	0.4
8	100	0.02	0.1

9	100	0.03	0.25



(a) **(b)**

Fig. 3(a) CNC setup with end mill and **(b)** Specimen with milling channel dimensions

4. Experimental results

4.1 End milling results for surface roughness evaluation

An illustration of the melt pools/beads formed during PBF process is shown in Figure 4. The building direction in 0 deg and 45 deg orientations is upwards i.e., Z-direction, whereas it is in X-direction for the 90 deg specimens.

Build orientation in additive manufacturing is a critical factor that significantly influences the quality, mechanical properties, and overall performance of the fabricated parts. The orientation in which a part is printed determines the distribution of material layers, which affects surface finish, dimensional accuracy, microstructure and consequently the mechanical strength of the final product[26]. Different orientations can lead to variations in stress concentration, support structure requirements, and build time, making it essential to carefully select the optimal orientation based on the intended application and material being used[27]. This aspect of additive manufacturing not only impacts the efficiency of the production process but also plays a pivotal role in achieving the desired functional characteristics of the part.

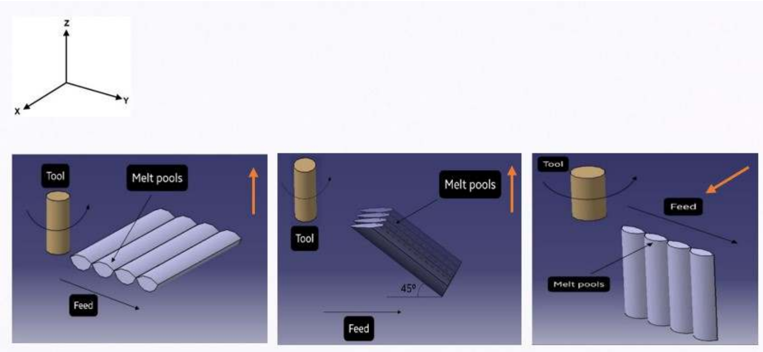


Fig. 4. Illustration showing the melt pool configuration and cutting tool direction, (a) 0 deg, (b) 45 deg, and (c) 90 deg (Orange arrows highlight the AM building direction)

The cutting tool encounters the laser scan tracks or technically referred as white boundaries during the milling pass andhence the build orientation influence is expected to affect the surface roughness results on 0, 45 and 90 deg specimens.The surface roughness results obtained are presented in Tables 3 and 4. Table 3includes the surface roughness results of the as-printed and as-cast specimens after end milling, whereas Table 4lists the surface roughness results of the aged specimens after end milling. It is easily discernible that the aged specimens achieved very low surface roughness levels when compared to the specimens subjected to end milling in the as-printed and as-cast conditions. This could be due to the machinability advantage of aged 18Ni300 maraging steel, as observed by Duro et al.[10] & Oliveira et al.[11].

In the maraged condition, 18Ni300 specimens exhibit excellent machinability owing to their reduced plasticity. The position of cutting line also impacts the chip separation phenomenon in the different material or sample condition, and hence could also explain the better surface quality achieved for the aged condition. Among all the build orientations, 0-deg specimens performed comprehensively better than 45- and 90-deg specimens, as revealed from Table 4. Although the lowest surface finish was obtained for conventional aged specimens i.e., 0.089 µm.

Table 3. Surface roughness results for ASP and ASC

Taguchi Array No.	Cutting Speed (F_1)	Feed Rate (F_2)	Depth of Cut (F_3)	Surface roughness (μm)			
				AM			CM
				0 deg	45 deg	90 deg	ASC
1	50	0.01	0.1	0.476	0.928	1.108	0.740
2	50	0.02	0.25	0.928	1.304	1.712	1.180
3	50	0.03	0.4	1.456	1.672	2.124	1.454
4	75	0.01	0.25	0.844	0.876	1.048	0.632
5	75	0.02	0.4	1.364	1.596	1.448	1.072
6	75	0.03	0.1	1.344	2.120	2.132	1.812
7	100	0.01	0.4	0.804	1.088	1.640	0.680
8	100	0.02	0.1	0.964	1.560	1.596	0.988
9	100	0.03	0.25	1.516	1.704	2.232	2.064

Moreover, 90-deg specimens had comparatively higher surface roughness values, especially in the as-printed milled sample condition. Such behavior could be due to the disadvantage possessed by 90-deg specimens in neither aligning to follow the shear plane or favoring to allow chip separation in proximity to the cutting line[28].

Table 4. Surface roughness results for DAT-AM and DAT-CM

Taguchi Array No.	Cut-ting Speed (F_1)	Feed Rate (F_2)	Depth of Cut (F_3)	Surface roughness (µm)			
				DAT-AM			DAT-CM
				0 deg	45 deg	90 deg	
1	50	0.01	0.1	0.111	0.161	0.245	0.089
2	50	0.02	0.25	0.339	0.394	0.455	0.345
3	50	0.03	0.4	0.539	0.607	0.634	0.654
4	75	0.01	0.25	0.277	0.395	0.217	0.214
5	75	0.02	0.4	0.302	0.464	0.418	0.519
6	75	0.03	0.1	0.422	0.442	0.473	0.863
7	100	0.01	0.4	0.171	0.207	0.428	0.342
8	100	0.02	0.1	0.280	0.422	0.385	0.693
9	100	0.03	0.25	0.367	0.548	0.598	0.905

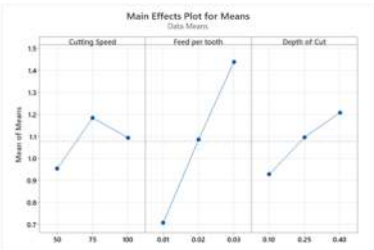
Surface Roughness Variation with Cutting Process Parameters

The influence of feed per tooth increment on surface roughness can be observed in all the build orientations i.e., 0, 45 and 90-deg specimens. Figures 5 and 6presents the ANOVA results for 0 deg AM specimens& CM specimens respectively. Observations regarding feed rate influence can be made through the orthogonal array trials- from 1 to 3, 3 to 6 and 6 to 9, as the feed per tooth is following increasing trend in those trials. This is present despite variations in depth of cut levels. Researchers have earlier reported that increasing feed per tooth significantly raises surface roughness due to a rise in uncut chip thickness[29]. Besides, the chip size formed also grows with increasing feed rates. It is interesting to note that the lowest surface roughness values obtained for both as-printed and aged specimens was at the lowest feed per tooth i.e., 0.01 mm/tooth, reinforcing findings from earlier investigations[12][30].Moreover, such observation was noted across build orientations and metallurgical conditions (both AM and CM). The best surface finish achieved was 0.476 µm in the as-printed milled 0-deg specimen, whereas it was 0.089 µm in the aged milled CM specimen.

ASP- 0 deg

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	10.1389	10.1389	5.0694	19.37	0.049
Feed per tooth	2	62.6458	62.6458	31.3229	119.68	0.008
Depth of Cut	2	11.9193	11.9193	5.9597	22.77	0.042
Residual Error	2	0.5235	0.5235	0.2617		
Total	8	85.2274				

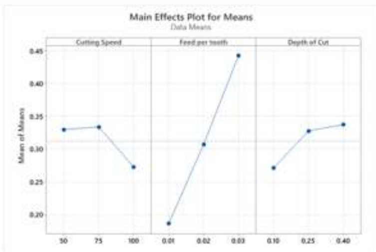


(a)

DAT- 0 deg

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	6.827	6.827	3.413	0.36	0.735
Feed per tooth	2	97.771	97.771	48.886	5.17	0.162
Depth of Cut	2	12.952	12.952	6.476	0.68	0.593
Residual Error	2	18.910	18.910	9.455		
Total	8	136.461				



(b)

Fig. 5. Surface roughness ANOVA tables and main effects plots of Cutting speed, Feed per tooth and Depth of cut regarding surface roughness of **(a)** AM-ASP 0 deg &**(b)** AM-DAT 0 deg

CM- ASC

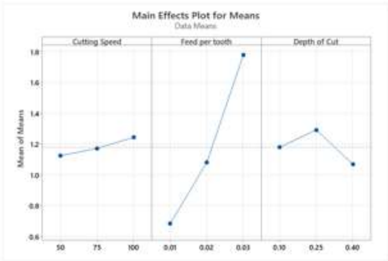
Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	0.199	0.199	0.0995	0.04	0.961
Feed per tooth	2	101.392	101.392	50.6959	20.73	0.046
Depth of Cut	2	1.773	1.773	0.8864	0.36	0.734
Residual Error	2	4.892	4.892	2.4460		
Total	8	108.256				

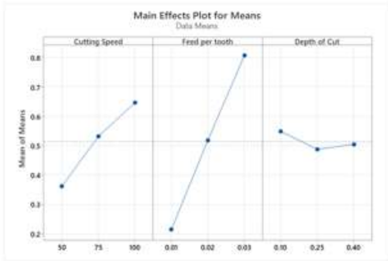
CM- AGED

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cutting Speed	2	72.943	72.943	36.471	5.79	0.147
Feed per tooth	2	249.090	249.090	124.545	19.77	0.048
Depth of Cut	2	8.088	8.088	4.044	0.64	0.609
Residual Error	2	12.602	12.602	6.301		
Total	8	342.723				



(a)



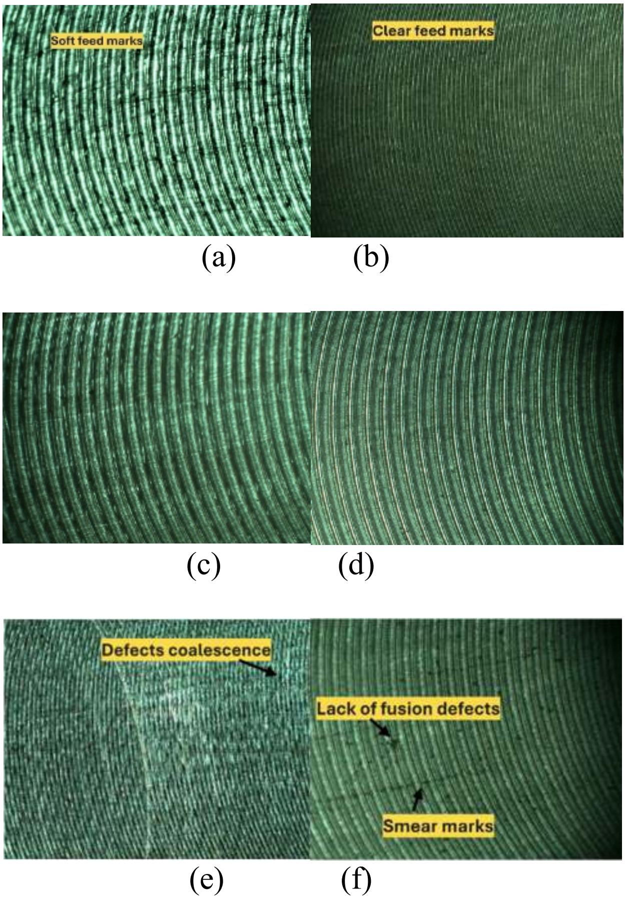
(b)

Fig. 6. Surface roughness ANOVA tables and main effects plots of Cutting speed, Feed per tooth and Depth of cut regarding surface roughness of **(a)** CM-ASC &**(b)** CM-DAT

In contrast, the effect of cutting speed was noted to have lesser comparative significance on surface finish, yet their interaction effect on generating compressive residual stresses on the surface and sub-surface levels was highlighted in several research investigations [31]. DOC was found to have an effect in some of the specimen build orientations, especially at highest cutting speed level (100 m/min) such as AM as-printed 90-deg and CM as-cast specimens along with aged AM 0-deg and 90-deg specimens. Such behavior could be due to the intense plastic deformation occurring at the higher cutting speeds and was also noted in other similar investigations [12].

4.2 Surface Defects

Figure 7 displays the surface defects' images of the different milled specimens. AM 0-deg specimens analyzed through optical microscopy revealed the characteristic feed marks after milling operation. 0-deg DAT specimen showcases clear feed marks owing to the strengthening effect from aging heat treatment [32], as opposed to softer feed marks in 0-deg ASP specimen. 45 deg specimens exhibited similar characteristics with respect to feed lines. It is worth noting that 90 deg AM specimens in the ASP condition revealed the typical defects' coalescence characteristic found in AM specimens subjected to subtractive manufacturing operations. Such behavior was also observed in other similar investigations with build orientation as a variable in their machining characteristics' assessment[11].



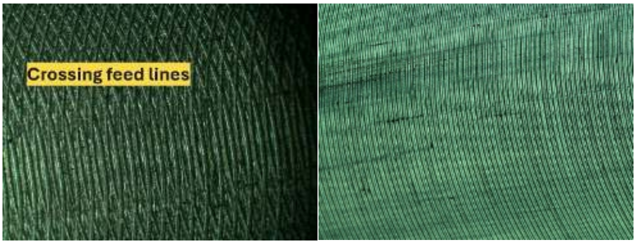


Fig. 7. Surface defects obtained after optical microscopy of (a) AM-ASP 0 deg, (b) AM-DAT 0 deg, (c) AM-ASP 45 deg, (d) AM-DAT 45 deg, (e) AM-ASP 90 deg, (f) AM-DAT 90 deg, (g) CM-ASC and (h) CM-DAT

90 deg AM-DAT specimens unveiled lack of fusion (LOF) defects arising out of the layer-based characteristics in additive manufacturing, which predominantly affects 90 deg components more than 0 and 45 deg specimens. Moreover, smear marks were also observed along with LOF defects. Crossing feed lines were noted on CM specimens before aging heat treatment, whereas separate and distinct feed marks were found to be present on specimens after DAT, highlighting the homogeneity arising out of conventional manufacturing processes[33][34].

5. Conclusions

This experimental research study assessed the machinability of 18Ni300 maraging steel for the different build orientations and sample conditions,with components made through conventional and additively manufacturing methods.

Based on the experimentation and results analysis, the following conclusions can be drawn:

1. Surface roughness is drastically influenced by feed rate followed by depth of cut and cutting speed for both metallurgical conditions of additively and conventionally manufactured 18Ni300 maraging steel.
2. The effect of cutting mechanism led to the lower surface quality in the 90-deg AM specimens, when compared to the 0-and 45-deg specimens in both the as-printed and aged sample conditions.
3. The best obtained surface finish was 0.089 μm in the directly aged conventional 18Ni300 specimen, whereas in the additively manufactured specimens it was 0.476 μm in the as-printed 0-deg specimen.
4. Aging heat treatment effect was clearly noted upon analyzing the milled specimens through optical microscopy technique; distinct feed lines on aged specimens were observed, whereas soft feed marks were found to be present on as-printed and as-cast specimens.
5. Pre-existing defects were identified on AM specimens, which could affect their surface integrity and service-related performance.

These findings provide valuable insights into the machining characteristics of 18Ni300 maraging steel and highlight the importance of optimizing end milling process parameters, especially for additively manufactured components in view of varying build orientations and heat treatment conditions.

Acknowledgements. The authors would like to acknowledge the support received from funding agencies of 'AICTE Doctoral Fellowship(ADF) Scheme' and 'The Institution of Engineers (India) under R&D Grant-in-Aid scheme'.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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