DOI: 10.2507/34th.daaam.proceedings.xxx

INFLUENCE OF DIRECT METAL LASER SINTERING ON THE ULTRASONIC VELOCITY MEASUREMENTS

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This Publication has to be referred as: Grozdanic, M[aria] & Mihaljevic, M[orana] (2023). The influence of direct metal laser sintering on the ultrasonic velocity measurements, Proceedings of the 34th DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/34th.daaam.proceedings.xxx

Abstract

As a result of additive manufacturing, where the part build-up is usually done layer by layer, parts have an anisotropic material behaviour, which directly affects the ultrasonic velocity. In ultrasonic testing, the ultrasonic velocity is one of the most important parameters to be adjusted to obtain the most accurate test results for the tested part, and it must be uniform throughout the whole volume of the part. This paper investigates whether the longitudinal wave velocity in a specimen, manufactured using the direct metal laser sintering process (DMLS), depends on the test direction. The ultrasonic velocity is determined in two perpendicular directions: the layer direction and the build-up direction. Detailed statistical data analysis is performed to determine whether there was a statistically significant difference between ultrasonic velocities in the same test direction (paired t-tests) and between the ultrasonic velocities at perpendicular directions (one-way ANOVA).

Keywords: ultrasonic velocity measurement; additively manufactured specimen; directional dependence; statistical analysis.

1. Introduction

Additive manufacturing (AM) is an advanced production technology that enables the production of objects from 3D model data through the process of joining materials, usually layer by layer. The use of non-destructive testing (NDT) on additively manufactured parts is increasingly common for determining various mechanical and physical properties of materials since they do not damage AM parts during testing [1]. Ultrasonic testing (UT) has found its application in the characterisation of AM parts as well [2], [3]. Material characterization using UT enables the determination of changes in acoustic parameters, which occur due to the propagation of ultrasonic pulses through the test specimen and their interaction on different microstructure. Commonly, UT is used to determine elasticity constants, microstructure, irregularities, and mechanical properties [4]. One of the relevant features for material characterisation is the ultrasonic velocity of the ultrasonic pulse [5], as an important acoustic parameter. The ultrasonic velocity is related to the elastic constants and density of the material, so it provides information about the mechanical, anisotropic, and elastic properties of the medium through which it passes. Several elastic properties of materials, such as Young's modulus of elasticity E, shear modulus G, and Poisson's ratio v, can be calculated with the ultrasonic velocities.

Honarvar et al. [1] made a review of ultrasonic testing applications in the material characterisation of AM parts. They stated that the main reasons for the effectiveness of the UT in the characterisation of AM parts are used additive manufacturing process and the capabilities of used ultrasonic technique.

1.1. Influential parameters of additively manufactured parts on the ultrasonic velocity

Before conducting ultrasonic testing, it is necessary to determine the ultrasonic velocity in the test specimen. The ultrasonic velocity is a characteristic of every material, and it results from the microstructure and metallurgical state of the material, as well as external influences such as temperature and stress. Consequently, a change in ultrasonic velocity in the same specimen can occur within the same material if the material is not a homogeneous structure [6]. Even though AM has many benefits, such as higher efficiency, producing highly optimized parts, flexibility in the development and production, production of prototypes, production of parts that are not impossible to make with traditional manufacturing processes, et cetera, AM also has disadvantages, such as anisotropy, heterogeneity, porosity, surface roughness. Porosity [7], mechanical properties of the material [8], and the degree of anisotropy [9] are highly dependent on process parameters, device settings, and the material in use. Castro-Sastre et al. [10] investigated the influence of used materials. They stated that properties of used material for AM, such as morphological shape and size of the powder particles, chemical composition, and existence of different phases, affect the manufacturing process and the properties of AM parts.

Porosity significantly impacts the properties of AM parts and their application. Pores are stress concentrators with a higher probability of initiating fracture and affecting mechanical properties; therefore, Cook et al. [11] investigated the effect of porosity on ultrasonic velocity. They concluded that the ultrasonic velocity waves decrease with an increase in the proportion of pores. To the same conclusion came Huang et al. [12].

The mechanical properties of components produced by additive manufacturing depend on the material and process parameters; therefore, the 3D printer must correctly adjust before production. The ultrasonic device used limits the settings of production parameters. Different parameters during the additive manufacturing process, such as layer thickness, production speed, laser power, deposition energy [13], and hatch spacing [7], affect the obtained specimen's mechanical properties, ultrasonic velocity, and microstructure. Javidrad et al. [9] investigated the effects of scanning speed, laser power, and the distance between the laser beam paths on the elastic constants of materials in different directions regarding the building direction. The elastic constants of the material were determined by measuring the ultrasonic velocity inside the specimens.

Anisotropic materials have direction-dependent properties. Anisotropy, in additively manufactured specimens, is related to the building direction, where the build-up direction is generally the weakest [14]. Nearly all additive manufacturing processes, due to the nature of building parts, typically material being added together layer by layer, have different properties in the build-up direction than those in the layer direction. Therefore, when producing specimens, it is necessary to take care of the orientation of the specimen regarding the building direction and the required function of the specimens to obtain desired values of its properties. Pandzic [15] investigated the influence of build orientation, layer height, and post-curing on AM part's elastic modulus and tensile strength. He concluded that different combinations of those three parameters lead to different observed property values. It is clear that because of anisotropy in the microstructure, anisotropic mechanical properties occur [16]. Therefore, the ultrasonic velocity can also differ significantly in different directions. Several authors investigated the dependence of the velocity of ultrasonic waves in different directions regarding the building direction in additively manufactured specimens. The specimens were made of different metal materials with different additive manufacturing processes and different process parameters. Lin et al. [17] measured the time-of-flight of ultrasonic waves and calculated the L-wave velocity in perpendicular directions in the specimens (in the build-up direction and the layer direction) on specimens of 316L stainless steel made by selective laser melting (SLM) process with different power laser (from 175 W to 250 W). They determined that the L-wave velocity in the layer direction is higher than in the build-up direction. Also, they found that increasing the laser power increases the density of the specimens. Consequently, with an increase in the density of the material, L-wave velocities increase. Kim et al. [7] investigated the influence of the distance between the laser beam paths on the phase velocity of specimens made of 316L stainless steel manufactured with the Laser Powder Bed Fusion process. They concluded that the phase velocity is always lower in the build-up direction, compared to the layer direction, for all distances between the paths of the laser beam. Sol et al. [18] investigated the potential anisotropy in additively manufactured AlSi10Mg specimens by the SLM process using the Pulse-Echo technique. Measuring and calculating the ultrasonic velocities in different directions, they concluded that anisotropy appears only in the transverse wave ultrasonic velocities, and L-wave velocities are almost the same in all directions.

The success of ultrasonic testing depends on the adjustment of the ultrasonic device. Therefore, before conducting ultrasonic testing on AM specimens, it is necessary to determine the ultrasonic velocity value in the testing direction so could the ultrasonic device be adjusted.

2. Methods

The additively manufactured specimen, shown in Fig. 1, is made of EOS ToolSteel 1.2709 (X3NiCoMoTi 18-9-5) on the EOSINT M280 3D printer from EOS GmbH with Direct Metal Laser Sintering (DMLS) manufacturing process. The DMLS process is based on the melting and sintering fine metal powder using a laser beam, layer by layer, to create a specimen of the desired characteristics and dimensions. The dimensions of the specimen are (140×15×15) mm.

Fig. 1. Additively manufactured specimen

The time-of-flight (t_{TOF}) measurements in the experimental part of this work were carried out with the following ultrasonic system (Figure 2):

- Probe: K5N
- Device: Krautkrämer USM 36,
- Oscilloscope: LeCroy 9310AM
- Couplant: gel
- Technique: pulse overlap

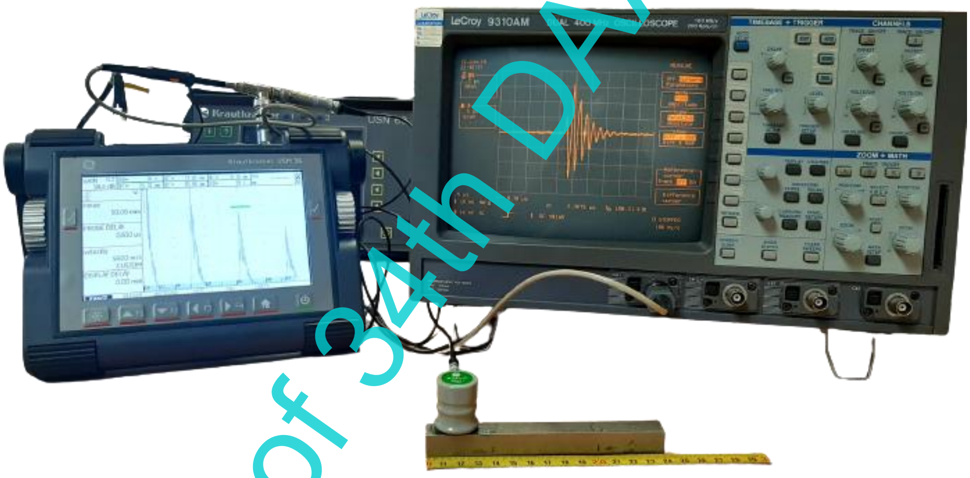


Fig. 2. Ultrasonic system

2.1. Ultrasonic velocity measurement

Ultrasonic velocity is determined by measuring the time-of-flight (t_{TOF}) and knowing an ultrasonic path (s). The ultrasonic path is the distance travelled, by the ultrasonic pulse, between two consecutive echoes from the back wall. It corresponds to the double thickness of the specimen. The velocity of ultrasonic longitudinal waves (v_{L}) calculates according to the equation:

$$v_{\mathrm{L}} = \frac{s}{t_{\mathrm{TOF}}} \tag{1}$$

Time-of-flight measurements were performed at two measurement places in the layer direction (x-axis) – M1 and M2, and at two measurement places in the build-up direction (z-axis) – M3 and M4. The measuring places are 20 mm from the edges of the specimen, and the central axis of the beam is 7.5 mm from both sides of the edges. The positions of the measuring places are marked in Figure 3.

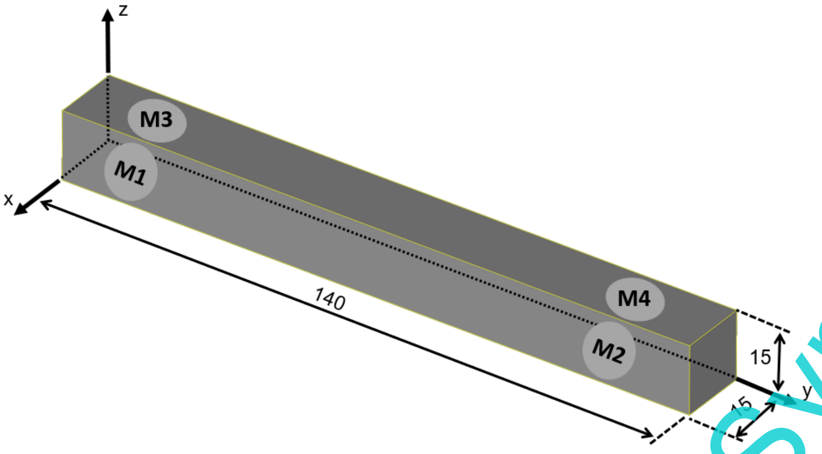


Fig. 3. Test axes and display of measurement places

The Pulse overlap technique is used. t_{TOF} is measured by overlapping ultrasonic pulses between echos from the back wall of the AM specimen. On the overlap between the first and the second echo from the back wall, five points were selected where t_{TOF} was measured. Measurements were repeated five times at the same measuring place. Therefore, 25 measurements were made at each measuring place, and the arithmetic means are presented in Table 1.

Measuring place	**Time-of-flight, t_{TOF} µs**
M1	5.3822
M2	5.3689
M3	5.3379
M4	5.3375

Table 1. Time-of-flight at measuring places

The thicknesses of the measuring places were measured with Mitutoyo LH-600 digital altimeters. At each measuring place, thickness measurements were performed three times, and the arithmetic means are shown in Table 2. Table 2 also presents ultrasonic paths.

Measuring place	**Specimen thickness, *d* mm**	**Ultrasonic path, *s* mm**
M1	15.0913	30.1825
M2	15.0570	30.1141
M3	14.9110	29.8221
M4	14.9126	29.8252

Table 2. Thickness and ultrasonic paths of the measuring places

3. Results and discussion

L-wave velocities are calculated using measurement results of t_{TOF} and specimen thickness d using (1). Type A standard measurement uncertainty was estimated according to the GUM method. The expanded measurement uncertainty is U = 2.5 m/s, with the coverage factor k = 2 and coverage probability P = 95 %. The results of the ultrasonic velocities with the expanded measurement uncertainty are expressed in Table 3.

Measuring place	**L-wave velocity, v_L m/s**
M1	5608 ± 2.5
M2	5609 ± 2.5
M3	5587 ± 2.5
M4	5588 ± 2.5

Table 3. Time-of-flight at measuring places

To determine whether there is a statistically significant difference between ultrasonic velocity in the same direction at two measuring places and different directions detailed statistical data analysis was performed using the Minitab software package. The results of the L-wave ultrasonic velocities are statistically processed and graphically presented below.

The box plots provide a visual summary of the data and show how the values in the data spread out. Thus they were made before statistical analysis.

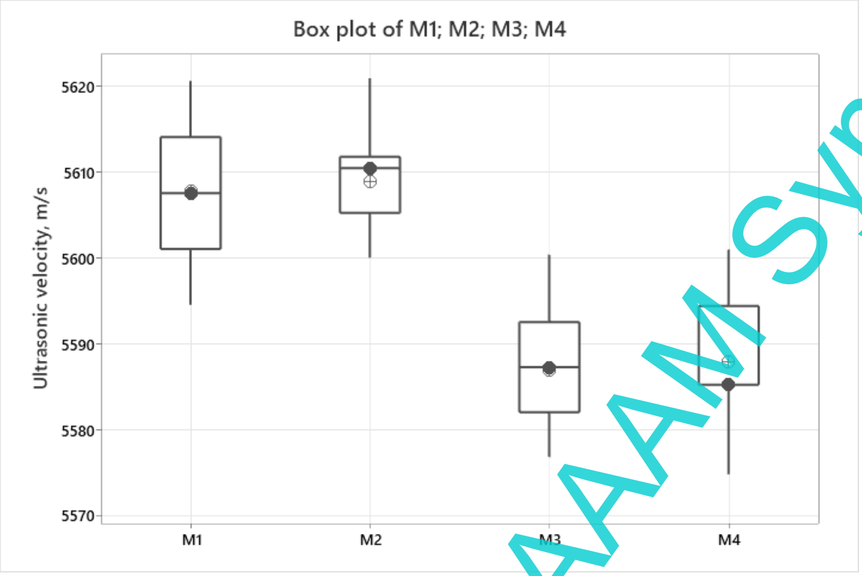
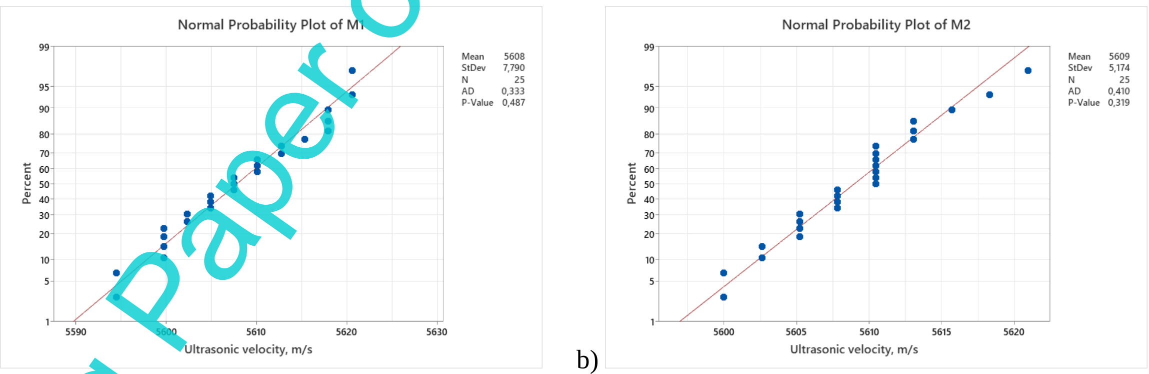


Fig. 4. Box plots for the ultrasonic velocities

Figure 4 shows the box plots for the ultrasonic velocities at all four measuring places (M1 – M4). The box plots show the minimum, the maximum, the lower and upper quartiles, the median (full circle), and the mean (circle with a cross). The graph shows that the measurement places in the same test directions (M1 and M2 in the direction of the x-axis; M3 and M4 in the z-axis direction) have similar velocities, while the difference is more significant in different directions. The difference in mean values of L-wave velocities between measurement places in the same direction is 1 m/s, while the differences in mean velocities in perpendicular directions and at the same ends of the specimen (comparison M1 and M3; comparison M2 and M4) are 21 m/s.

For statistical analysis, it was necessary to check the normal distribution of the specimen data. Testing whether the data has a normal distribution was performed with the Anderson-Darling test.



a) b)

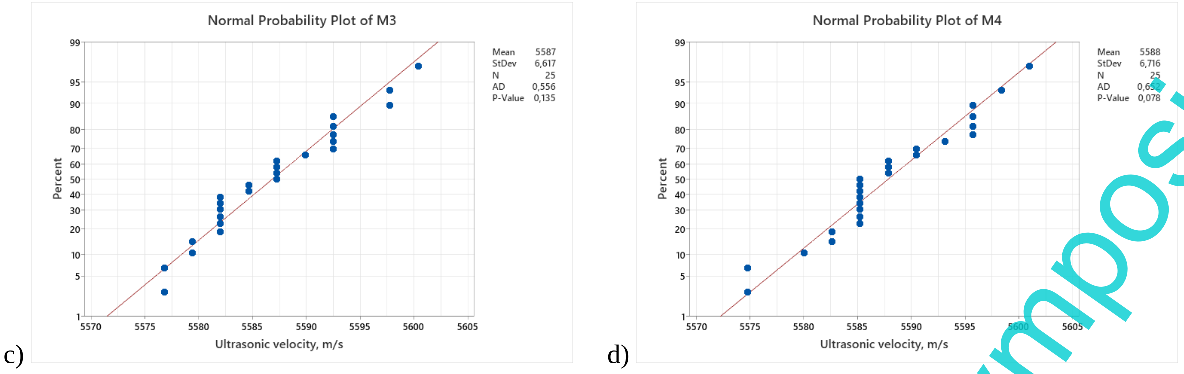


Fig. 5. The normal probability plots of ultrasonic velocities at measurement places: a) M1; b) M2; c) M3; d) M4

The Anderson–Darling test established the normal distribution of the results at all four measurement sites (Figure 5), as *P*-values at all four measuring places are higher than the significance level (*P*-value > 0.05). The null hypothesis (which assumed that results follow a normal distribution) is accepted with the error probability of $\alpha = 5\%$.

To determine whether there is a statistically significant difference between the L-wave velocities means in the same direction, but at different measurement places (comparison M1 and M2; comparison M3 and M4), paired t-tests were performed. The results of the t-tests are presented in Table 4.

Measuring places	Mean	Standard deviation	Standard error of the mean	*t*-value	$t_{crit.}$	*P*-value
M1 and M2	-1.13	8.23	1.65	-0.69	2.06	0.498
M3 and M4	-1.01	11.87	2.37	-0.42	2.06	0.675

Table 4. Results of Paired t-tests

The estimate for the population mean difference in ultrasonic velocities between M1 and M2 is -1.13, with 95% confidence that the population mean difference is between -4.53 and 2.26. Comparing the obtained *P*-value, which is 0.498, to the significance level $\alpha = 0.05$, it is evident that the difference between the means is not statistically significant (*P*-value > α). The decision is to fail to reject the null hypothesis and to conclude that the difference between the means of ultrasonic velocities in the layer direction is not statistically significant. The same analysis is performed for the build-up direction. The estimate for the population mean difference in ultrasonic velocities between M3 and M4 is -1.01, with 95% confidence that the population mean difference is between -5.90 and 3.89. Since the *P*-value of 0.675 is higher than the significance level $\alpha = 0.05$, the difference between the means is not statistically significant. The decision is to fail to reject the null hypothesis and to conclude that the difference between the means of ultrasonic velocities in the build-up direction is not statistically significant. Based on the results of t-tests was concluded that the difference of 1 m/s in the same direction (the layer direction and the build-up direction) is not statistically significant.

To determine whether there is a statistically significant difference between the arithmetic means of the L-wave velocities at different measurement places, an analysis of variance with one variable factor (ANOVA) – the measurement place/the test direction - was performed. The ANOVA is summarized in Table 5.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	*P*-value
Measurement place	11113	3	3704.23	84.02	< 0.01
Error	4232	96	44.09		
Total	15345	99			

Table 5. ANOVA table

The *P*-value from Table 5 is compared to the significance level of 0.05 to assess the null hypothesis. The null hypothesis states that all the ultrasonic velocity means are equal. The alternative hypothesis states that not all means are equal. Since the *P*-value (the exact *P*-value is $9.50 \cdot 10^{-27}$) is less than the significance level, the null hypothesis is rejected and concluded that not all ultrasonic velocity means on all measuring places are equal. This result indicates that the test direction on AM specimen significantly affects ultrasonic velocity.

4. Conclusion

Longitudinal wave velocity in the additively manufactured specimen, made of X3NiCoMoTi 18-9-5 with the DMLS manufacturing process, depends on the test direction. The ultrasonic velocity in the layer direction (x-axis) is higher than the ultrasonic velocity in the build-up direction (z-axis). Differences between ultrasonic velocities on the same sides of the specimen (comparison M1 and M2; comparison M3 and M4) are 1 m/s, which indicates uniform ultrasonic velocity in the same direction. It is confirmed by performing paired t-tests, where obtained *P*-values (for the x-axis *P*-value is 0.498, and for the z-axis *P*-value is 0.675) are higher than the significance level of 0.05. On the contrary, the differences in velocities in perpendicular directions and at the same ends of the specimen (comparison M1 and M3; comparison M2 and M4) are 21 m/s. ANOVA analysis was conducted to determine the existence of a statistically significant difference between the arithmetic means of the L-wave velocities at measuring places. ANOVA analysis confirmed that the difference between L-wave velocities means in different test directions is statistically significant (P-value < 0.01) and that the test direction on AM specimen significantly affects ultrasonic velocity. Since the accuracy of the adjustment of the ultrasonic device affects the accuracy of the ultrasonic test results, a uniform ultrasonic velocity is mandatory throughout the test specimen. The reduction in the difference in ultrasonic velocities in different directions can be enhanced, by changing the microstructure, that is, by achieving a more uniform microstructure. To achieve a more uniform microstructure it is necessary to subject the specimen to heat treatment; therefore, the next step of the research is subjecting the specimen to heat treatment to achieve more uniform ultrasonic velocity throughout the whole volume of the specimen along all directions.

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