

Investigating the Influence of LMD Process Parameters on the hardness of Inconel 718

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1 Abstract

This study investigates the influence of six laser metal deposition (LMD) process parameters on the hardness of Inconel 718 (IN718). A modified Taguchi L12 experimental design was used to systematically vary parameters including X-step, Z-step, powder flow rate, nozzle flow rate, laser power, and feed rate. Twelve as-deposited samples were fabricated and tested using Vickers microhardness (HV3), with data analysis carried out through contour plots, ANOVA, and Tukey HSD. Results showed statistically significant differences in mean hardness across the samples, particularly when comparing high and low specific energy combinations. In general, lower specific energy—achieved through reducing laser power or increasing scan speed—was associated with higher hardness, likely due to faster cooling. However, because multiple parameters changed simultaneously, the individual effect of each parameter could not be isolated. Moreover, hardness data for some samples contained minor inconsistencies, which underscores the importance of careful measurement and further validation. Despite these limitations, this study provides a useful framework for optimizing LMD parameters to improve hardness in IN718, offering insights for both industrial applications and future research on additive manufacturing process control.

Keywords: Inconel 718, additive manufacturing, laser metal deposition, material hardness, Vickers hardness testing, HV3, process parameters, ISO 6507-1:2023, mechanical properties, parametric study, contour analysis

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2 Introduction

Additive Manufacturing (AM), commonly referred to as 3D printing, has been a viable manufacturing method for the past three decades. While early adoptions were driven by its ability to quickly transform digital designs into physical prototypes, advancements in materials, precision and reliability have enabled AM to become a practical solution in the manufacture of end-use components across various industries, including aerospace, automotive and medical applications [1]. In particular, the aerospace industry, which is not constrained by the need for rapid mass production, remains a principal beneficiary of these advancements.

This project explores a specific branch of AM, known as laser metal deposition (LMD). In contrast to laser powder bed fusion (L-PBF), where part size is constrained by the dimensions of the build chamber of the machine, LMD offers greater flexibility due to its open architecture and compatibility with multi-axis systems, enabling the manufacture of larger-scale components [2][3].

Despite these advantages, LMD-fabricated components are prone to inherent issues such as hot cracking, internal porosity, layer delamination and variation in localised microstructure [4]. Microstructure, particularly grain morphology plays a critical role in determining a material's hardness [5]. While this study does not directly investigate the effects varying process parameters has on the microstructure, it aims to explore how these parameters influence resulting hardness of Inconel 718 (IN718), with the understanding that such mechanical properties are often affected by underlying microstructural changes.

IN718 is used in this study due to its widespread application across various industries, especially the aerospace industry. Due to its high strength and excellent high temperature performance so it is used in many engine components where high temperature resistant materials are required.

IN718 has favourable weldability, excellent corrosion resistance, good fabricability and strong high-temperature properties [6][7][8]. These properties make IN718 a widely used material across various industries, particularly, the aerospace industry, where it is commonly employed in the manufacture of engine components [9].

Hardness testing was chosen as the main testing parameter in this study because it provides a reliable proxy for assessing the mechanical integrity of IN718 - particularly in small, as-deposited samples where tensile testing may be impractical. Additionally, LMD-fabricated components can exhibit inhomogeneous mechanical properties due to process-induced microstructural variations. Microhardness testing enables the evaluation of multiple locations across a single sample, providing insight into the spatial variability of mechanical performance.

2.1 Aims and Objectives

This project aims to investigate the influence of six systematically varied LMD process parameters on the hardness of IN718. Establishing ISO 6507-1:2023 compliant correlations between manufacturing parameters and mechanical performance.

2.2 Objectives:

1. Parameter selection and sample fabrication

- produce twelve samples with controlled variation in:
 - X-step (1.2 mm, 1.4 mm)
 - Z-step (0.6 mm, 0.8 mm)
 - Powder flow (7 g/min, 11 g/min)
 - Nozzle flow (4 L/min, 6 L/min)
 - Laser power (800 W, 1200 W)
 - Feed rate (600 mm/s, 700 mm/s)

2. Standardised hardness testing

- Conduct Vickers micro-hardness (HV3) following ISO 6507-1:2023 standards, ensuring:
 - minimum spacing between two points must be at least three times the mean diagonal length of the indentation [10].
 - the distance between the centre of any indentation and the edge of the test piece shall be at least 2.5 times the mean diagonal length of the indentation[10].
 - care must be taken when preparing the surface for testing, to prevent alteration to the surface hardness due to excessive heating or cold-working[10].

3. Data analysis and visualisation

- Calculate mean hardness, standard deviation and ANOVA results for each parameter set.
- Generate MATLAB contour plots to map hardness distributions.

4. Establish parameter hardness relationships

- Identify statistically significant relationships ($p < 0.05$) between:

- Single parameters and hardness
- Parameter interactions

5. Industrial recommendations

- Propose optimised parameter combinations for target hardness ranges.

2.3 Scope of study

This study investigates the influence of six LMD process parameters — X step, Z step, powder flow rate, nozzle flow rate, laser power and feed rate — on the hardness of Inconel 718 (IN718). The scope is limited to the as-deposited condition, with no post-deposition heat treatments applied. Mechanical performance was evaluated exclusively through Vickers microhardness (HV3) testing; other material properties were not considered. A modified Taguchi L12 experimental design was employed to guide parameter selection. Data analysis focused on mean hardness trends, standard deviation, and confidence intervals, while hardness contour plots were used to assess spatial variation across each sample. No microstructural analysis was conducted.

3 Literature review

3.1 Inconel 718 (IN718)

IN718 is a precipitation-hardening austenitic nickel-chromium superalloy, widely used in the aerospace, automotive, and nuclear industries due to its good fatigue life at high temperatures, excellent creep resistance, and high strength [8]. It is used so extensively in aircraft engine components that it now accounts for over 30% of the weight of a modern engine [9].

3.2 Hardness of additively manufactured IN718

The typical hardness of cast IN718 that has been solution treated and aged is around 409 HV [11]. However, additive manufacturing processes can produce different microstructures compared to cast material, often resulting in lower hardness values, particularly in the as-built condition (before any post-processing treatments).

The hardness of laser powder bed fusion (L-PBF) fabricated IN718 varies depending on the orientation of the tested surface, due to the layered nature of the printing process. This directional dependence is a common characteristic of additively manufactured components, which often exhibit anisotropic mechanical properties. Reported hardness values for as-built L-PBF IN718 range from approximately 279.45 ± 9.45 HV to 349.18 ± 10.73 HV, depending on orientation [11]. For consistency in comparison with the present study, the hardness in the XZ plane (build direction/thickness), 279.45 ± 9.45 HV, will be used as a reference.

The hardness of as-built IN718 fabricated using electron beam melting (EBM) was reported to be approximately 420 ± 10 HV. The study by Balachandramurthi et al. [12] observed minimal variation in hardness across different build planes and therefore grouped the measurements together.

In a study by C. Gullipalli et al., the hardness of as-built IN718 fabricated using laser metal deposition (LMD) was reported to range approximately between 266 HV and 281 HV [5].

The hardness of IN718 produced through L-PBF and LMD is lower than that of cast and EBM produced IN718, this is driven by rapid cooling that IN718 experiences during both L-PBF and LMD processes, which limits the formation of intermetallic precipitates of γ'' (Ni_3Nb). These precipitates are coherently aligned within the matrix and contribute to the increased hardness and strength of IN718 [5].

Furthermore, Gullipalli et al. observed that the grain size of IN718 was influenced by the cooling rate and a linear relationship between the hardness and the reciprocal square root of grain width was established [5].

3.3 Laser metal deposition

LMD, which is a form of Directed Energy Deposition (DED), uses a laser beam as a thermal source to create a weld pool on the surface of existing material (the substrate). A nozzle sprays a fine powder into this weld pool, where it re-solidifies and bonds with the substrate. This process is repeated, building up layers until the desired geometry is achieved [13]. The advantage of LMD over typical AM processes, such as L-PBF and EBM, is that deposition material can be added onto existing components, which means that LMD can be used to repair components with low waste.

3.4 Influence of LMD process parameters on hardness

A similar investigation into the effects of LMD process parameters on the hardness of Inconel 718 was conducted by B. Chen and J. Mazumder. In their experiment, they varied laser power, traverse speed (also known as feed rate), powder flow rate and laser beam diameter [14]. In the present study, three additional parameters were varied: X and Z step and nozzle flow rate (also known as carrier gas flow rate). However, unlike Chen and Mazumder's experiment, laser diameter was kept constant in the present study. Furthermore, their experiment involved printing 100 layers, compared to the six deposition layers in this study, with the

vertical build height being determined by the Z-step parameter. Additionally, they used a stainless steel substrate, unlike the tool steel used in this experiment.

The hardness of all their tested samples ranged approximately between 180 HV and 330 HV. The maximum values for all samples were observed near the substrate–deposition interface, also known as the fusion zone, where the deposited material initially bonds with the substrate. This is attributed to the denser microstructure in that region, resulting from the higher cooling rate near the substrate.

3.5 Summary

Although IN718 is a widely used material in many industries, there is limited literature on optimising LMD process parameters to achieve targeted hardness values, particularly when tool steel is used as a substrate. This is likely because, in repair applications the substrate is typically also IN718. In this study, tool steel has been used as it is more cost effective, easier to machine and allows the focus to remain on the quality and behaviour of the deposition material. Nonetheless, substrate hardness will still be tested to determine if the LMD process has any impact on the substrate. If changes are observed, their depth will be visible in the contour plots.

4 Methodology

This study investigates the effects of six LMD process parameters on the hardness of Inconel 718 (IN718) using a structured Design of Experiments (DoE). Twelve samples were fabricated with controlled parameter variations. Vickers hardness testing was incorporated to test the hardness of each sample, following ISO 6507-1:2023 standards. Statistical analysis in the form of contour plots and analysis of variation (ANOVA) identified significant parameter effects.

4.1 Materials

The samples were fabricated at the Advanced Manufacturing Research Centre (AMRC) at the University of Sheffield, so exact fabrication conditions are unknown. The substrate material has not been confirmed by AMRC, but based on measured hardness values around 620 HV, it would suggest that the substrate is a tool steel, as these values exceed the typical ranges for Inconel or stainless steels. However, without confirmation from AMRC or compositional analysis, this identification remains inferred. The powder used was IN718, the exact chemical composition of the pieces tested in this study cannot be confirmed, but the typical chemical of IN718 can be seen in table 1, the exact powder particle size is unconfirmed, but can be assumed to be around 60 to 110 μm [15].

Table 1: Typical chemical composition of Inconel 718.

Element	Ni	Cr	Fe	Nb + Ta	Mo	Ti	Al	Co
Weight percent-age (%)	50.00-55.00	17.00-21.00	17.00-19.00	4.75-5.50	2.80-3.30	0.65-1.15	0.20-0.80	1.00 max.

Chemical composition of Inconel 718 adapted from [16].

4.2 Design of experiment

A modified Taguchi L12 array experiment design was employed to test six LMD parameters (X-step, Z-step, powder flow rate, nozzle flow rate, laser power and feed rate), each at two levels (table 2). Please note that beam diameter was kept constant at 2 mm, as was the total number of layers, which remained fixed at six. As parameter ranges are not fully orthogonal, it is not a full Taguchi L12 array, instead industrially relevant parameter ranges have been prioritised. This approach was chosen as it is more efficient than a full factorial design, which would mean 64 separate samples would need to be fabricated and tested. A comparison between the modified Taguchi L12 used in this study and the standard Taguchi L12 can be seen in Tables 3 and 4.

Table 2: LMD Process parameters for fabricated samples.

Run	X (mm)	Z (mm)	Pow (g/min)	Noz (L/min)	Power (W)	Feed (mm/s)	SE (J/mm ²)
1	1.2	0.6	11	6	1200	600	1.000
2	1.2	0.6	7	6	1200	700	0.857
3	1.2	0.8	7	4	800	700	0.571
4	1.4	0.6	7	4	1200	700	0.857
5	1.2	0.8	11	4	1200	600	1.000
6	1.4	0.8	11	4	1200	700	0.857
7	1.2	0.8	11	6	800	700	0.571
8	1.2	0.6	7	4	800	600	0.667
9	1.4	0.6	11	4	800	600	0.667
10	1.4	0.8	7	6	800	600	0.667
11	1.4	0.6	11	6	800	700	0.571
12	1.4	0.8	7	6	1200	600	1.000

Note: Abbreviations - X: x-step, Z: z-step, Pow: powder flow rate, Noz: nozzle flow rate, Feed: feed rate, SE: Specific Energy.

Table 3: Comparison between standard Taguchi L12 array and modified LMD experimental design.

Feature	Standard Taguchi L12	Modified LMD Design
Total Runs	12	12
Factors	Up to 11 generic factors (F1-F11)	6 process-specific factors (X-step, Z-step, etc.)
Levels per Factor	2 or 3	2 (all factors)
Orthogonality	Strictly orthogonal	Partially orthogonal
Interactions	Main effects + some 2-way	Prioritizes known LMD interactions
Energy Consideration	Not included	Specific energy (J/mm ²)
Design Focus	General purpose	LMD process constraints

4.3 Hardness testing

This study incorporated Vickers hardness testing, strictly adhering to ISO 6507-1:2023 standards using a Struers DuraVista-40 and an Innovatest Falcon-500.

Firstly, each sample was prepared using 1200-grit SiC paper until all large scratches were no longer visible under 10x magnification, with care taken to ensure that surface hardness was not altered by excessive heat or cold working. It is important each sample is properly prepared, as large scratches or contaminants may cause issues with the automatic indent measurement optic.

As the samples were curved at the bottom edge of the deposition area they had to be clamped to ensure they remained steady during testing. This was done using an engineer's clamp. A spirit level was used to ensure proper alignment of the samples on the test bed.

The number of indentations per sample varied because samples were not equal in size. ISO Minimum indent spacing guidelines were followed, requiring that the centre of each indent to be at least 2.5 times the mean diagonal length (MDL) from the edge of the test piece and the distance between the centre of two adjacent indents must be no less than three times the MDL[10].

The minimum spacing was calculated by taking the MDL from three arbitrary readings from the softest region - the deposition area of sample 1, the MDL of these indents was 0.136 mm, meaning:

- the distance from the edge of the test piece to the centre of any indent must be no less than $0.136 \times 2.5 = \mathbf{0.34 \text{ mm}}$.
- the distance between any two adjacent indents must be no less than $0.136 \times 3 = \mathbf{0.41 \text{ mm}}$.

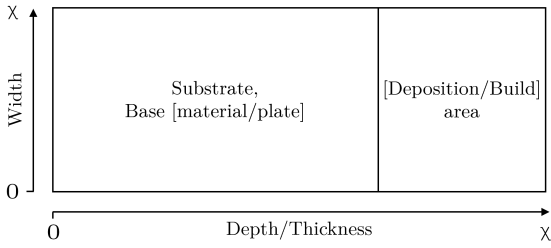


Figure 1: Dimension definitions.

For this study, horizontal spacing varied by region: 1 mm spacing was used on the substrate, while 0.75 mm spacing was applied in the deposition area. If a test point crossed the substrate–deposition interface (the area where the substrate ends and the deposition area begins), 0.75 mm spacing was used. Vertical spacing remained constant at 1 mm. Indents were made in a set grid pattern on each machine. As sample thickness varied, the number of columns (i.e., the number of test point routes along the thickness; see dimension definitions in Figure 1) also varied. However, since all samples had similar widths, the number of rows (i.e., the number of test point routes along the width) was kept constant at four. The indent spacing and grid pattern are explained in Figure 2.

As there was no way to vary indent spacing on either hardness tester two separate test runs were needed, one for the base plate (1 mm spacing) and one for the deposition area (0.75 mm spacing).

For the first test run (base plate), the test piece was oriented as shown in figure 1, the starting point of the grid testing pattern was set at the top left corner of the sample, ensuring that the first test point was at least 0.34 mm away from the edge of the sample. Four rows were then added, each 1 mm apart and columns were added until the substrate–deposition interface was reached. The hardness tester would test each point across the row, then move down to the next row once all points in the current row had been tested. For the second run (deposition area), the starting point of the grid began 0.75 mm away from the last test point on the top row, columns were added until no more eligible test points could be added.

4.4 Data analysis

Hardness data was analysed using both statistical and visual methods to identify relationships between process parameters and mechanical performance. For each of the twelve samples, the mean Vickers hardness was calculated based on all indentation measurements, along with the standard deviation, standard error and 95% confidence interval. These metrics were used to quantify the central tendency and the reliability of the measured hardness values to compare hardness variability across the samples.

To compare results between samples and identify trends, a bar chart was generated using Excel, displaying the mean hardness for each sample along with the corresponding 95% confidence intervals. This allowed visual identification of samples with higher or lower average hardness and the confidence in these measurements.

Additionally, contour plots were generated using MATLAB, these plots allowed spatial variation across the sample to be visualised.

A one-way analysis of variance (ANOVA) was performed to assess the statistical significance of each process parameter's effect on hardness. ANOVA works by comparing the variation between group means to the variation within groups. If the between-group variation is significantly greater than the within-group variation, it suggests that at least one group mean is statistically different from the others. In this study, a significance threshold of $p \leq 0.05$ was used to determine whether a process parameter had a statistically significant effect on hardness.

In this study, each of the six parameters was tested at two levels across twelve different samples. Mean hardness were group bases on each parameter level and a p-value was calculated to determine significance. Although the modified Taguchi L12 design does not fully isolate interaction effects, the ANOVA allowed identification of parameters with the strongest individual effects on IN718 hardness.

4.5 Limitations

While the modified Taguchi L12 array enabled efficient testing of six process parameters with a limited number of samples, its fractional factorial nature introduces partial confounding. As a result, certain interaction effects between parameters cannot be fully isolated or distinguished from main effects.

The study focuses exclusively on the as-deposited condition of IN718, no post-deposition heat treatments were applied. This restricts the findings as they cannot be applied to service ready components. Furthermore, only hardness was measured; other mechanical properties such as tensile strength, fatigue resistance and fracture toughness were not investigated.

Surface preparation and indentation spacing followed ISO 6507-1:2023 standards, however small variability in polishing may have introduced some inconsistency in individual measurements. Additionally, the small sample size and lack of replication means that variability due to machine conditions could not fully be accounted for.

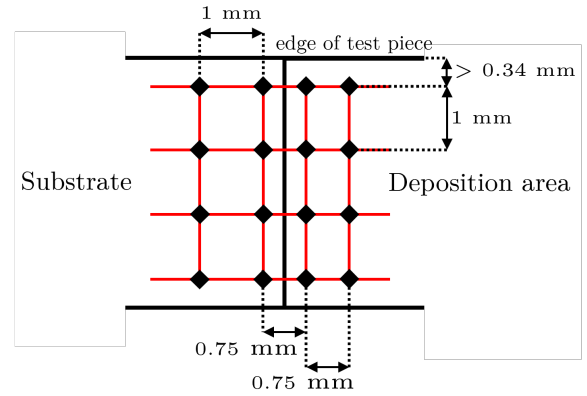


Figure 2: Indentation spacing used.

5 Results

5.1 Overview of experimental results

This chapter presents the hardness results obtained using Vickers microhardness (HV3) in accordance to ISO 6507-1:2023 from the twelve LMD-fabricated IN718 samples, along with statistical and graphical analysis used to identify trends and parameter influence.

While the main focus of this study was hardness of the deposited material, the hardness of the substrate was also measured to determine if any process parameters had any noticeable effect on the substrate.

In total, 772 valid indentations were made across all samples, with 308 of those being made in the deposition area and the remaining 464 being made on the substrate. Each sample included between 76 to 112 valid indentations with the average number of indentations being 90, with 16 to 36 valid indentations on the deposited region and 52 to 76 on the substrate. The number of indentations was dependant on the size of the sample, with around two thirds of the samples area being the substrate.

Table 4 summarises the mean hardness of the deposited material for each sample, including the statistical variation and level of confidence in each measurement. Substrate and deposition area mean hardness calculations have been done separately as they are two different materials with vastly different hardness values.

5.2 Summary of hardness results

Table 4: Summary of process parameters and hardness results in deposition area for each sample.

Run Order	X (mm)	Z (mm)	Pow (g/min)	Noz (L/min)	Power (W)	Feed (mm/s)	SE (J/mm ²)	Mean hardness (HV)	95% CI (HV)	SD (HV)	n
1	1.2	0.6	11	6	1200	600	1.000	271.0	±3.6	10.6	36
2	1.2	0.6	7	6	1200	700	0.857	270.0	±4.2	9.8	24
3	1.2	0.6	7	4	800	700	0.571	277.2	±5.9	11.0	16
4	1.4	0.6	7	4	1200	700	0.857	267.0	±9.4	20.0	20
5	1.4	0.8	11	6	1200	600	1.000	262.2	±6.8	18.2	32
6	1.4	0.8	11	4	1200	700	0.857	264.4	±7.5	19.3	28
7	1.2	0.8	7	4	800	600	0.671	258.2	±6.7	18.7	32
8	1.2	0.8	11	6	800	700	0.667	274.5	±4.6	9.9	40
9	1.4	0.6	11	4	800	600	0.667	267.3	±5.4	15.0	32
10	1.4	0.6	7	6	800	600	0.667	258.4	±4.5	9.7	20
11	1.4	0.6	11	6	800	700	0.571	273.8	±7.9	18.7	24
12	1.4	0.8	7	6	1200	600	1.000	260.0	±4.0	9.4	24
Global	—	—	—	—	—	—	—	266.5	±1.8	15.9	308

Note: Abbreviations - X: x-step, Z: z-step, Pow: powder flow rate, Noz: nozzle flow rate, Feed: feed rate, SE: Specific Energy, 95% CI: 95% confidence interval, SD: standard deviation, n: number of indentations done in deposition region of sample

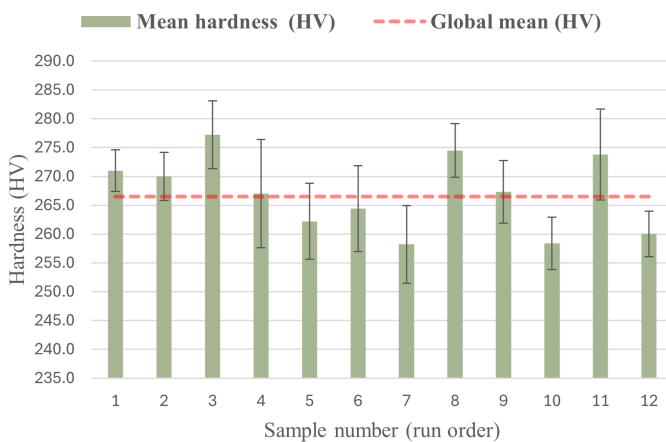


Figure 3: Mean hardness of deposited material per sample with 95% confidence intervals.

Table 4 shows the mean hardness results, including 95% CI, standard deviation and number of indentations for all twelve LMD-fabricated IN718 samples and figure 3 visualises these results, for comparison between samples. Sample 3 recorded the highest mean hardness at 277.2 HV, while sample 7 exhibited the lowest at 258.2 HV. Several samples displayed overlapping confidence intervals, this suggests that the observed differences in mean hardness may not be statistically significant. This implies that any variation in hardness across the samples could fall in the bounds of measurement of uncertainty or natural variability, rather than clearly attributable to changes in parameters. However, this cannot be confirmed until further analysis has been completed, this will be addressed in the subsequent ANOVA section.

Table 5: Summary of hardness results in substrate area for each sample.

Sample	Mean Hardness (HV)	95% CI (HV)	SD (HV)	n
1	631.8	± 7.1	22.2	40
2	622.0	± 5.5	17.1	40
3	630.3	± 7.7	22.7	36
4	607.5	± 11.2	33.0	36
5	634.5	± 8.3	25.9	40
6	616.4	± 13.5	42.3	40
7	601.7	± 12.1	35.7	36
8	622.2	± 4.9	15.3	40
9	621.9	± 6.2	19.5	40
10	618.0	± 8.0	24.9	40
11	630.1	± 7.9	24.6	40
12	617.5	± 10.5	31.1	36
Global	621.5	± 2.6	28.4	464

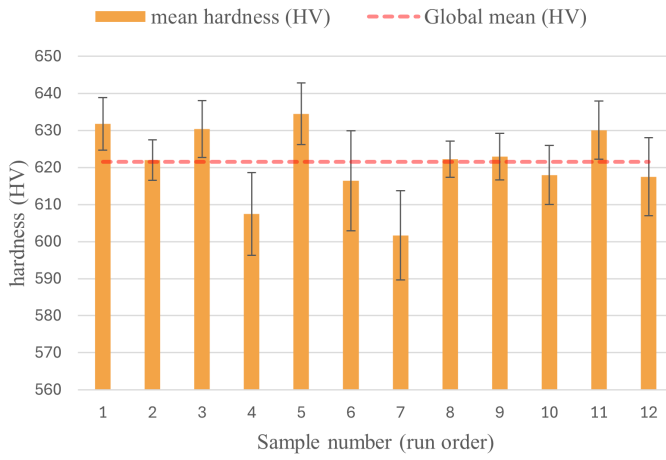
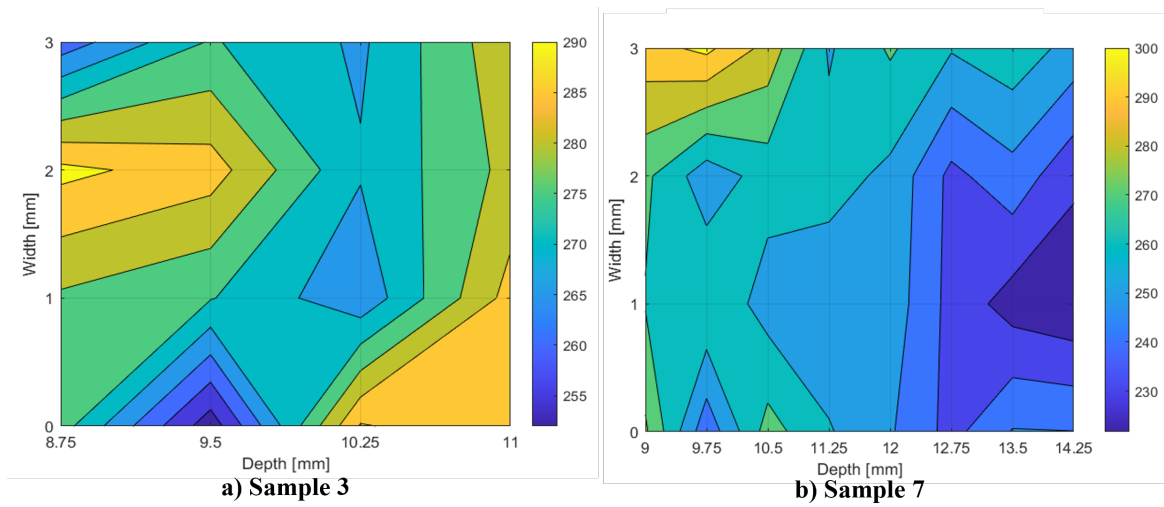


Figure 4: Mean hardness of substrate area per sample with 95% confidence intervals.

5.3 Spatial hardness distribution



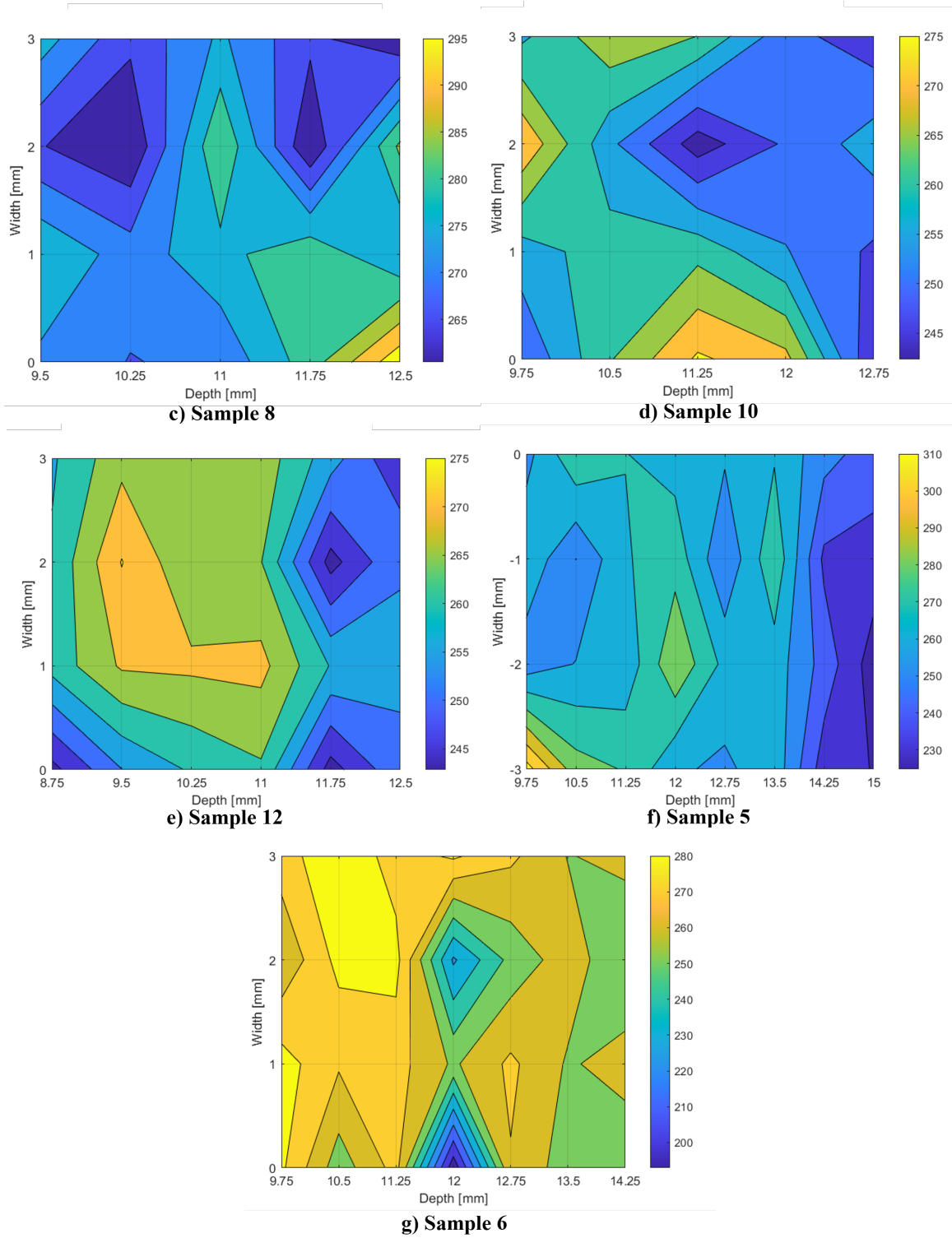


Figure 5: Notable contour plots

note: remaining contour graphs can be seen in appendix

Contour plots were generated for all samples to visualise the spatial distribution of hardness across the build cross-section. These plots highlight localised hardness variation that are not captured by mean values alone. The y-axis represents the width of the sample and the x-axis represents the distance from the bottom of the substrate.

Figure 5a shows the contour plot for sample 3, which recorded the highest mean hardness in the deposition area. The hardness values range approximately between 255 HV and 290 HV (35 HV difference), which is on the low end compared to the rest of the samples, with the average range being around 50 HV. The distribution appears relatively uniform, with the only one localised region recording hardness below the global mean, there is also a localised high hardness region near the substrate-deposit interface and another towards the top of the deposition.

Figure 5b shows the hardness distribution within the deposition area of Sample 7, which recorded the lowest mean hardness among all samples. The hardness range for this sample is approximately 230 HV to 300 HV (difference of 70 HV), which is among the largest observed across all samples. This suggests a relatively scattered hardness distribution. A single localised region of higher hardness is present, with values markedly different from the rest of the sample.

Figures 5c, 5d and 5e (samples 8, 10 and 12) exhibit the lowest approximate hardness range, around 30 HV, suggesting relatively uniform hardness across these samples. In contrast, figures 5f and 5g (samples 5 and 6) have the highest approximate range, close to 80 HV, suggesting a greater degree of hardness variation within those samples.

5.4 ANOVA results

Table 6: One-way ANOVA summary for hardness results across samples

Source	SS	df	MS	F / p-value
Between Groups	10613.87	11	964.90	F = 4.23
Within Groups	67213.95	295	227.84	p = 7.56×10^{-6}

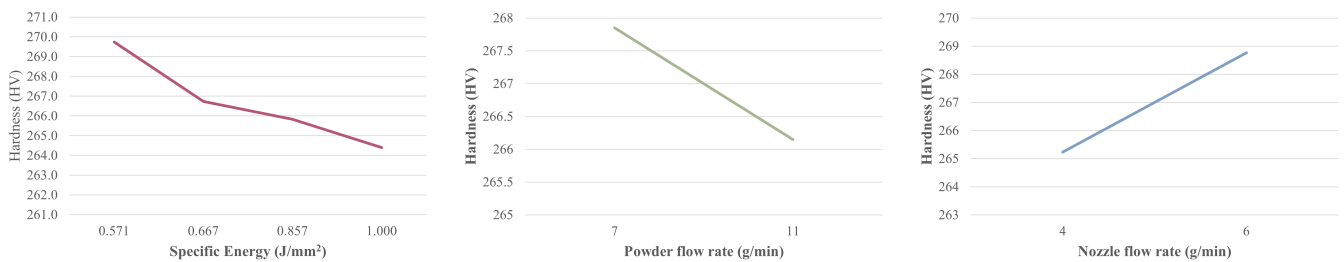
Table 7: Tukey HSD results: significant differences in mean hardness between samples ($p \leq 0.05$)

Group 1	Group 2	Mean Diff	p-value
1	7	-12.76	0.0282
3	7	-18.95	0.0031
3	10	-18.76	0.0132
3	12	-17.17	0.0244
7	8	16.25	0.0103
7	11	15.59	0.0086
8	10	-16.05	0.0406
10	11	15.40	0.0399

A one-way ANOVA was conducted to assess whether the mean hardness differed significantly between the twelve LMD-fabricated IN718 samples. The test returned an F-value of 4.23 and a p-value less than 0.05, indicating that at least one sample's mean hardness was significantly different from the others.

To identify which specific samples differed, a Tukey HSD post hoc test was performed. The results revealed statistically significant differences between several sample pairs, including Sample 3 and Sample 7 ($p = 0.0031$), Sample 3 and Sample 10 ($p = 0.0132$), and Sample 1 and Sample 7 ($p = 0.0282$), among others. These comparisons highlight which process parameter combinations led to distinguishable changes in hardness. The full set of significant comparisons is presented in Table 7.

5.5 Main effects plots



(a) Main effect of specific energy on mean hardness (b) Main effect of powder flow rate on mean hardness (c) Main effect of nozzle flow rate on mean hardness

Figure 7: Main effect graphs

6 Discussion

6.1 Findings

The one-way ANOVA results showed that there were statistically significant differences in mean hardness across the twelve samples. This was confirmed by the low p-value, indicating that at least one sample had a mean hardness that was significantly

different from the others. From the bar chart and confidence intervals, Sample 3 recorded the highest mean hardness, while Sample 7 had the lowest. In terms of hardness range, Figures 5f and 5g had the widest range of around 80 HV, whereas Figures 5c, 5d, and 5e had the most uniform distributions, with ranges of around 30 HV.

Although the ANOVA and Tukey HSD tests confirmed that several sample pairs had statistically significant differences in hardness, each sample in the experiment was fabricated with a unique combination of six process parameters. Because of this, it's not possible to say which specific parameter caused the difference. However, from existing literature it is known that cooling rate has a direct impact on hardness [5]. Therefore, it would be expected that process parameters which promote faster cooling—such as lower laser power, higher feed rate, or reduced powder flow—would result in samples with increased hardness. In the study carried out by Chen and Mazumder they noted an inverse relationship between specific energy and cooling rate, meaning that the higher the specific energy the lower the cooling rate [14]. Based on this it would be expected that samples fabricated with parameters that result in a lower specific energy would increase hardness. The results of this study support that trend, as shown in figure 7a.

Specific energy (SE) formula: $SE = \frac{P}{vd}$,

P: laser power, v: scan speed (feed rate) and d: laser diameter [17]. To achieve a lower specific energy, scan speed or laser diameter can be increased, or laser power can be decreased. These adjustments reduce the amount of energy delivered per unit area, resulting in faster cooling and potentially increasing hardness in the deposited material.

There is a small potential for other parameters to increase the cooling rate. Increasing powder flow rate could increase cooling rate, as more powder requires more energy to melt, the results of this study, as seen in figure 7b did not support this hypothesis. That said, the difference in mean hardness between the two powder flow levels was minimal, and given the simultaneous variation of other parameters, it is not possible to isolate the impact of powder flow alone with certainty.

Additionally nozzle flow rate may have an effect on cooling rate as an increased gas flow can improve convective cooling around the melt pool. This study did find that increasing nozzle flow rate increased hardness, as shown in figure 7c. However, this increase was only minor and it is not possible to confirm whether the increase is down to the parameter change or down to variability in results.

6.2 Limitations and future improvements

Upon reviewing the raw data from the hardness tester, it was noted that several individual indentations from Samples 7, 10, and 12 appeared to be misread or inconsistent with the surrounding measurements. These inconsistencies may have led to artificially low average hardness values for these samples. Due to time constraints and the project deadline, it was not possible to repeat the hardness tests or validate the affected indentations. As such, the reported mean hardness for these samples may underestimate the true values, and any conclusions involving them should be interpreted with this in mind. In the future, the samples should be re-tested to validate the data.

That said, there are a few limitations worth noting. The biggest one is that no microstructural analysis was done on any of the samples. This means I can't say whether the changes in hardness were due to grain size, grain morphology, or precipitate formation. Also, hardness was the only mechanical property measured, so the results can't tell us anything about tensile strength or fatigue performance. Lastly, because the substrate was made from tool steel rather than IN718, there might have been some thermal effects or hardness gradients near the interface that wouldn't exist in a real repair application.

7 Conclusion

This project aimed to investigate the influence of six laser metal deposition (LMD) process parameters on the hardness of as-deposited Inconel 718. A modified Taguchi L12 experimental design was used to fabricate twelve samples with systematically varied input parameters. Hardness was measured using standardised Vickers microhardness (HV3) testing, and the results were analysed statistically using ANOVA and Tukey HSD methods.

The results confirmed that certain parameter combinations produced statistically significant differences in hardness. In general, samples produced with lower specific energy values tended to exhibit higher mean hardness, aligning with trends reported in existing literature. Sample 3, which had one of the lowest specific energy values, recorded the highest mean hardness, while Sample 7, with a higher specific energy, recorded the lowest. Main effects plots showed that increasing feed rate and reducing laser power were associated with increased hardness, suggesting that faster cooling plays a key role.

However, due to the experimental design, the effects of individual parameters could not be isolated. Additionally, minor inconsistencies were identified in the raw hardness data for several samples, which may have slightly affected the reported values. Despite these limitations, the study successfully met its objective and provides a useful reference for selecting LMD parameters to optimise hardness in as-deposited IN718.

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9 Appendix

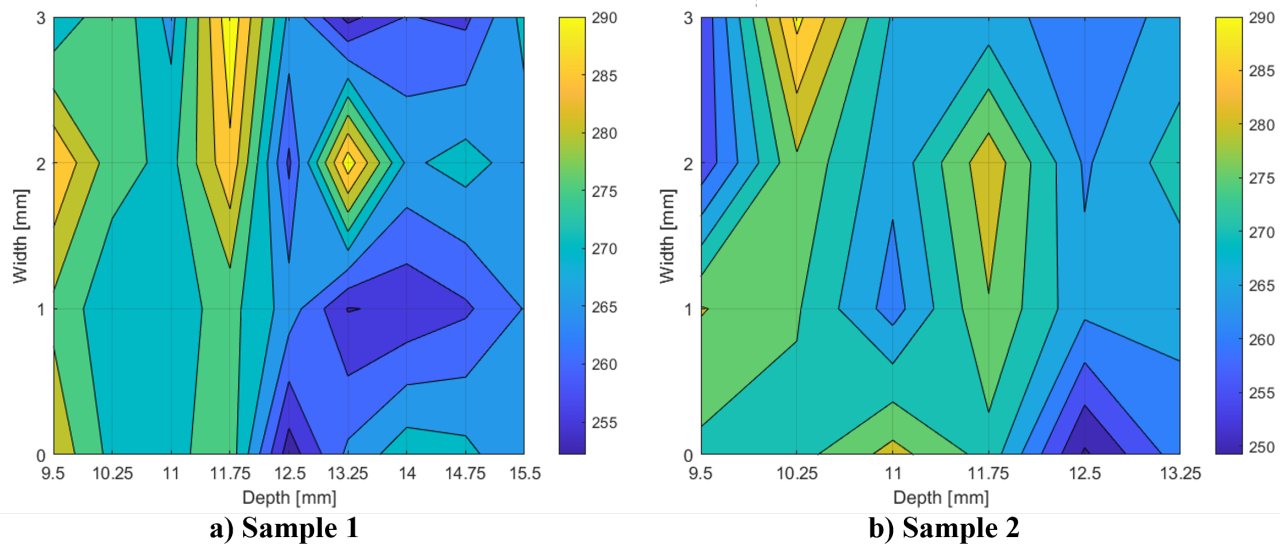


Figure 8: Contour graphs of deposition area of sample 1 and 2

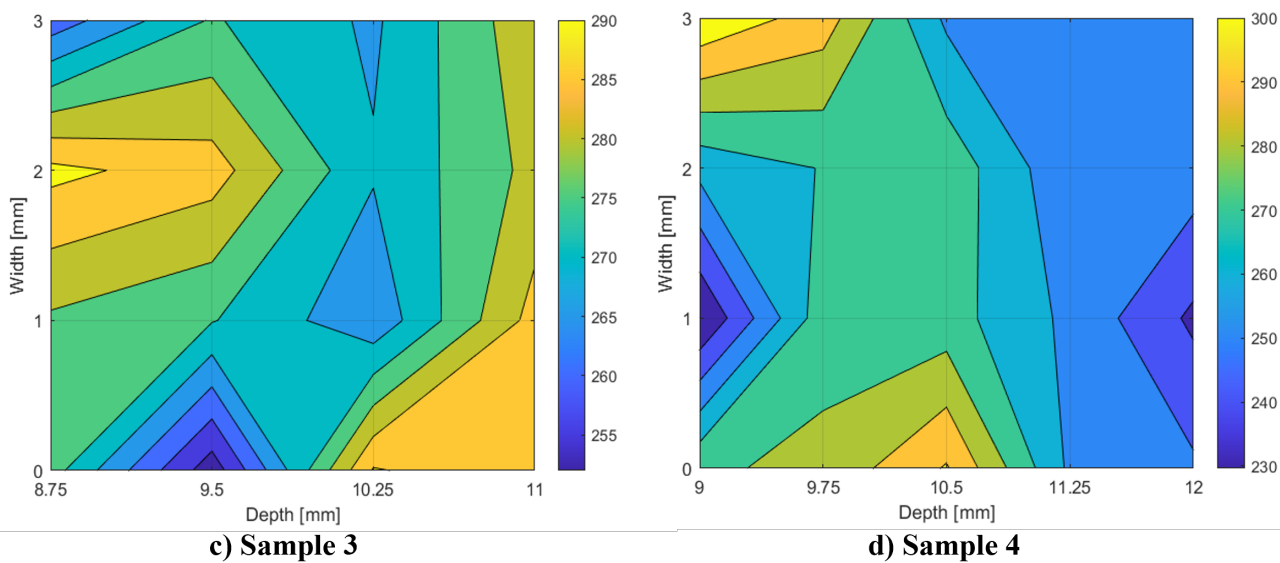
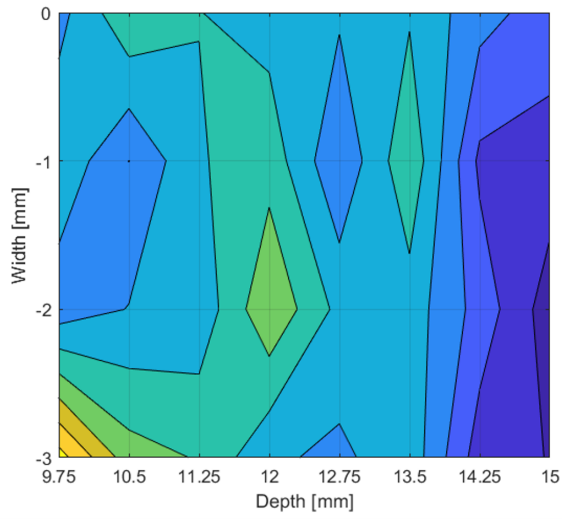
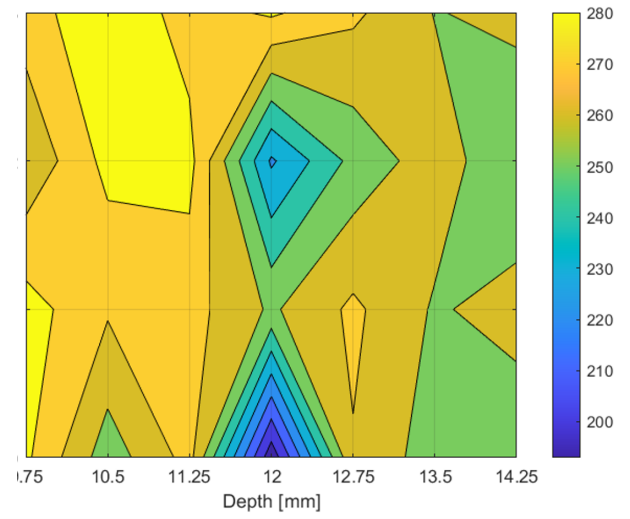


Figure 9: Contour graphs of deposition area of sample 3 and 4

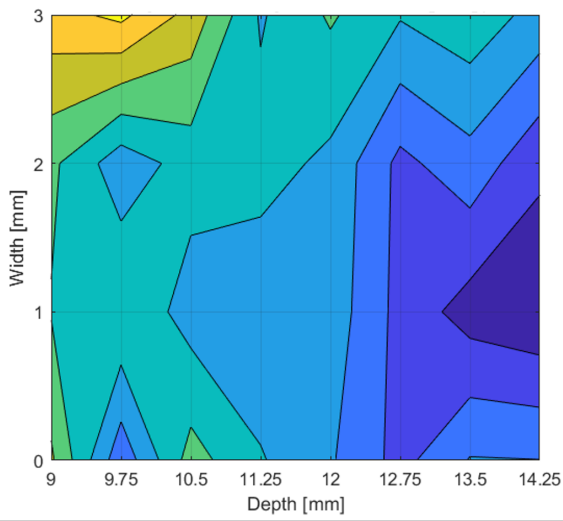


e) Sample 5

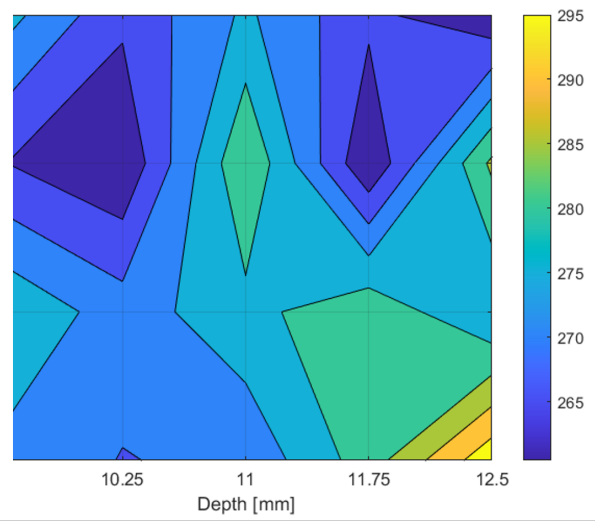


f) Sample 6

Figure 10: Contour graphs of deposition area of sample 5 and 6

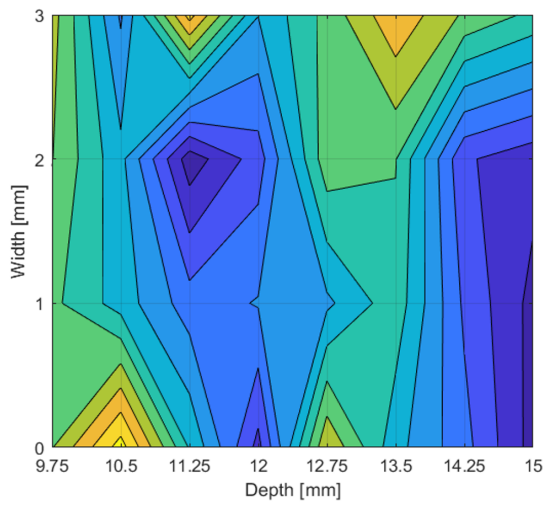


g) Sample 7

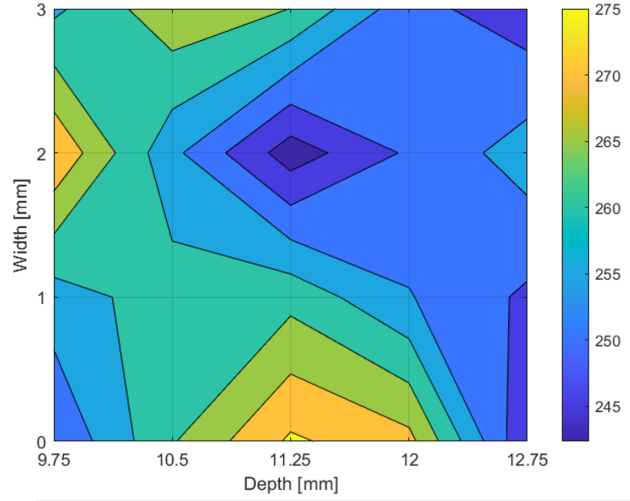


h) Sample 8

Figure 11: Contour graphs of deposition area of sample 7 and 8

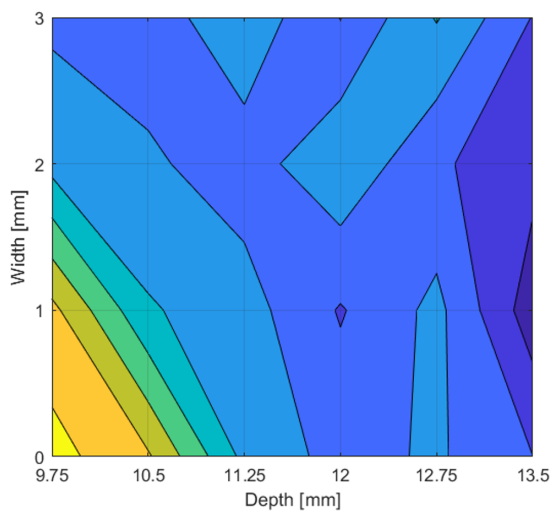


i) Sample 9

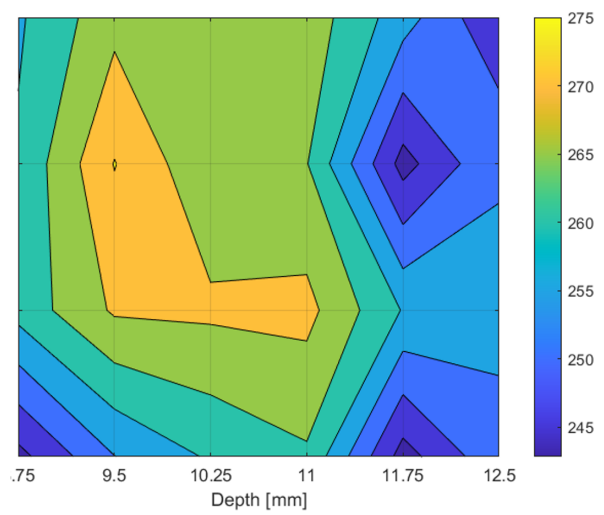


j) Sample 10

Figure 12: Contour graphs of deposition area of sample 9 and 10



k) Sample 11



l) Sample 12

Figure 13: Contour graphs of deposition area of sample 11 and 12

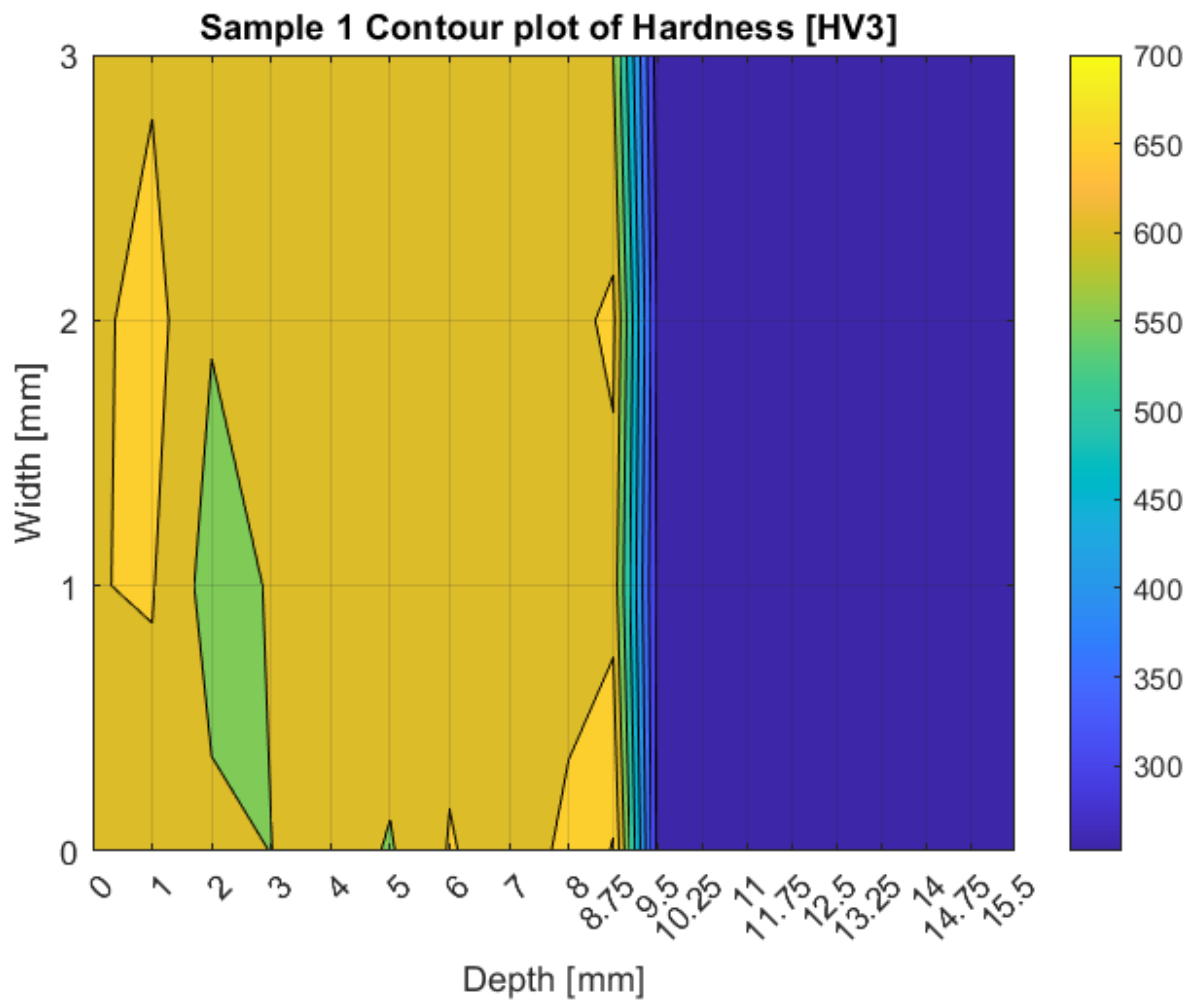


Figure 14: Contour graphs of substrate and deposition area of sample 1

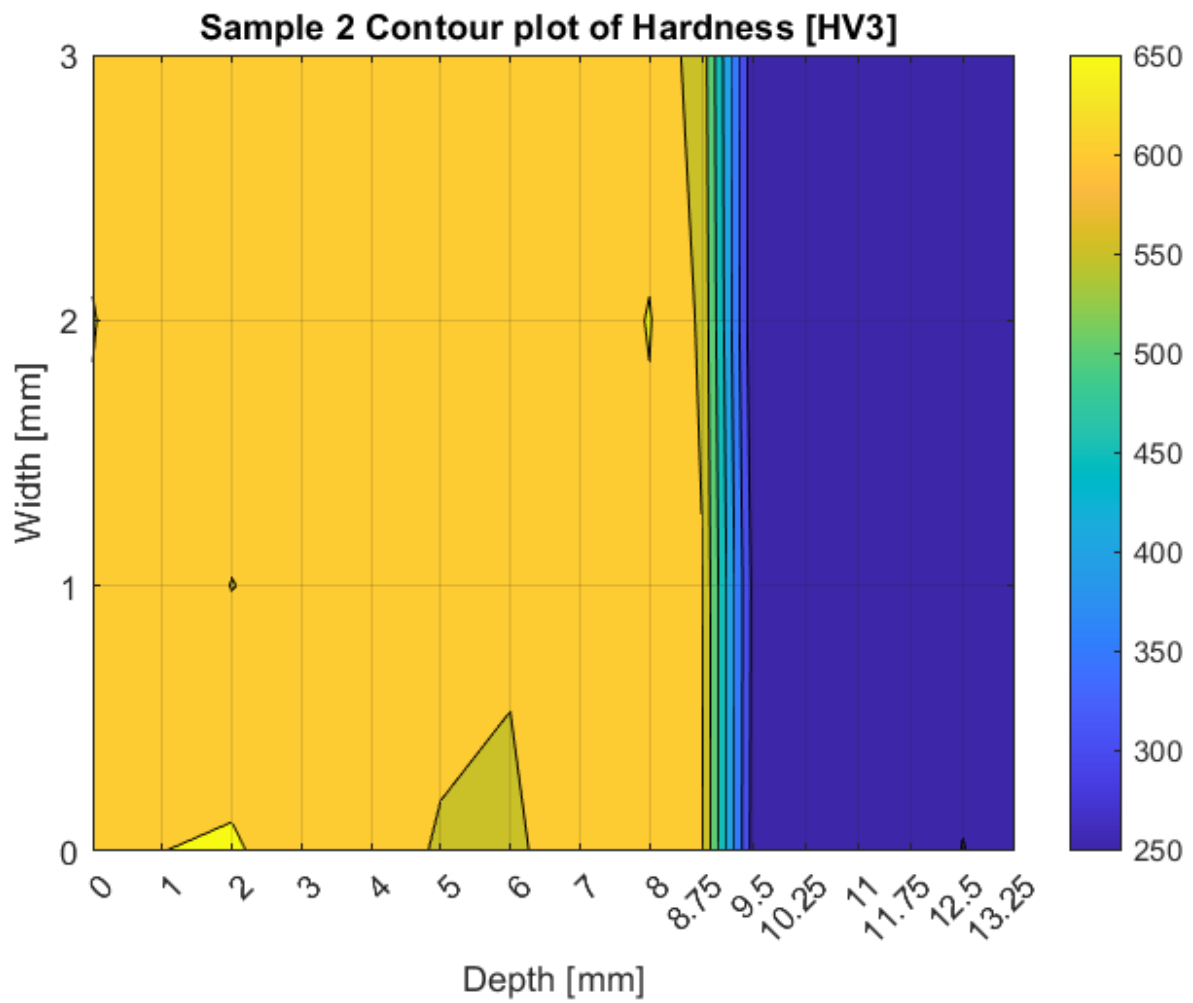


Figure 15: Contour graphs of substrate and deposition area of sample 2

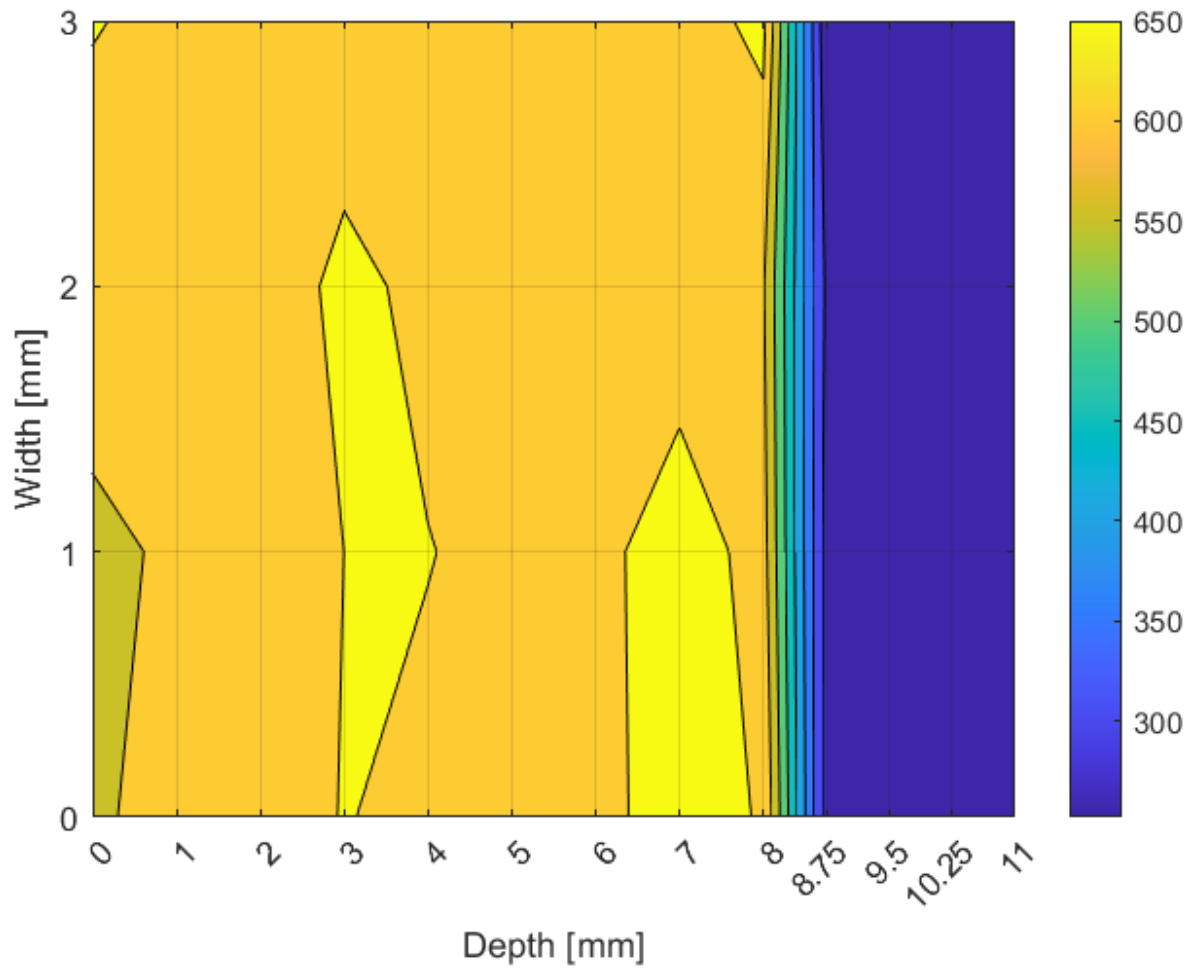


Figure 16: Contour graphs of substrate and deposition area of sample 3

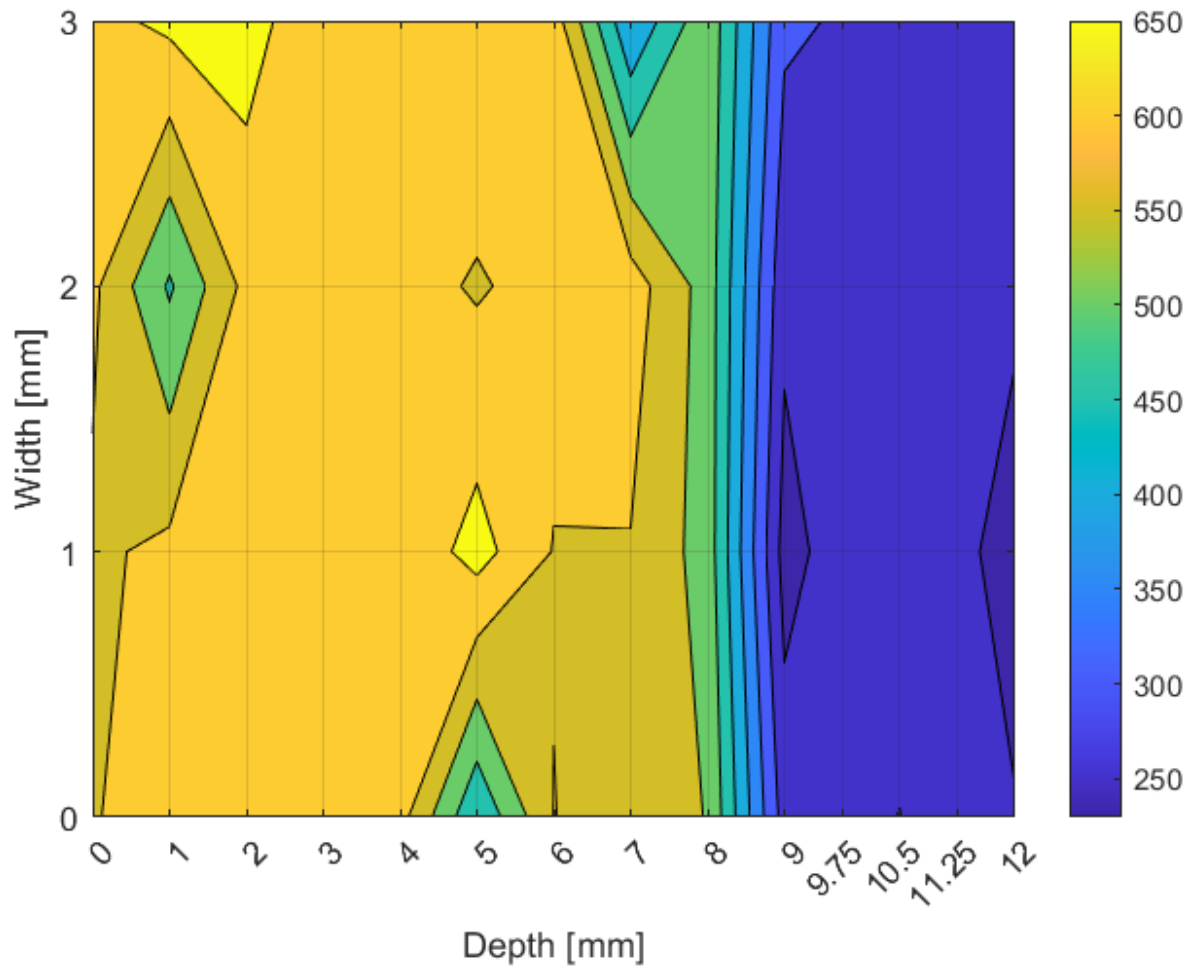


Figure 17: Contour graphs of substrate and deposition area of sample 4

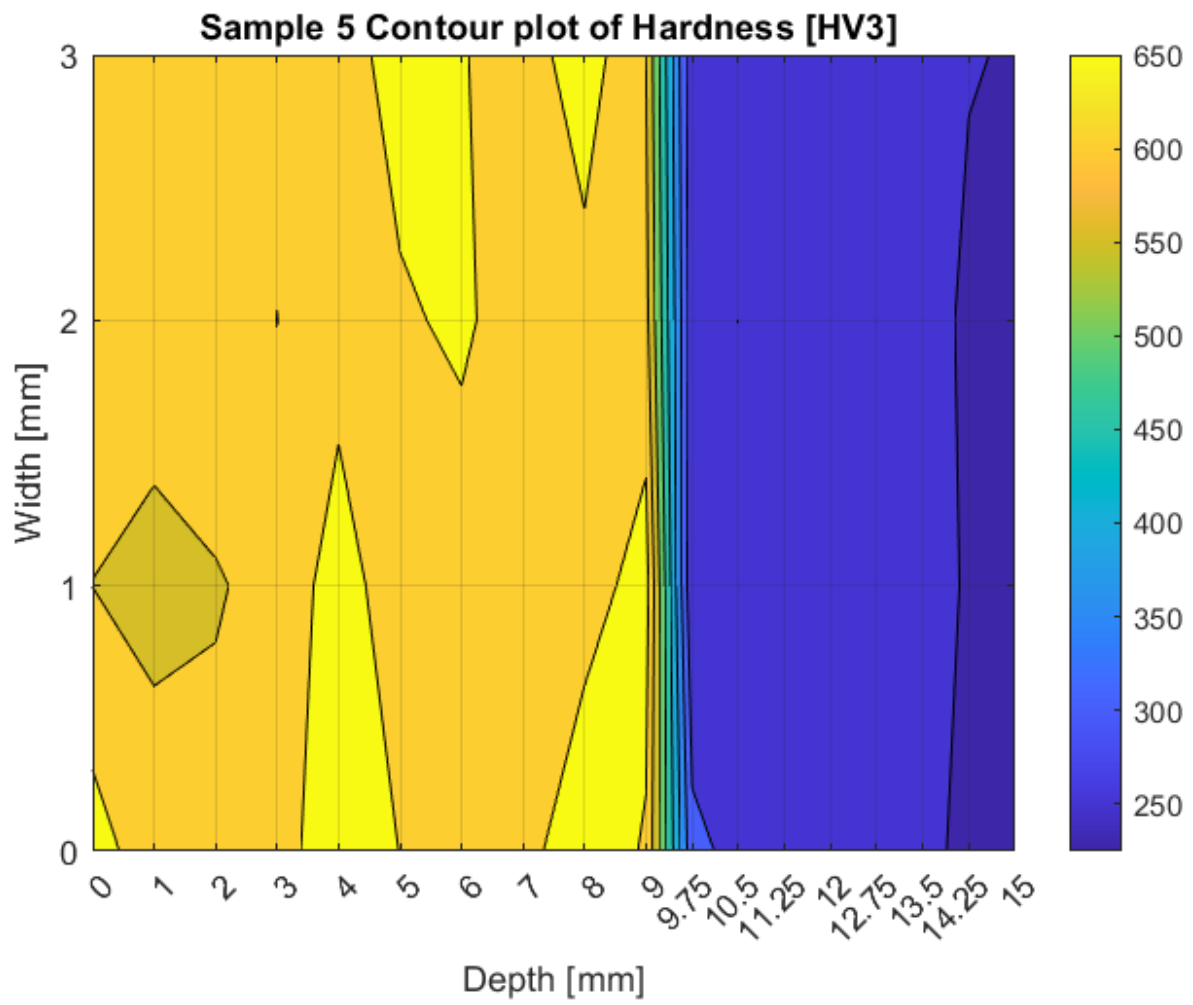


Figure 18: Contour graphs of substrate and deposition area of sample 5

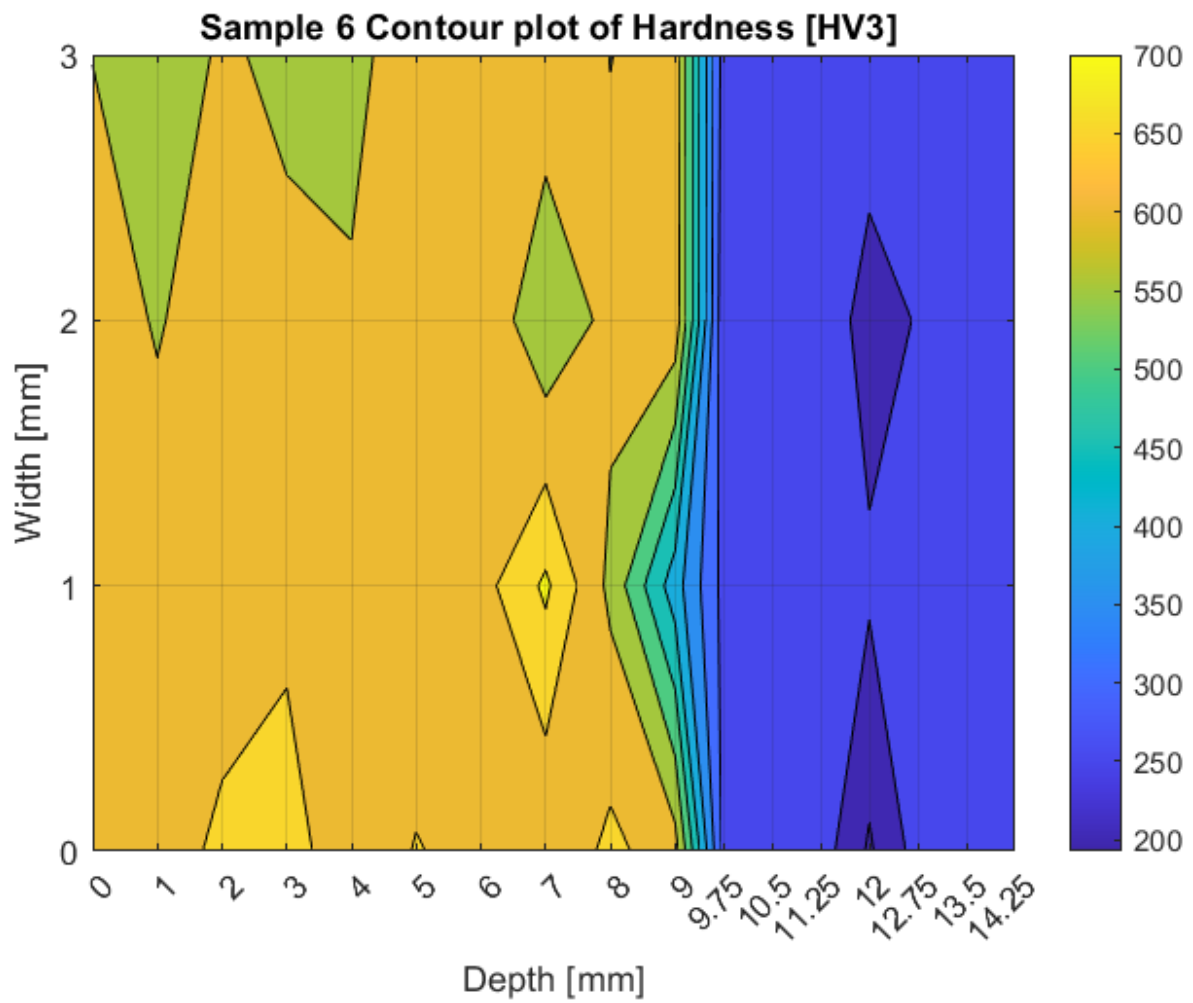


Figure 19: Contour graphs of substrate and deposition area of sample 6

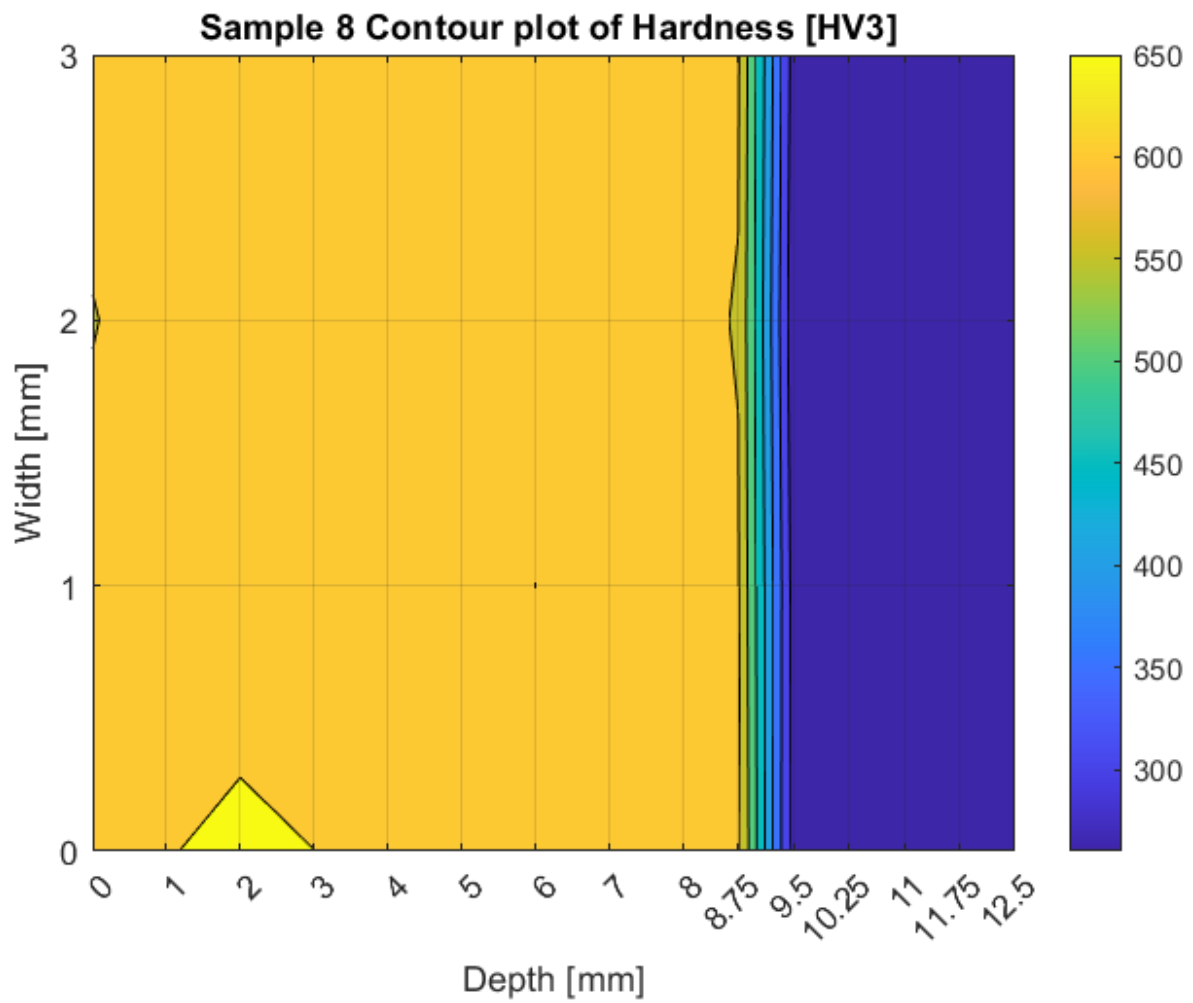


Figure 20: Contour graphs of substrate and deposition area of sample 7

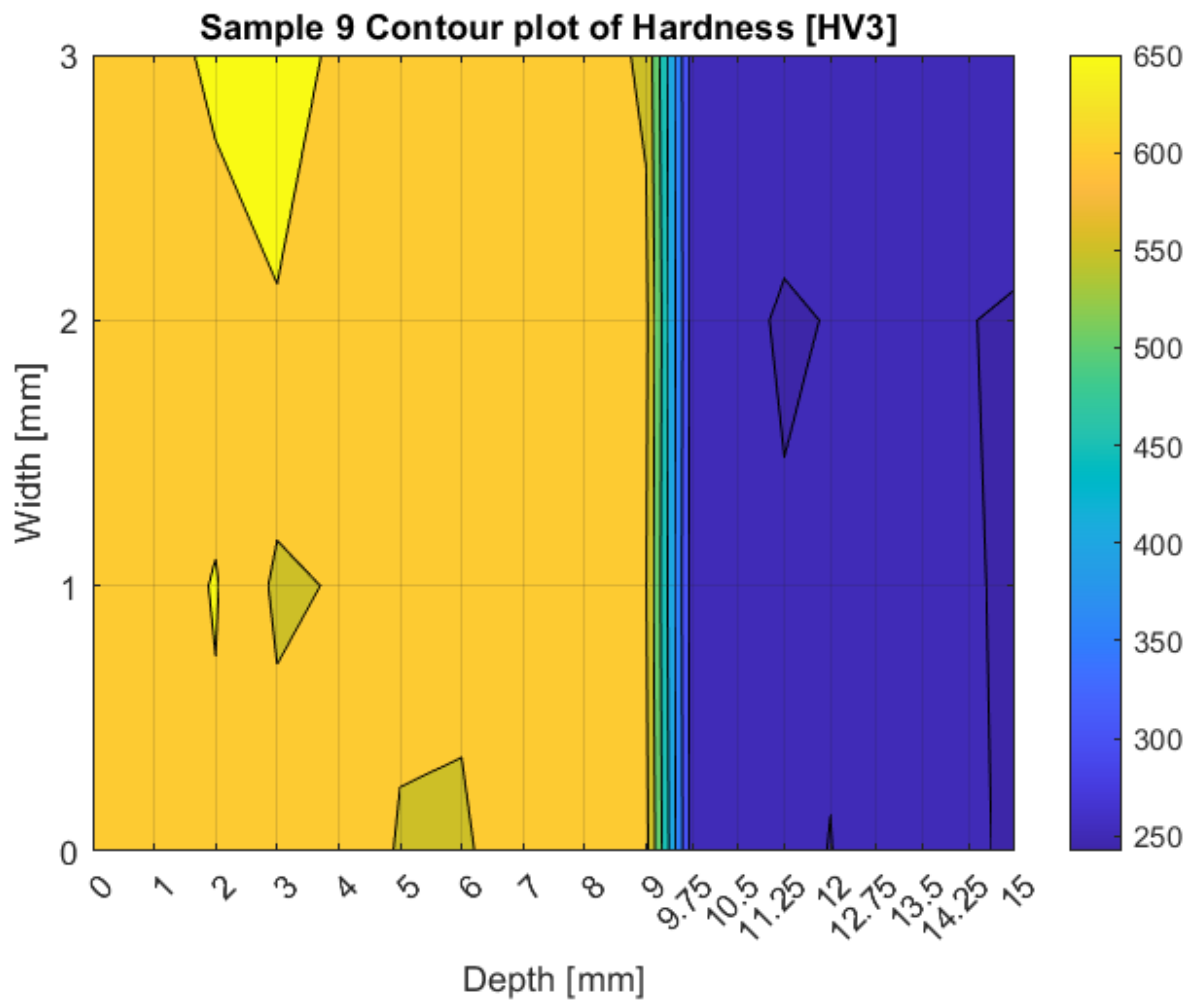


Figure 21: Contour graphs of substrate and deposition area of sample 9

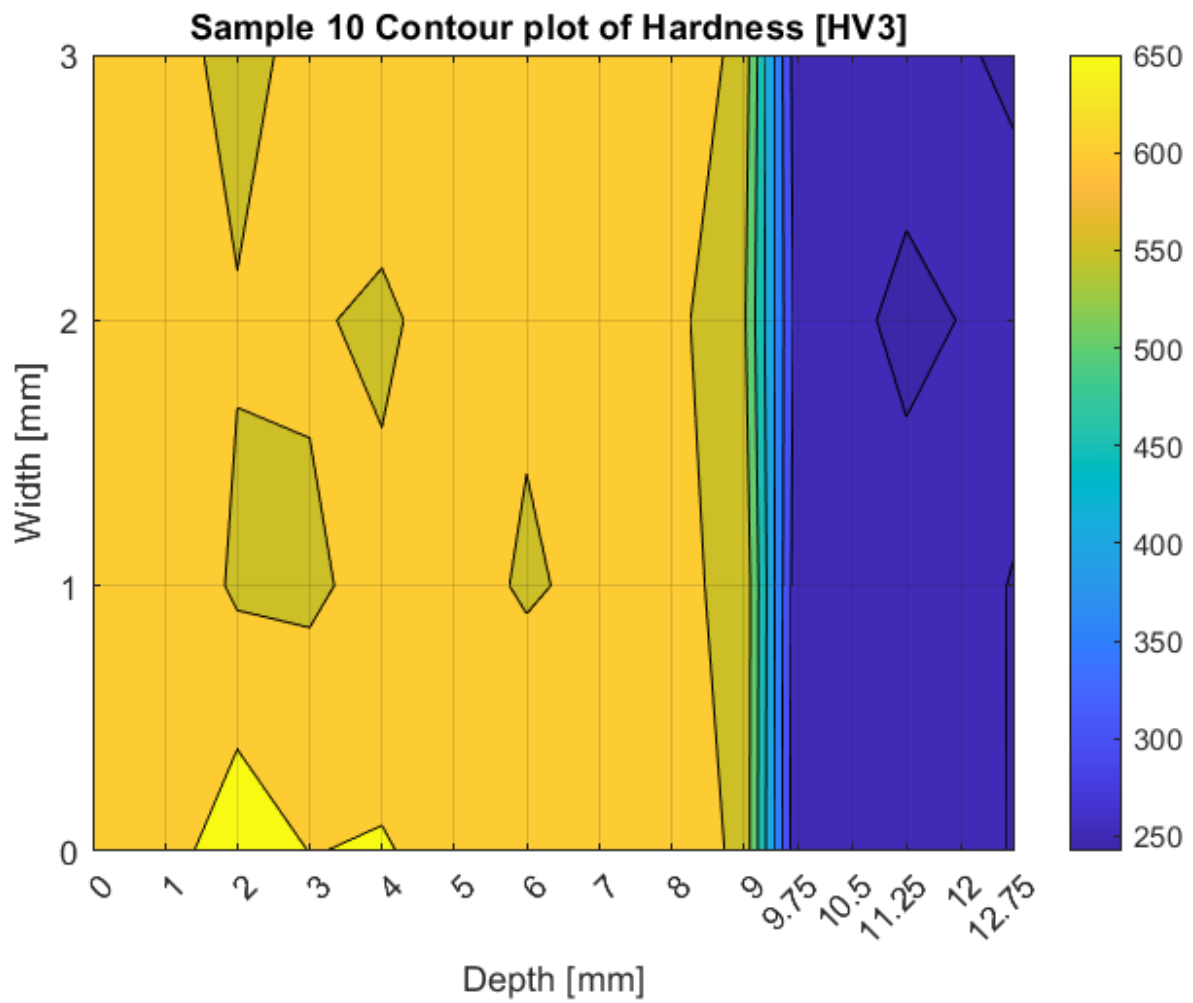


Figure 22: Contour graphs of substrate and deposition area of sample 10

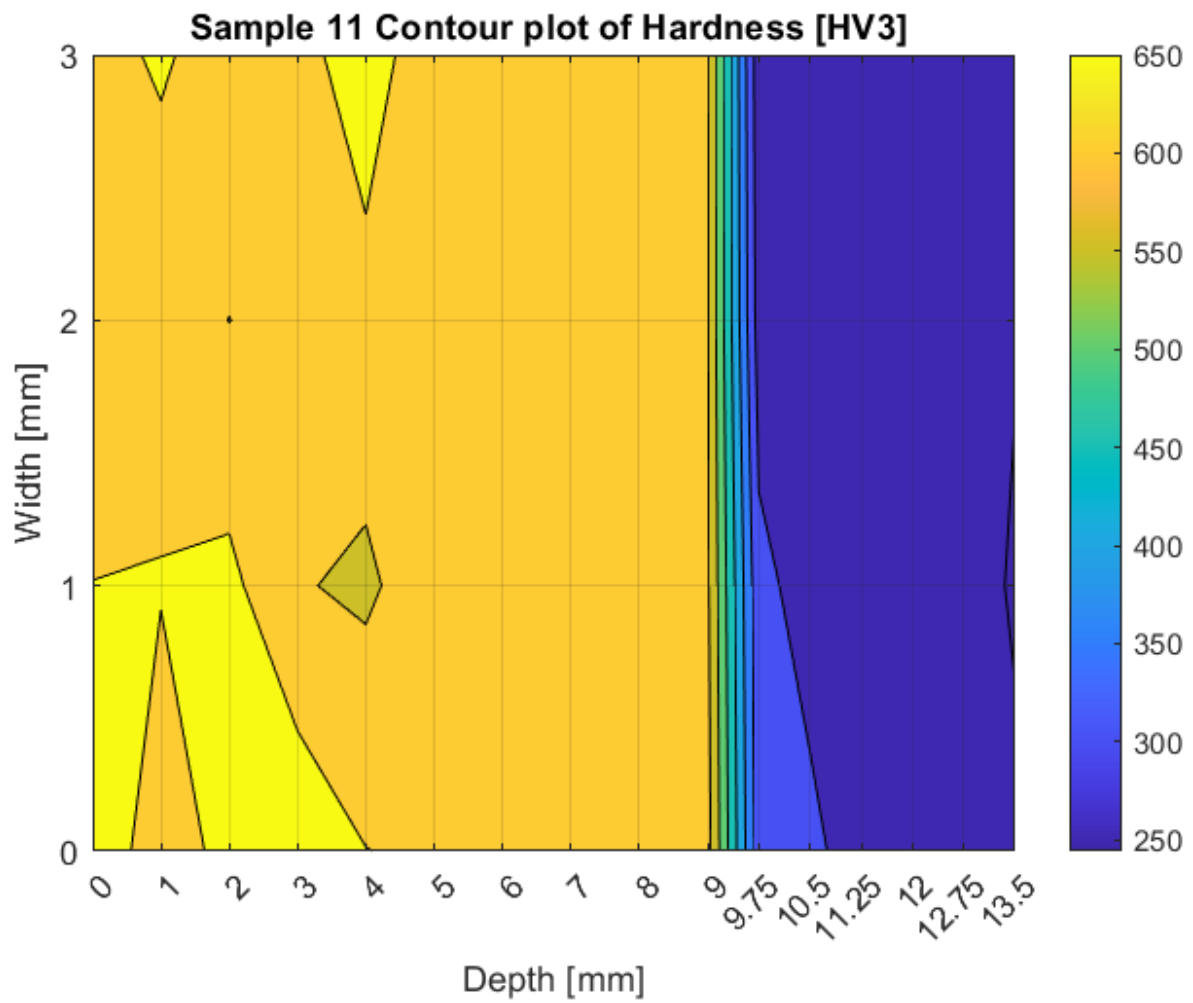


Figure 23: Contour graphs of substrate and deposition area of sample 11

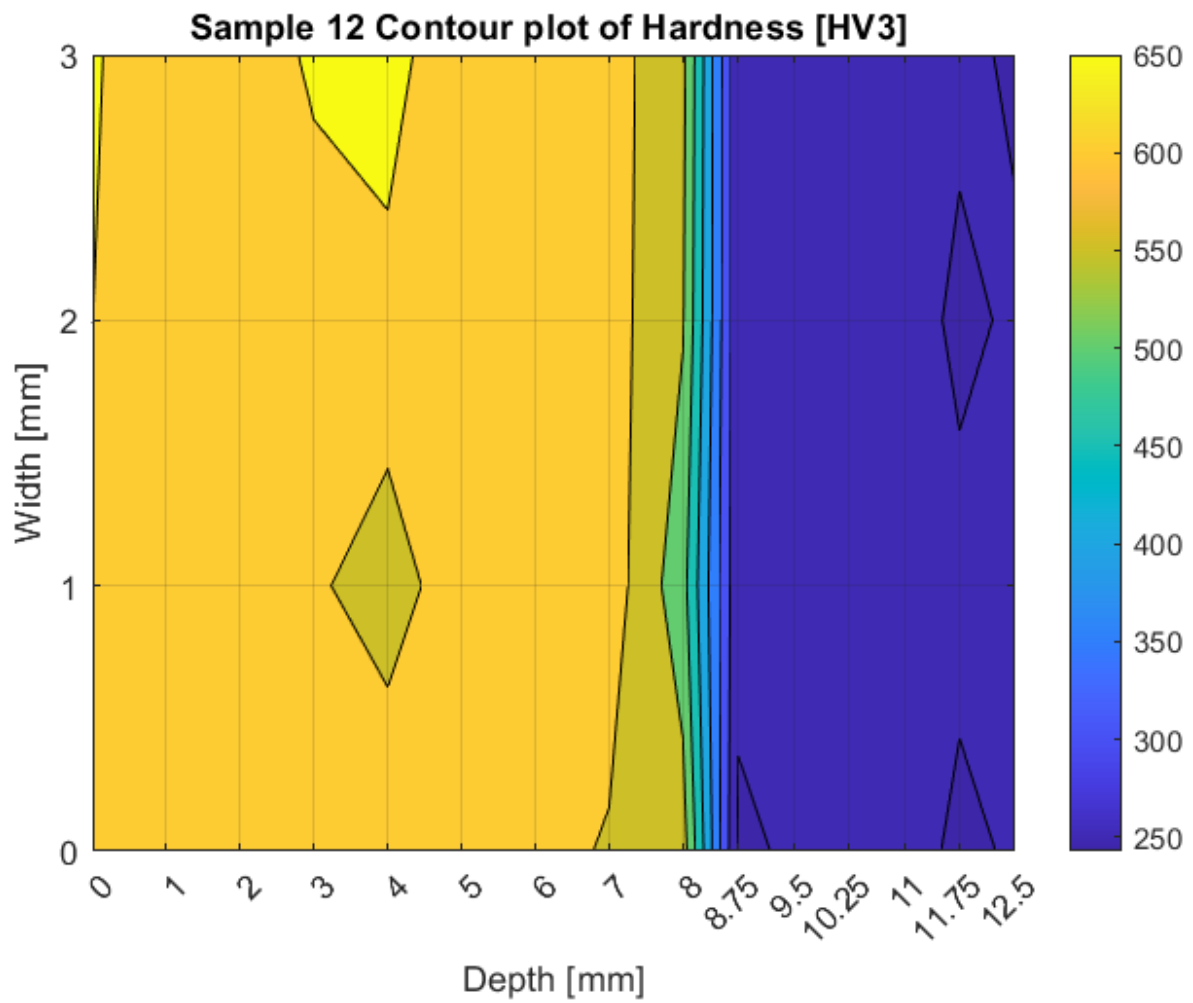


Figure 24: Contour graphs of substrate and deposition area of sample 12