Powder Bed Defects Classification: An Industry Perspective

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Abstract. The manufacture of defect-free parts has been a key discussion topic with the widespread adoption of additive manufacturing by industry. While significant research has been performed on the detection of powder bed defects, the focus has been on the classification of the defects according to defect type. However, when looking at creating a closed loop feedback system, it is important for the machine to make autonomous decisions regarding defects. The focus of this paper will be to create a defect severity classification matrix based on industry partner experience as well as published literature that can be used to autonomously classify defects

1 Introduction

With the widespread adoption of Additive Manufacturing (AM) technologies in industries such as aerospace and medical [1], it is important to ensure that the parts manufactured adhere to the stringent quality requirements specified by these industries. This means that the quality of these parts must be verified throughout the entire part manufacturing lifecycle. However, during the physical manufacturing process there are sometimes defects that occur that can only be detected using Non-destructive Testing methods such as micro Computer-Tomography (μCT) after the part has been manufactured [2]. A significant number of studies have been conducted to detect defects when they occur and to classify these defects according to type [3]. However, a closed loop feedback system is required that can make automated decisions regarding defects on the powder bed. This requires the capability to determine the potential impact of the defects on the part itself and the overall outcome of the build.

This makes it important to determine the relationship between the defects and the part quality. However, this is not entirely possible using literature alone as there is information available

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in the form of non-documented experience from machine operators that can prove to be far more useful than literature alone.

2 Background

Before the impact of defects on the outcome of the build and the part quality can be discussed, it is first necessary to briefly discuss the components of powder-bed based AM processes. Like most of the AM technologies, powder-bed based AM (as illustrated in Fig. **1**) is a layer-upon-layer manufacturing process. Powder-bed based technologies typically consist of a powder delivery source, a powder bed, a re-coater/scraper and a powder fusion source (energy system).

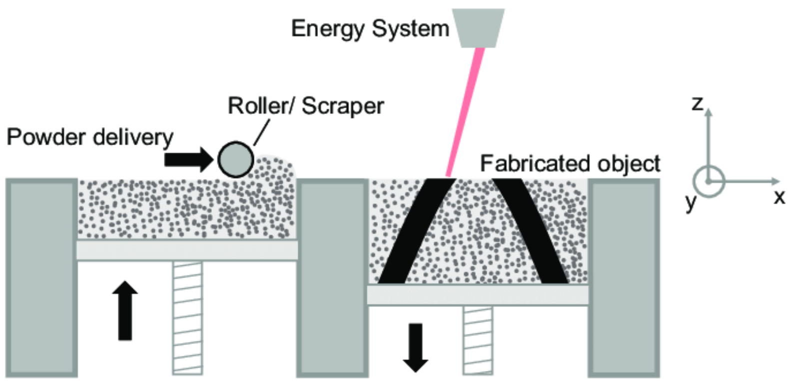


Fig. 1. Powder Bed Fusion Machine Components [4]

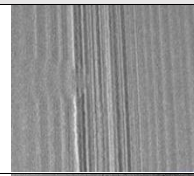
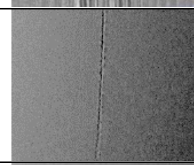
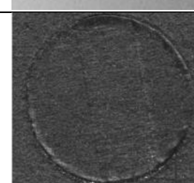
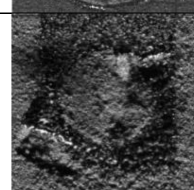
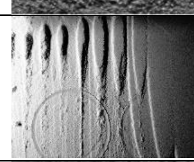
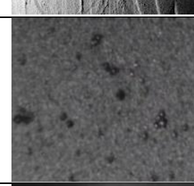
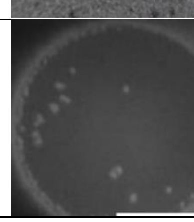
The basic method of operation is that the re-coater spreads a layer of powder over the build plate, and the powder fusion source (laser/electron beam/chemical binder) fuses the powder particles together in the shape of the part geometry for each layer. The build platform will then be lowered by the pre-determined layer thickness in preparation for the re-coating cycle. This entire re-coating and powder fusion process is then repeated for each layer of the part until the entire part has been manufactured.

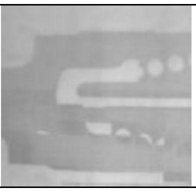
It is during this re-coating and powder fusion cycle that defects often occur. For the purposes of this study, only defects that directly relate to the re-coating and powder fusion cycle will be considered. However, it must be noted that not all the powder fusion related defects will be discussed as part of this study due to the specialised equipment required to analyse these defects as well as specialised knowledge required to interpret the collected results. In articles published by Lu and Wong [5] and Waller et. al [6] it was noted that a significant gap exists between the different industries as to what can be considered a critical defect. It was also noted that this gap will only be fully addressable as the AM industry matures and extensive long-term studies have been performed.

2.1 Powder-bed Defects

The defects that will form part of the study are listed in Table 1 below. Although this may not be an exhaustive list of defects, it does list those defects most commonly appearing in literature and that have been encountered by the authors in their experience with using powder-bed based technologies. It is worth noting that most of these defects, excluding the lack of fusion porosity (LOFP), are obvious enough that when they occur, they can be captured using a normal computer vision camera [3,7,8]. The LOFP defect are mostly only detectable in-situ using a near-infrared spectrum or thermal camera [9].

Table 1. Powder-bed defects

Type of Defect	Cause	Illustration
Re-coater Hopping [3, 12]	Re-coater blade striking the part.	
Re-coater Streaking [3,8,10]	Damaged re-coater blade or debris stuck to re-coater	
Debris on the powder bed [5, 10]	Spatter or balling on powder bed	
Super Elevation [7,10]	Part warpage above powder surface	
Part Failure [7,10]	Damage due to re-coater strike	
Powder Short Feeding [9, 11, 12]	Insufficient powder distribution	
Soot and Spatter [3, 9]	Spatter particles ejected from the melt pool	
Lack of Fusion Porosity [9]	Lack of fusion of new layer due to spatter particles	

Jet misfire and misprint [9]	Powder fusion in the wrong places due to software glitches or control system communication problems	

3 Defect Impact Assessment

For the development of a closed loop feedback system, one of the first things that must be assessed about each of the defects listed in Table 1 is the impact that it may have on the outcome of the parts being manufactured. This is to enable a corrective action when a defect occurs, the impact of the defect on the outcome of the part must be determined. This will prevent the system from intervening in defects that may have little to no effect on the outcome of the part or ignoring defects that can compromise the successful outcome of the part. Some defects may have a direct impact on the individual part quality [13], and it is necessary to determine the degree of this impact. The next step will be to categorise the defects according to their severity so that, when the defects occur on the powder bed surface, the appropriate actions can be taken.

3.1 Defect grading

As discussed in the previous section, it is necessary to grade the impact or severity of the defects according to a pre-determined scale. The use of a pre-determined scale will ensure that a specific impact or severity will be treated in the same way every time. This can prevent the incorrect classification of a defect due to varying linguistic meanings of different levels of severity.

In a study on defects that occur when manufacturing parts using Inconel 718 metal powders, a defect grading scale was proposed by Brown et.al [14]. This scale graded defects according to categories based on the effect that a defect could have on the outcome of the manufactured part as follows:

- Degradation of Mechanical Properties
    - Horizontal and Vertical Lack of Fusion Porosity
    - Powder Short feeding
    - Contour Separation
- Out of Tolerance Geometrical Features
    - Worm Track (Part Strikes)
- Minor or no observed effect on performance
    - Spherical Porosity
    - Welding Defects
- Unknown effect
    - Rough Surface (Underside of overhang surfaces)

This grading scale was created specifically for application to defects that occur during the actual build process. It can be hypothesized that although this scale was created for Inconel 718 metal powders, it should be applicable to any type of material or machine as the impact of the different defects will be the same and the causes of the defects should remain unchanged. It has been noted that, in some cases when the feedstock powder is changed some of the defects may become more severe or disappear entirely but this is also expected as some defects that appear in metal powders, do not really appear in polymer powders [15]. The study conducted by Brown et. al. [14] was compared to various sources in literature, and there were significant correlations between what this study discovered and the consulted literature sources [16, 17, 18, 19]. Although the impact of the different identified defects can be graded using this proposed grading scale, it must be noted that the priority of each defect will be dependent on the quality requirements dictated by the client. An example of this will be the difference in quality requirements between the investment casting and the aerospace industry. In the investment casting industry, the surface finish and geometric tolerances of the additively manufactured part will be of a much higher importance than porosity or tensile strength of the part. This is mostly due to the fact that, for the investment casting industry, the part will be dipped in a ceramic slurry and the part will be burned out before the casting is made [20]. On the other hand, for the aerospace industry the mechanical properties of the part are of a much higher importance as the parts are often manufactured with machining tolerances already as part of the design, thus slight geometric deviations can be machined to within specification.

3.2 Proposed Defect Priority Grading Scale

In a software package developed by a Canadian start-up company named 3dque, a defect classification/grading method was developed and applied to material extrusion (MEX) fused deposition modelling (FDM) additive manufacturing technologies [22]. The software has the capability of identifying 14 different defects that may occur when manufacturing parts using FDM. The system also gives the operator the option to select a specific response that the system must take when a defect is detected. According to the creators, the system also has the capability to autonomously correct a number of the defects without requiring human intervention. Although this method was specifically applied to MEX technologies, it can be argued that the basic idea could also be applied to other AM technologies such as the powder-bed based technologies.

Based upon industry experience and information collected from literature, it was decided that enough information was available to create a custom grading scale that could be used to classify defects according to the impact that they may have on the outcome of the part. However, it was considered useful to add an additional category to the scale, namely surface finish. In literature, it was discovered that some of the identified defects can have an effect on the surface finish of the final part [7, 8]. Thus, it was considered necessary to add surface finish to the defect impact grading scale as in certain industries a high quality as-built surface finish is important [20]. Based upon this information, the following defect effect/impact grading scale has been drawn up as illustrated in Table 2.

Table 2. Proposed Defect Impact Grading Scale

Defect	Defect Effect	Impact
Short feeding LOFP	Degraded Mechanical performance	4
Re-coater Hopping Part Strike Misprint Super Elevation	Out of tolerance geometric features	3
Spatter Re-coater Streaking Debris	Compromised surface finish	2
Soot	No observed effect on performance	1

In the initial phases of this study, it was proposed that a failure mode and effect analysis (FMEA) could be used to determine the priority for each of the defects. However, as is the case with a number of risk assessments including FMEA, the frequency of defect cause occurrence is required to conduct the risk assessments. Unfortunately, at the time of writing this article, there is limited information available with regards to how frequently the different causes result in a defect forming during the manufacturing process. Because this type of information is limited, subjective estimates would have to be made for these values. This could greatly affect the outcome of the risk assessment methods and produce inaccurate results.

As discussed in the previous section, part quality requirements are mostly dictated by the client or the industry standards under which the parts are manufactured e.g., aerospace, casting, medical, etc. This means that the priority for each of these defects must be assessed on a case-by-case basis and that a generic "one size fits all" approach will not be ideal. In most cases it would be logical to argue that the defects should be prioritised according to their inherent impact on the outcome of the build. However, there may be circumstances where the effect of a "lower impact" defect may be more important than a defect that could potentially be detrimental to the successful completion of the build. For example, it would make sense to have the option of either making use of the impact value as a priority or assigning a custom priority value to each defect. For this reason, a different type of method is proposed that can be adapted to the required quality parameters. Based upon the data illustrated in Table 2, a custom priority value can be assigned to each defect. This priority value can then be passed to an in-situ monitoring system that captures images of the powder bed surfaces and detects the defects when they occur on the powder bed [3, 9, 21]. For the initial phase of this study, a simple 3 level priority scale is proposed, namely:

- High (3)
- Medium (2)
- Low (1)

At first glance this scale may seem very simple and insignificant. However, if too large a scale is used to prioritise the defects, it may become a daunting task to the operator to setup before each build. Since this is a proposed method of defect classification and prioritization, the scales may have to be adjusted as data is collected during actual builds. This priority value can then be used to determine how the monitoring system will respond to detected defect. Table 3 illustrates the impact values for each defect as well as the proposed priority values.

Table 3. Defect Impact & Priority Grading Scale

Defect	Consequence/Impact	Impact	Priority
Short feeding	Degraded Mechanical performance	4	3
LOFP	Degraded Mechanical performance	4	3
Hopping	Out of tolerance geometric features	3	2
Part Strike	Out of tolerance geometric features	3	2
Misprint	Out of tolerance geometric features	3	2
Super Elevation	Out of tolerance geometric features	3	2
Spatter	Compromised surface finish	2	1
Streaking	Compromised surface finish	2	1
Debris	Compromised surface finish	2	1
Soot	No observed effect on performance	1	1

Once all of the defects have been prioritised, it is now possible to start looking at possible alert actions that can be taken when defects have been detected. Based upon information gathered from literature and expert experiences, there are a few corrective actions that can be taken while the build is in progress, e.g., stopping individual parts inside the build, re-coating a short fed layer, etc. However, extensive studies and testing on possible in-situ corrective actions must still be performed before a fully autonomous corrective action system may be viable. For the purpose of this research study, the classification system will only focus on alerting the machine operator to the various defects that may have occurred on the powder bed surface. The alert conditions will also be directly correlated to the priority levels. The three alert conditions that will be implemented are listed as follows:

- Pause Build, Alert operator, Log Defect (Priority Level 3)
- Alert Operator, Log Defect (Priority Level 2)
- Log Defect (Priority Level 1)

For the first alert condition, the build will be paused pending operator input. This alert condition would be useful for defects that have the highest priority, or in terms of impact, defects that pose the greatest risk to the successful outcome of the part being built. The second Alert condition will typically be for defects that have a medium level of priority. In terms of impact, this would be for defects that can have an impact on the part quality but can possibly be corrected in-situ. At this point the operator could then also decide to manually pause the build to correct the defect that had occurred. The last alert condition is typically for defects that have the lowest priority, or in terms of impact, defects that typically have very little to no impact on the outcome of the part.

A final version of the proposed risk assessment, prioritization and alert condition matrix is displayed in Table 4.

Table 4. Defect Impact, Priority and Response Matrix

Defect	Consequence/Impact	Impact	Priority	Alert Condition
Short feeding	Degraded Mechanical performance	4	3	Pause Build
LOFP	Degraded Mechanical performance	4	3	Pause Build
Hopping	Out of tolerance geometric features	3	2	Alert Operator
Part Strike	Out of tolerance geometric features	3	2	Alert Operator
Misprint	Out of tolerance geometric features	3	2	Alert Operator
Super Elevation	Out of tolerance geometric features	3	2	Alert Operator
Spatter	Compromised surface finish	2	1	Log
Streaking	Compromised surface finish	2	1	Log
Debris	Compromised surface finish	2	1	Log
Soot	No observed effect on performance	1	1	Log

Although the matrix in Table 4 has been filled in completely, the priority and response values can be customised completely to suit specific industry quality requirements and do not necessarily have to follow the determined defect impact values. If no custom priority values have been entered into the matrix, the default impact values as determined from literature will be used. In this case an impact level of 4 will invoke alert condition 3, impact level 3 will invoke alert condition 2, and impact levels 2 and 1 will invoke alert condition 1. This will give the operator the choice to treat defects according to the intrinsic impact that they pose to the build, instead of using a customised defect impact profile.

4 Conclusion

With the rapid adoption of AM technologies in industry, the need for quality guaranteed parts has increased. This means that each step of the manufacturing process must be verifiable to ensure that the part's quality is up to specification. One of the areas that has received significant attention is the actual build process. During the build process, there are often defects that occur during the re-coating and powder fusion cycle. Although a significant amount of research has been dedicated to detecting these defects when they occur, the classification of the defects according to the impact that they may have on the outcome of the part has been lacking. In this study, an in-depth analysis has been performed on the defects that are detectable during the build process. Based upon a thorough literature review and industry experience, the defects were classified based on the impact that they may have on the outcome of the part. Once the defects were classified, an impact, priority and alert condition matrix was established that can be applied to real time build monitoring systems. These priorities and alert conditions can then be used to alert operators to defects that occur during the build process. This in turn can provide the operator with the opportunity to intervene in the build process and either correct the defect or stop the part/build prematurely and prevent a further loss of raw materials and machine hours.

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