Diagnosis of fatigue cracks in structural elements manufactured by additive manufacturing

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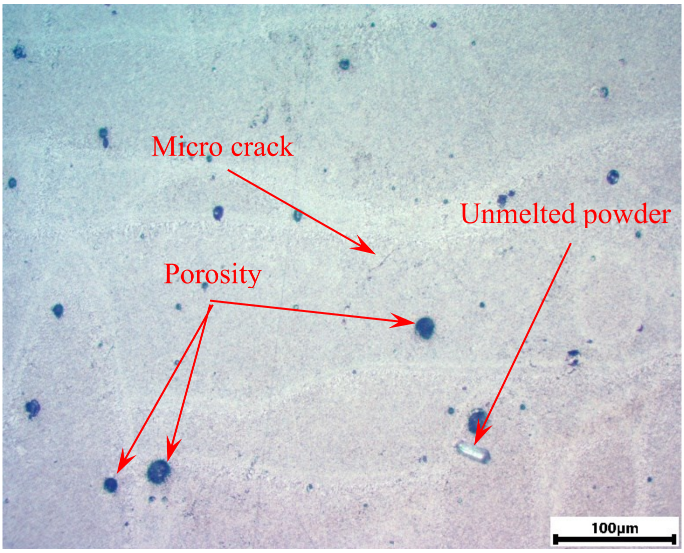
Abstract. Recently, the production of metal structural elements using additive processes is gaining popularity. They allow the production of an element of any geometry and structure, while reducing the mass of the produced part. Unfortunately, the AM technology causes structural elements to be burdened with numerous defects in the form of porosity, unmelted powder, weak interlayer bonds or residual stresses, etc. These defects translate into the possibility of an early, uncontrolled fatigue crack. For this reason, it is important to find ways to quickly detect damage caused by random variable loads. The work presents methods of diagnosing cracks and fatigue damage in structural elements produced using 3D printing. The division of research methods allowing for the detection of defects in structural elements and the characteristics of the most popular methods, taking into account their advantages and limitations, were presented. Methods appropriate for a given type of material, test conditions and damages are indicated. The most important methods of diagnosing defects in printed elements include: penetrating, ultrasonic, radiographic, eddy current and thermal imaging methods.

1 Introduction

Unconventional techniques, based on additive manufacturing, are increasingly being chosen for the production of structural elements for special applications. 3D printing from powdered metals is used in various industries, including in medicine, aeronautics, aviation and automotive [1]. The production of metal structural elements using 3D printing is widely used due to the possibility of making parts with complex geometry easier, reducing the number of production stages and reducing the amount of material used, because without much difficulty it is possible to make perforated elements with a mesh or lattice structure [2]. This allows the weight of structural elements to be reduced compared to standard manufacturing techniques. In the aerospace industry, a 1 kg lighter aircraft saves at least 3,500 USD in fuel costs over its lifetime [3]. In aviation, you can find many structural elements produced by incremental techniques, mainly from the Ti6Al4V titanium alloy. This material is used to make turbines, stiffen the hull or landing gear. Due to their application, these elements must meet certain safety requirements. Fatigue failure of a structural element in an aircraft can lead to a catastrophe. The properties of the same material by producing an element with different techniques (additive or traditional) differ significantly and can lead to other mechanisms of fatigue cracks [4]. Additive technologies are not yet able to produce a structural element with the required mechanical properties and surface roughness to meet most applications [5]. Defects and geometrical inaccuracies limit the use of AM construction elements in all branches of industry today. The improvement of the mechanical and fatigue properties of AM elements is currently achieved through the use of heat and surface treatment [6].

a)



b)

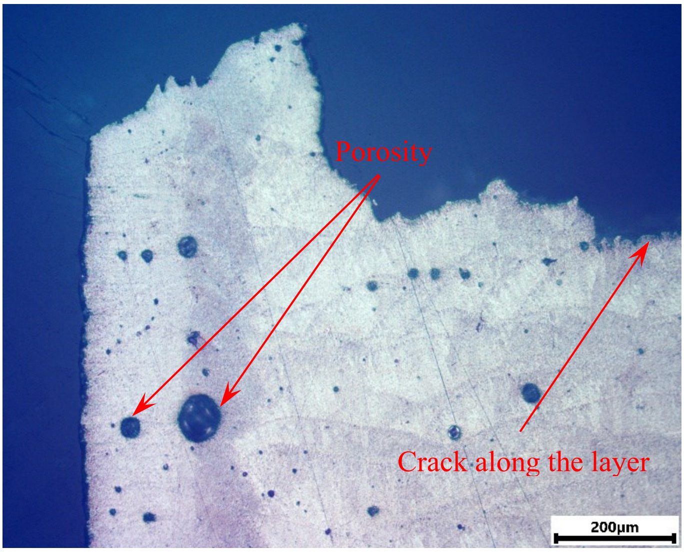
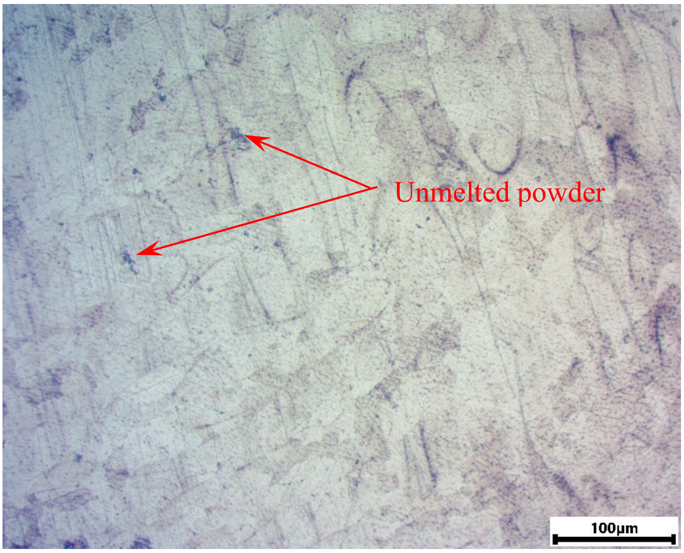


Fig. 1. Microstructure of AlSi10Mg aluminum alloy produced by SLM technology: a) as-build state on a surface parallel to the build direction, b) after a static tensile test on a surface perpendicular to the build direction [own research]

Figure 1 presents microscopic photos of AlSi10Mg aluminum alloy and 316L steel made by additive technology. Parts produced by AM are characterized by a number of defects, i.e. unmelted powder, porosity resulting from shielding gas entrapment, poor interlayer bonding, microcracks, etc. and a high surface roughness parameter, which reduces fatigue life. The cracking pattern of samples subjected to static loads and the microstructure of the Ti6Al4V alloy produced in AM were described in earlier works [4, 7]. In paper [8], defects in the microstructure of additively manufactured 316L steel were described. The defects occurring in the structural elements produced by AM affect the early appearance of fatigue cracks.

a)



b)

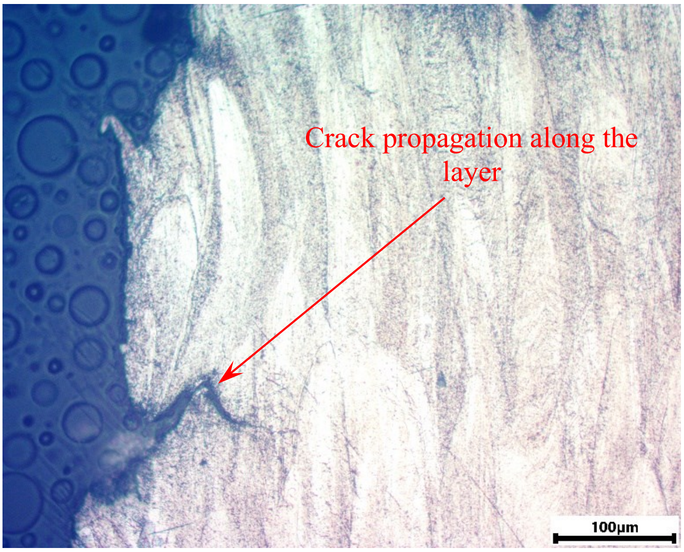


Fig. 2. Microstructure of L316 stainless steel produced by SLM technology: a) as-build state on a surface parallel to the build direction, b) after a static tensile test on a surface perpendicular to the build direction [own research]

Therefore, the most appropriate method for diagnosing fatigue failure of additively manufactured structural members should be determined.
The method of detecting fatigue damage in AM-fabricated elements should be characterized by the possibility of quick detection, adaptation to complex geometric structures and poor surface quality, and detect many types of defects, and above all, be inexpensive [9]. The methods of diagnosing fatigue damage can be divided into non-destructive and destructive. Many of them can be adapted to evaluate objects produced using additive methods, including 3D printing from metal powder. The division of methods for diagnosing fatigue cracks in structural elements manufactured using additive methods is presented in Table 1.

Table 1. Methods of diagnosing fatigue cracks in structural elements [10,11].

No.	Detection method
1	Visual research
2	Penetration method
3	Magnetic particle method
4	Magneto-inductive method
5	Ultrasonic method
6	Radiographic method
7	Eddy current method
8	Acoustic emission method
9	Thermographic method
10	Tightness method

Due to their characteristics and potential application, the following methods deserve special attention: penetrating, ultrasonic, radiographic, eddy current and thermal imaging. Selected methods are described in the following sections.

2 Methods description

2.1 Penetration method

Penetrant testing is a part of non-destructive methods, as it uses the capillary effect to identify surface damage to components. This method consists in the application of a fluorescent or colored penetrating substance on the surface of the tested element. As a result of capillary phenomena, the preparation penetrates and settles in discontinuities. Excess penetrating substance is removed after drying. Then the developer is applied, which, with the participation of light, reacts with the penetrating substance and reveals damage to the surface of the element. One of the most important factors determining the sensitivity of the method are the type and properties of the penetrating substance. Preparations containing fluorescent dyes are considered the most sensitive [16]. The penetration method is a highly sensitive research technique and allows for intuitive results. The limitation of the method is the inability to use it in unfinished research of rough and porous elements produced using 3D printing. Before performing the test, it is necessary to remove paint coatings and all kinds of impurities from the surface of the element [10]. This method is successfully used by NASA to test the surface of the most important elements of rocket engines powered by liquid fuel [20].

2.2 Ultrasonic method

Ultrasonic testing is one of the basic non-destructive testing methods. The use of ultrasonic waves makes it possible to detect internal defects in metal elements. A transmitting probe is used to excite ultrasonic waves. The waves propagating inside the element encounter various defects that affect the return signals recorded by the receiver. The difference in the time of the return of the waves allows the identification of damage to the element. The registration takes place on a phosphor display, where the height and location of the echo indicate the size, location of the defect, and may also indicate its general nature. Ultrasonic methods are sensitive to cracking, partial penetration and infusion defects. However, the limitations of the method are lower sensitivity to pores and inclusions, e.g. slag, present in the material. These methods do not allow detection of surface damage. There are a number of factors that affect the ultrasound examination. The most important are the projection direction, probe efficiency, coupling between the probe and the tested element, as well as the excitation frequency [13, Wang X. G., 2017]. Another limiting factor, apart from the depth of the examination, is its sensitivity. It allows the detection of only damage that exceeds the dimensions allowed by the relevant standards [23].

In order to minimize the limitations associated with the ultrasonic method, the laser ultrasound method is successfully used. This modification allows for higher resolution by generating a broadband signal with the use of laser pulses. Composite studies have shown that longitudinal waves, which are reflected from individual layers, allow to obtain images in the quality close to X-ray computed tomography [15]. The limitation of the laser ultrasound method in the analysis of metal structures is the lack of effective generation of longitudinal waves without surface ablation. However, there are known examples of the use of other types of waves in this type of research. In the literature, there are examples of the use of laser-generated surface waves [17], transverse waves [18] and Lamb waves [19].

2.3 Radiographic method

Testing of defects in elements manufactured with the use of additive techniques can be carried out using X-ray methods. This type of research is carried out with the use of X-ray or gamma-graphic devices. They require access from both sides of the tested element. The harmful ionizing radiation used in this process makes it impossible for other people to stay in the research area [10]. Despite some obstacles, this technique can be successfully used to assess discontinuities in structural elements. Qian et al. used X-ray computed tomography to assess the growth of fatigue cracks caused by defects in the AlSi10Mg alloy produced using additive techniques [22]. In turn, Lopez et al. in addition to the ultrasound method, they used the radiographic method in non-destructive testing of the evaluation of materials produced using additive techniques [24].

2.4 Eddy current method

Another method that allows the detection of fatigue cracks in structural elements manufactured using additive techniques is the eddy current method. It is a non-destructive form of evaluation of structural elements. The principle of the method is based on the use of electromagnetic induction to detect defects in elements made of materials that conduct

electricity. Detection of discontinuities is done by measuring changes in induced eddy currents. This method uses alternating excitation and an alternating magnetic field generates an eddy current. The resulting change in the eddy current allows the detection of existing damage inside the printed elements.
The method makes it possible to perform damage detection in difficult conditions and to diagnose cracks and unmelted pores [11]. Literature sources present the results of the use of the eddy current method in the detection of defects during the processing of composites [21]. It is possible to use the eddy current technique in elevated temperature conditions, however, the temperature affects the electromagnetic properties of the tested material. Components produced using additive methods are often characterized by the complexity of the temperature field. Therefore, in these cases, the application of the aforementioned detection method is difficult [11]. In addition, the disadvantages of the method include the limited depth of the test and the sensitivity of crack detection, as well as the possibility of detecting damage that is larger than the dimensions allowed by the relevant standards [23]. Nevertheless, this method has numerous advantages. It can be successfully used to test painted elements, it is characterized by appropriately high sensitivity and reliability in detecting defects, and it also enables the identification of damage in hard-to-reach places [10].

2.5 Thermographic method

This method consists in displaying damage contours as a result of the thermal intensity of infrared radiation of elements produced using 3D printing technology. The change in radiation intensity between the resulting defect and the undamaged material becomes visible in the infrared. Damage and discontinuities occurring in printed elements affect their material properties, which may manifest themselves as changes in heat conduction, and consequently affect the temperature field in metal elements. The method requires the use of an appropriate heat source and a thermal imaging camera that reads the temperature of printed elements. The observed anomalies indicate the location of material defects [10]. Research by Bartlett and colleagues used a long-wave thermal imaging camera to take pictures of the individual layers applied in the manufacturing process. During the tests, special attention was paid to places where the average temperature of the layers differed by 1% and they were classified as damage. The use of the method allowed the detection of defects in real time. The conducted experiments allowed to diagnose 82% of unmelted defects and 100% of unmelted defects larger than 500 µm. However, this method has some limitation. It enables the detection of only 33% of microporosity defects [12].

3 Conclusion

There are many methods that allow the detection of defects in structural elements, and at least some of them are particularly suitable for detecting fatigue cracks in structural elements manufactured using additive methods. The most important are the penetrating, ultrasonic, radiographic, eddy current and thermovision methods. Each of these techniques has its advantages and limitations. Under certain conditions, some of the methods may be better or worse suited for identifying defects. For this reason, it becomes important to choose the right method depending on the material used in 3D printing and the possibility of conducting the test.

The penetration method is a highly sensitive research technique. However, the inability to use it in the study of rough and porous elements is a significant disadvantage. In addition, it requires the removal of paint coatings and impurities before performing the test [10].

In turn, the ultrasonic method is sensitive to cracks, partial penetration, as well as infusion defects. The disadvantages of this method include less sensitivity to pores and inclusions in the material and the inability to detect surface damage. [13, 14]. Another limiting factor, apart from the depth of the examination, is its sensitivity. It allows the detection of only damage that exceeds the dimensions allowed by the relevant standards [23]. For this reason, the method of laser ultrasound is successfully used, which results in obtaining a higher resolution by generating a broadband signal with the participation of laser pulses.

Also, the radiographic method can be successfully used to assess the growth of fatigue cracks caused by defects in materials produced using additive techniques [22]. However, this technique requires access from both sides of the tested element, and the ionizing radiation used makes it impossible for outsiders to stay in the place of testing [10].

The eddy current method makes it possible to perform damage detection in difficult conditions, to diagnose cracks and unmelted pores [11]. In addition, the limited depth of the test and the sensitivity of crack detection should be considered as disadvantages of the method [23]. The advantages of the method include the possibility of testing painted elements, relatively high sensitivity and reliability of defect detection, as well as the identification of damage in hard-to-reach places [10].

The thermal imaging method requires the use of an appropriate heat source, as well as a thermal imaging camera that reads the temperature of printed elements [11]. The thermal imaging method, like the eddy current method, allows the detection of unmelted defects. The disadvantage of the method is the limited detection of micropores [12].

These methods are characterized by high sensitivity and can be successfully used in the assessment of damage to structural elements produced using additive methods.

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