Journal of Additive Manufacturing Technologies
DOI: 10.18416/JAMTECH.2111494

Infinite Science | Publishing

Experimental determination of thermal emissivities for Ti6Al4V in selective laser melting

M. Y. Kayacan[1]*, N. Yilmaz[2] and A. Özsoy[3]

[1,2,3]Isparta University of Applied Sciences, Isparta, Turkey
**Corresponding author, email: mevlutkayacan@isparta.edu.tr*

Abstract

This study was carried out in order to precisely measure the temperatures, which play an important role in reducing the errors that occur during the manufacturing of Ti6Al4V materials by the Selective laser melting method. In order to use thermal cameras in the SLM method, the thermal emissivity values of samples with different surface properties depending on the temperatures were experimentally determined. Emissivity values were determined up to a temperature of 550°C due to oxidation. Emissivity measurement was obtained by verification with the help of surface thermocouple. Emissivity values were obtained between 0.31-0.40 in measurements depending on the surface roughness and temperatures up to 550°C. The changes on the surface properties depending on the temperature cause changing of the emissivity.

Keywords: Selective laser melting, Temperature measurement, In-situ monitoring, Thermal emissivity.

1. Introduction

Selective laser melting (SLM) method has developed in recent years thanks to the advantages of manufacturing of complex parts. With this development, it has started to be among the common manufacturing methods that especially for aviation and healthcare industries [1]. Besides the fact that the many advantages it provides, it also has some problems in terms of manufacturability. There are some failures that occur due to the thermal accumulation and heterogeneous distribution during manufacturing, and these phenomenons decrease the structural integrity of the part. The heat generated during manufacturing does not accumulate equally in all areas of the part and cannot be transferred to the outside of the part homogenously. As a result, temperature gradients are formed on the part. In case of increasing temperature gradients in the manufacturing process, different rates of thermal expansion are observed and internal thermal stresses occur. Internal stresses remain in the part and turn into residual stresses due to fast and unbalanced cooling. Residual stresses can cause deformation of the parts by being released both during manufacturing and the use of the end product.

The reduction of temperature gradients during manufacturing is important to get proper parts in additive manufacturing. It should be aimed to have a homogenous temperature distribution and to have low temperature values. These aims can be achieved by optimizing the manufacturing parameters, extending the production periods, ensuring the conditions in which the heat transfer rate will increase, and balancing the temperature distribution of the base platform. Measurements are taken by the thermal cameras in order to ensure a homogenous temperature distribution during manufacturing [2]. Thermal cameras are positioned inside in some cases and sometimes outside of the manufacturing chamber. Two prerequisites must be met in order to be able to take measurements during additive manufacturing with a thermal camera. The first of these is to provide measurement calibrations of the thermal camera. The other is that emissivity measurements can be made depending on the material being measured, surface properties, ambient temperature and part temperatures. According to the literature, the emissivity values of Ti6Al4V materials are at the level of 0.05 if the surface is very smooth. Emissivity can increase up to 0.60 when the surface is rough and dull (may be oxidized) [3]. These values are valid for the 7.5-13μm spectral wavelength that is needed by the Optris PI160 model for measurement. In order to determine which coefficients are valid for Ti6Al4V material produced with SLM with different surface properties, analytical method was used in the emissivity determination studies in the literature [4]. In this study, the emissivity values, which the surface where the temperature measurement will be taken, are determined by taking measurements with a thermal imager at the same time with a calibrated surface type (K) thermocouple (surface TC), which varies according to temperature and surface properties. Thus, accurate temperature measurement can be achieved by using the temperature-dependent emissivity values during manufacturing.

2. Materials and Methods

With the SLM method, temperatures occurring in manufacturing were measured during the manufacturing process by means of a thermal imager. There are two different requirements for temperature measurements in the SLM method. The first of these is that different emissivity values can be defined in different areas on the obtained thermal images. Because there are metal powders and samples that have been solidified by laser processing at the same time. Second, emissivities must change depending on both surface roughness and part temperatures. During manufacturing, both temperatures and surface roughness change due to different manufacturing parameters. The thermal imager used in measurements is defined as the Optris PI160 model process monitoring type. The camera resolution is about 1 mm and the measurement speed is 7.8x10^{-3} fps (number of unit frames per second). The temperature band that the camera can detect is between 0 and 1500°C. Before starting to determine the temperature with thermal cameras, much information such as the measured environment and material properties is needed. The most needed data are the ambient temperature, the thermal emissivity value that changes depending on the surface characteristics of the material, and the material temperature. In addition to these, if there is a material with a low transmissivity between the measured material and the camera, the transmissivity rate and the transmissivity coefficient of the material measured are required. If any of these data is missing, the temperatures obtained may be erroneous [3,5].

Before the thermal measurements were taken within the scope of the study, the thermal camera was calibrated. The calibration process was carried out by the company in which the camera was supplied and sent. After this process, the emissivity values of the surfaces to be measured under different temperatures were determined. There are two different methods accepted in the literature for emissivity measurement in common [6]. The first of these is known as the comparative emissivity measurement. In this measurement method, a material surface that has a certain emissivity value is provided and placed side by side with the material whose emissivity is to be determined. The material which is usually called the black body has an emissivity of 1. Although this material can be supplied, it can also be obtained by applying a black coating to a surface by kindling smoke. The second method is to measure the temperatures of the surface with a thermocouple. Experiments are concluded by determining the emissivity value required to match the data measured from the camera and the data taken from the thermocouple. Within the scope of the study, a thermocouple-supported system was preferred because it was thought to give more accurate results. In this method, a surface thermocouple is placed on the center of the measured surface of the part. A thermocouple is also used for room temperature measurement. Afterward, as the temperature of the heated part rises from the bottom to the top, the temperature-dependent emissivity values are determined by changing the emissivity value so that the temperature value measured by the thermocouple and the temperature value in the thermal camera is the same [7,8]. The ambient temperature must be defined momentarily in the thermal camera. Figure 1 shows the experimental setup.

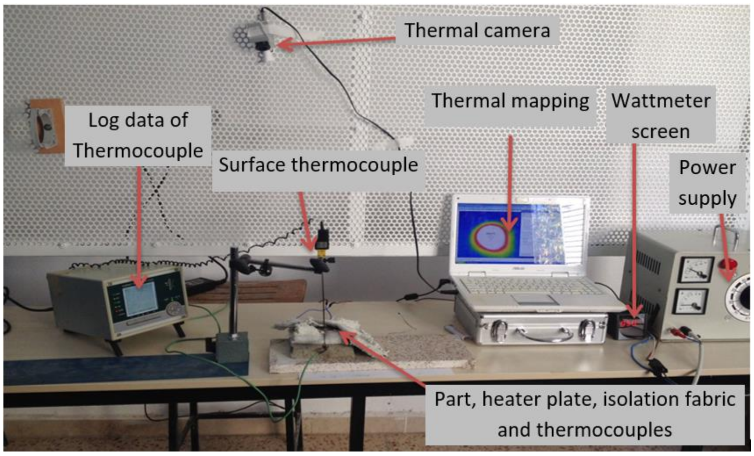

Fig 1. Thermocouple assisted emissivity definition test set up.

As seen in Figure 1, a heating plate was placed under the examined plate in order to increase the surface temperature of the plate whose emissivity will be determined in a controlled and gradual manner. The temperature on the heating plate was supplied by electricity from a regulated side. The surface temperature of the area where the plate/piece surface temperature was measured with the thermal camera was physically measured with a K type thermocouple. The thermocouple, which senses the surface temperature, was placed on the surface of the part and measured by applying a mechanical pressure on it. Outdoor temperature was also measured with another type K thermocouple. The data obtained from the temperature measurements were recorded with the Almemo 5690-2 data logger. The heat load delivered in the plate heater was measured with the Wattmeter (power indicator). When the plate temperature, heated by the electrical power taken from the transformer, reached the desired temperature, the applied power remained constant, and a certain period of time was waited for the temperature to stabilize. While the surface temperature was stable, the surface temperature was measured, and the emissivity value that would provide the same temperature as the thermal imager was adjusted and this value was recorded. After the electrical power was increased with the transformer and the temperature reached a desired upper value, the emissivity that provided the part surface temperature was adjusted again manually. The emissivity value, which ensures the same temperature value measured from the thermal camera and surface type thermocouple, was recorded. The gradual temperature increase on the part surface was continued until it was observed that the material was oxidized (in common up to 550°C). Thus, the change in emissivity with temperature was determined. In order to observe the effect of surface roughness on emissivity, the same procedure was applied for two pieces with two different roughness. In Figure 2, the heater plate and part connection are shown schematically.

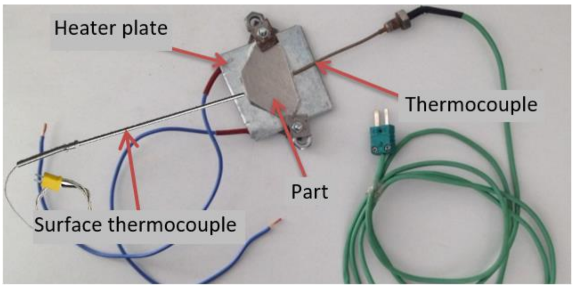

Fig 2. The heater plate, the test part and the thermocouple connections.

This study was carried out for two different parts made of the same material since material surface emissivity will be used in the production of both the intermediate layers and the upper surface in the production of parts with the SLM method. These are a sample produced according to the parameters used in the inner layer manufacturing and another sample produced according to the parameters used in the upper layer manufacturing. Since the samples manufactured according to the parameters used for both the intermediate and the last layer have different roughness, it also allows the determination of the effect of roughness on emissivity. The same parameters are used in the processing of inner layers and top layers. The laser power was 170W, scanning speed 1150 mm/s, scanning distance 100µm, layer thickness 30µm, powder size of Ti6Al4V 20µm. However, scanning strategies have become different. While the inner layers were processed (laser melting) during manufacturing, the lines of 5mm bandwidth were followed sequentially. While the last 3 layers are manufactured, the entire surface is processed in a single line. Thus, a smoother texture can be obtained on the upper surface. The surface roughness (Ra) of the upper layers was determined as 2.65µm, and the surface roughness (Ra) of the inner layers was determined as 5.85µm. Surface roughness was measured by Mitutoyo with a diamond tool. All interlayers of a part in progress, except the lower and upper 3 layers, are defined as the inner surface. Figure 3 shows the difference between the two surfaces.

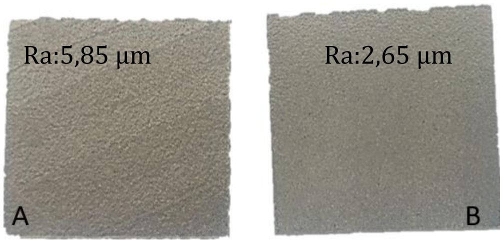

Fig 3. Textures of different Ti6Al4V sample surface. Interlayer surfaces (A), Top surfaces (B).

3. Results and Discussion

In order to perform temperature measurements precisely, emissivity measurements were obtained from both the upper and middle surfaces of the manufactured samples and powders. In this way, temperatures of all surfaces were recorded during manufacturing. With the image processing software named Pix connect, different emissivity values for different areas can be defined according to the needs of the photos obtained from the thermal camera. By drawing the boundaries of the measured samples and other parts on the software, a more precise temperature measurement was made with the emissivity values valid for each piece separately. Thus, both the powder temperatures were obtained in accordance with the reality, and the part geometries were clearly revealed. Since the manufacturing parameters on the outer surfaces of the samples are different from the manufacturing parameters on the inner parts, the energy density is higher. Surface properties are also different from inner regions. Therefore, different emissivity measurements were carried out for surfaces manufactured with different parameters. Table 1 shows the emissivity values that vary depending on the temperature taken from the upper and inner layers of the samples.

As can be understood from the Table 1, there was no change in ambient temperature. In order to reach the temperature values obtained with the thermocouple, the emissivity values have changed instantaneously. Temperature tolerances between the two measurements were obtained as ± 3°C. In order to understand the changes that occur due to the differentiation of manufacturing parameters depending on the temperatures, the emissivity values obtained for both surfaces are shown graphically in Figure 4. If the emissivity values are determined from variable values depending on the temperature as shown in Figure 4, it is possible to encounter an error of ± 5 °C [3]. It was understood that the surface with two different roughness and surface topography showed an opposite increasing and decreasing emissivity change during the manufacturing process.

Table 1. Emissivity measurements taken from the upper surfaces and inner layers of the samples.

Ambient Temperature °C	**Top Surface of Samples**			**Interlayer areas of samples**		
	Surface TC °C	Thermal Camera °C	Emissivity	Surface TC °C	Thermal Camera °C	Emissivity
24	148	148	0.347	150	150	0.358
24	220	221	0.335	218	219	0.358
24	232	233	0.337	228	233	0.350
24	245	346	0.332	239	243	0.350
24	261	261	0.328	251	257	0.350
24	276	272	0.335	275	282	0.350
24	300	300	0.336	300	304	0.360
24	305	304	0.339	296	297	0.377
24	310	311	0.340	293	294	0.386
24	315	316	0.341	291	292	0.382
24	320	320	0.342	315	318	0.370
24	322	323	0.342	322	322	0.377
24	325	326	0.342	323	325	0.377
24	327	328	0.343	321	323	0.377
24	330	330	0.343	318	321	0.377
24	337	337	0.344	354	357	0.365
24	342	342	0.343	353	356	0.383
24	349	350	0.343	352	356	0.385
24	355	355	0.342	354	356	0.384
24	365	366	0.342	358	361	0.377
24	376	377	0.342	373	376	0.377
24	382	381	0.343	381	384	0.377
24	390	390	0.343	392	393	0.377
24	395	395	0.342	393	395	0.396
24	400	401	0.342	395	397	0.396
24	406	407	0.342	402	403	0.388
24	411	411	0.335	408	410	0.400
24	418	418	0.327	422	425	0.400
24	433	434	0.318	428	432	0.400
24	439	440	0.320	447	450	0.390
24	444	444	0.322	452	456	0.390
24	449	449	0.324	450	456	0.391
24	463	464	0.321	487	491	0.390
24	464	464	0.316	490	500	0.400
24	468	468	0.313	529	530	0.379
24	479	480	0.312	522	524	0.391

When Figure 4 is examined, it is understood that both emissivity values are initially close to each other. It has been determined that Ti6Al4V material will have a thermal emissivity between 0.3-0.4 if it is produced by the DMLS method. However, while the emissivity value of the inner layers increases due to the increase in temperature, the emissivity value of the upper surface decreases as the temperature increases. When the data in the literature were examined, it was seen that the temperature-emissivity relationship differed depending on the material type and surface properties.

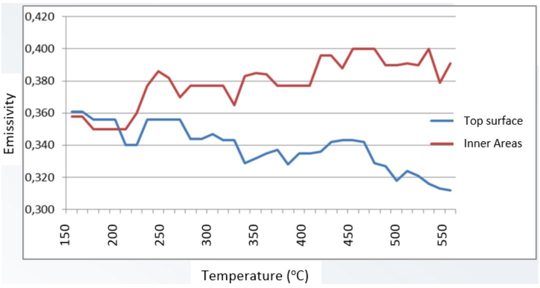

Fig 4. Graphical results of emissivity measurements.

Thermal emissivity tends to increase in some cases, it tends to decrease in some cases, a linear relationship cannot be established in some cases and it does not change in some cases [9, 10]. For this reason, it would not be correct to correlate thermal emissivity and temperature with an absolute increase or decrease. However, the data obtained from the literature and the study showed that the emissivity value tends to increase in cases where the surface is rougher, while the emissivity values tend to decrease on smoother surfaces [11]. It is known that surface properties may change depending on temperature. For these reasons, some situations that are difficult to predict may occur in terms of changes in emissivity values. Emissivity values will need to be re-determined for each material and surface feature.

As a result of the emissivity tests carried out, it can be suggested to use an average emissivity value of 0.38 for the inner layers. It can be recommended to use 0.34 emissivity value when manufacturing the layers close to the surface (the last 3 layers). If the 0.38 and 0.34 emissivity values determined as average are used, the measurement errors due to emissivity may be around a maximum of ±10 °C at temperatures of 500°C. Experiments were not continued after 550°C. Because after this temperature, oxidation has been observed on the part surface. According to the literature, the sensitivity of the data obtained after 550-600°C of oxidation in Ti6Al4V materials is not reliable [12]. After oxidation, the emissivity increased rapidly due to the increased opacity of the surface. Figure 5 shows the oxidized surface encountered after 600°C temperature.

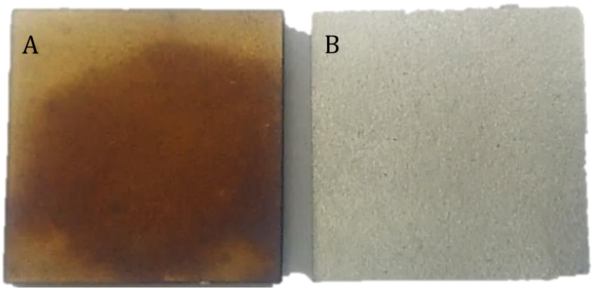

Fig 5. Oxidized surface (A), Normal part surface (B).

According to the results of the study, oxidation started earlier in samples with high surface roughness. In the visual examinations, there was a color change on the surface at lower temperatures and the surface became dull. It has been evaluated that the mounds causing surface roughness are more easily affected by external influences. Therefore, it has been interpreted as having more reactive surface properties. The importance of determining the emissivity depending on the temperatures that will affect the surface topography has been understood on the samples produced by the SLM method, in cases where temperature measurement is aimed to be made during the manufacturing process. The temperature of samples during manufacturing are varied depending on the factors such as powder geometries, material properties, manufacturing parameters, and scanning strategies. To obtain accurate temperature measurements, emissivity values of the surfaces should be defined depending on the temperature changes. Thus, temperature distribution on the parts can be investigated.

4. Conclusions

As a result of the study, the thermal emissivity of Ti6Al4V material manufactured with SLM is around 0.34 on average and varies between 0.31-0.40 depending on the temperature. In cases where instantaneous measurement is required, 0.34 emissivity definition can be made as a standard, if thermal cameras do not have a variable emissivity definition. In samples with high surface roughness, emissivity values increased due to temperature due to early oxidation. In samples with low roughness, the emissivity values decreased slightly with temperature. In order to make precise temperature measurement, camera calibration should be made by finding thermal emissivity values for each material depending on temperatures and surface properties. In subsequent studies, changes in emissivity values depending on surface roughness can be examined.

Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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