Mechanism of internal stress formation in titanium alloy samples, obtained by additive manufacturing

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Abstract. The paper presents the results of residual stress formation study in Ti-6Al-4V alloy samples, obtained by additive manufacturing. An analogy of residual stress formation mechanism observed in samples during 3D-printing and laser beam welding technology is shown. The effect of annealing on residual stress level is investigated.

1. Introduction

Analysis of residual macro stresses by the X-ray «sin²ψ» method is one of the approach to comprehensive assessment of resource and properties in titanium alloys products, obtained by additive manufacturing [1–4]. The X-Ray diffraction method allows to determine the intensity of stress $\sigma_\varphi$, which acts in the plane of the main normal stresses $\sigma_1$ and $\sigma_2$ and makes up an arbitrary $\varphi$ angle. Whereas, the plane of the main stresses action coincides with the test samples plane (figure 1). Moreover, there are methods to determine the main stresses separately.

The singularity of 3D-layers formation during SLM and DMD methods makes it possible to consider the stresses formation in samples as in local laser beam welding. And then we use the mathematics statistics method (“addition of quantities”) to estimate residual macro stresses. At the first stage we examined the features of stress formation in titanium alloys during laser beam welding.

When the laser beam hit the material surface it is partially scattered (absorbed) and reflected by the surface. The laser beam energy spent on the powder particles welding obeys the Bourguer-Lambert exponential law (1):

$$I(x) = I_0(1-R)e^{-\alpha x},$$

where $I(x)$ – intensity of laser beam radiation at depth $x$; $I_0$ – the intensity of the laser beam hit the material surface; $R$ – reflection coefficient; $\alpha$ – absorption coefficient.

The light quanta of the laser beam radiation are absorbed in the metal by valence electrons. That leads to an increase in the frequency of their thermal vibrations and crystal lattice phonons, in other words, radiation transits into heat. According to the ratio the transition (heating) rate depends strongly on the absorption coefficient (about $10^{-5}$ cm$^{-1}$ for metals). As the material temperature increases, the surface melts and the properties change in the transition areas. Moreover, that leads to the change of diffusion and phase processes and as a result to the metastable and stress-strain states formation.

It is necessary to notice several features about welding of titanium and its alloys:

- High chemical activity of titanium in liquid phase condition;
- A tendency to the grain growth during the temperature increase;
- A tendency to gases accumulation in the fusion zone and the embrittlement of heat-affected zone and the weld itself;
- The “repeatability” of the size (monodispersity) and chemical composition of the weld particles (without segregation)

Modes of particles welding (addition of layers) in the process of additive manufacturing are selected due to the following conditions: creating of the favourable structure, crystallographic texture, perverting of lea
dles and ensuring the desired product properties.

2. Macro stresses formation study of samples obtained by 3D-printing

In the present work the following mode of selective laser melting was used:

A high scanning speed of 7 m/s and spot diameter at the focus of 50 μm allows to remove heat from the local melting area efficiently, reduce the risk of metastable microstructure formation and decrease the chance of melted area saturation with a gas phase. Coincidently, the particles’ diameter size of up to 50 μm with verified chemical compositions makes it possible to uniform dispersion of the heat flux not only over the surface, but also at the depth of the grown layer, which leads to a decrease in the anisotropy of the mechanical properties. Moreover, a fiber laser of 400W and a volume build rate of 10 cm³/h provide layer-by-layer repeatability of product properties.

The macro stresses formation in product obtained by different methods of additive manufacturing is special in nature due to the special features of the surface scanning by the laser beam (figure 2). It turns into a continuous weld, in which a quenching-structure is formed. It should be noted that simultaneously with it, the “classical zones” characteristic of the weld are blurred, that is – the weld, the heat-affected zone and the base metal. The reasons for this are the temperature-time conditions of the additive manufacturing process. The energy density of the laser beam has a higher density compared to other fusion methods, and in particular, is several thousand times higher than the energy density during the arc welding. In this regard, a very intense local heating of the “weld” bath occurs, followed by the formation of a narrow and deep melting zone. The area of the melting zone is tiny, combined with a high concentration of energy in the beam, leads to the formation of a relatively narrow heat-affected zone. Due to the segregation of molten metal in the “welding pool” and thermal expansion/contraction in adjacent areas that have not melt, significant local elastic deformations arise in the weld and heat-affected zone which do not disappear after the end of the welding cycle and the removal of temperature deformations - this forms residual stresses, the value of which depends on the welding temperature and on the chemical composition of the alloys.

![Figure 1. Scheme of stresses action relative to the sample surface for «sin2φ» method: φ – angle determining the total stress orientation; ψ – angle of the surface rotation relative to the symmetric position during the asymmetric X-ray photography.](image1)

![Figure 2. One of the laser beam scanning patterns used for AM: where σx and σY – stresses in the sample plane.](image2)
Depending on the axis of the stresses action orientation relative to the longitudinal direction of the beam, longitudinal and transverse stresses are distinguished. It is known that the longitudinal and transverse stresses are tensile in the melting zone during welding but they differ in magnitude. In a first approximation, they can be correlated with the main normal stresses acting in the surface layer (depending on the dispersion of particles) in a plane-stressed state \((\sigma_X \text{ and } \sigma_Y, \text{ respectively})\). The X-ray method allows to determine both the sum of the main stresses in the surface layer \((\sigma_0=\sigma_1+\sigma_2)\) and each component individually. That was performed for the samples cut from products obtained by SLM and DMD methods before and after additional heat treatment [1, 2].

The analysis of internal stresses was carried out using the \(\langle \sin \psi \rangle \) method. The basis of this method is the fact that in all crystallites of the product, the interplanar spacings \(d\) of atomic planes change identically, consistently oriented relative to the acting elastic stresses. Moreover, a change in the interplanar spacing \(\Delta d_{HKL}\) leads to a shift of the X-ray lines by an angle \(\Delta \theta_{HKL}\) in accordance with the following relation (2):

\[
\Delta d_{HKL} = d_{HKL} \cdot \tan \theta \cdot \Delta \theta_{HKL}
\]

The change in interplanar distance \(d_{HKL}\) for a family of crystallographic planes \((HKL)\) determines deformation (3):

\[
\varepsilon_{\psi, \varphi} = \frac{1 + \nu}{E} \cdot \sigma_{\psi} \cdot \sin^2 \psi + \varepsilon_{\perp}
\]

For a thin surface layer (~50 \(\mu\)m) participating in the formation of a diffracted beam, a plane-stress state occurs, i.e. we can take \(\sigma_3 = 0\). The deformation in the normal direction to the surface \(\varepsilon_{\perp}\) is determined through the Poisson's ratio only by the main normal stresses \(\sigma_1\) and \(\sigma_2\) (4):

\[
\varepsilon_{\psi, \varphi} = \frac{1 + \nu}{E} \cdot \sigma_{\psi} \cdot \sin^2 \psi - \frac{\nu}{E} (\sigma_1 + \sigma_2).
\]

From (4) it follows that to determine the sum of the main stresses \((\sigma_1+\sigma_3)\), it is sufficient to measure the strain along the normal to the surface \(\varepsilon_{\perp}\), and to determine the stresses in a given direction it is necessary to measure \(\varepsilon_{\psi, \varphi}\) for several values of the angle \(\psi\) (see figure 1).

Based on the results of X-ray photography at different angles \(\psi\), a graphical dependence is constructed in the coordinates \(\varepsilon_{\psi, \varphi} - \sin^2 \psi\). The slope of the resulting straight line determines the magnitude of the stresses based on the relation (5):

\[
\sigma_{\psi} = \frac{E}{d_0 (1 + \nu)} \cdot \frac{d_{\psi, \varphi 2} - d_{\psi, \varphi 1}}{\sin^2 \psi_2 - \sin^2 \psi_1}
\]

where \(d_0\) – interplanar distance in a loose sample.

However, obtaining samples without stresses is always associated with evaluation difficulties about additional technological operations. Therefore, it is considered to be possible for most tasks to replace the value of \(d_0\) with the value of the interplane distance when shooting at an angle \(\theta\) to the surface of the sample \((d_\perp)\). In this case, the normal to the surface of the sample coincides with the normal to the system of reflecting planes. The error of such a replacement does not exceed 0.1%.

In this work, we determined the interplane distances for the (200), (004), and (202) \(\alpha\)-phase reflections of the Ti-6Al-4V alloy. The survey was carried out in the range of angles \(2\theta = 70^\circ \ldots 90^\circ\) with four values of the angle \(\psi\) \((0^\circ, -10^\circ, -30^\circ, -50^\circ)\).

In the calculations, the anisotropy of the elastic constants included in the calculation formula (4), which was calculated through the elementary moduli of compliance, was taken into account. For the direction of the normal to the plane, the values of Young's modulus and Poisson's ratio were 110 GPa and 0.33, respectively.

According to the results of the experiments, stress distribution diagrams were plotted along the growth direction (GD). It should be noted that the stress distribution in the sample plane \(\sigma_x\) and \(\sigma_y\) has a slight scatter (figures 3, 4) (up to 80 MPa in the x (LGP) and y (TD) directions) and on average do
not exceed 350 MPa. Moreover, their distribution is strongly dependent on the scanning mode of the laser beam (figure 2).

**Figure 3.** Design scheme for determining stresses in samples obtained by AM methods: \( \sigma_x \) and \( \sigma_y \) stresses in the plane of the sample; \( \sigma_z \) stress in the direction of growth of the sample.

**Figure 4.** Plot of stress distribution in samples obtained by selective laser melting: \( \sigma_x \) and \( \sigma_y \) stresses in the plane of the sample.

It was shown that in the initial state in the samples obtained by selective laser melting, the stresses acting along the growth direction (GD) have a tensile character and reach high values (up to 700 MPa), while in the samples obtained by the DMD method, they reach values approaching the yield strength and amounting to about 950 MPa. That explains the appearance of cracks and the leash of the product obtained by direct metal deposition.

The most common type of heat treatment for stress relieving is annealing. Therefore, the next step in the study of residual stresses was annealing. For the SLM method, vacuum annealing was used according to the heating mode of 820°C and holding for 2 hours followed by cooling with a furnace, and for the DMD method – heating to 800°C, holding for 1 hour and cooling in air.

In the first case, the residual stresses decreased by more than half and did not exceed 320 MPa, in the second case they decreased by a third and amounted to about 600 MPa (table 1). Note that the direct metal deposition method has significant drawbacks, since it is observed in the initial state: segregations of the chemical composition, gas pores and structural inhomogeneities, high residual stresses and low physical and mechanical properties, annealing did not lead to an improvement in performance.

| Treatment mode | Stresses, (HKL) MPa |
|----------------|---------------------|
|                | (200) | (004) | (202) |
| Initial state  | 633   | 767   | 378   |
| Vacuum annealing: 820°C, 2 hours, furnace cooling | 320   | 280   | 290   |

### Table 1. The distribution of residual macrostresses in SLM samples obtained by selective laser sintering in the growth direction (GD).

3. **Conclusions**
Modern technologies of additive manufacturing (SLM and DMD) make it possible to obtain complex product forms with sufficiently high physical-mechanical and operational characteristics. However, the features of production by these methods require additional technological operations in the form of thermochemical (thermal) processing, which will allow not only the structure to be regulated in a...
regulated manner, but also to change the physical and mechanical properties in a wide range. In particular, using vacuum annealing, it is possible to achieve a significant relaxation of the internal stresses generated during 3D printing.

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