THE STUDY OF THE NICKEL SUPERALLOY ZHS32 STRUCTURAL AND LOW PLASTICITY STATES AFTER DEPOSITION AND HEAT TREATMENTS

Hanna ZVIAHINTSEVA, Mykola CHERVIAKOV, Oleksandr YAROVYTSYN, Ivan VOLOSATOV

Paton Welding Institute of NAS of Ukraine, Kyiv, Ukraine, zvanna@paton.kiev.ua

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Abstract

The nickel-based superalloy ZhS32, which has a cast directional structure, is ideal for use in the aviation industry and can withstand operating temperatures of 950–1050 °C. The successful practical application of the microplasma powder welding deposition (MPWD) process using the ZhS32 Ni-based superalloy on aircraft blades has been confirmed at the E.O. Paton Electric Welding Institute. The thermal deformation parameters of crystallization in the deposition process differ greatly from the parameters of directional crystallization in the manufacture of the base metal blades; therefore, the specified structures of deposited metal are investigated, taking into account the tendency towards a low-plastic state or hot cracking in certain manufacturing parameters. This study examined the structural states of the ZhS32 alloy after deposition ('as-built') and after follow heat treatments that are usually applied to directionally crystalized ZhS32. A set of short-term strength mechanical tests was performed on the same samples. These consisted of critical fracture strain (ε_{cr}) and tensile strength as a function of temperature, as determined by the original method using longitudinal static tensile testing within a temperature range of 20–1100 °C. These dependencies were investigated using discrete simulations to determine the tensile strength of the deposited metal in response to the welding thermal deformation cycle.

Keywords: Nickel-based superalloy, mechanical properties, deposited metal, microstructure, heat treatment

1. INTRODUCTION

ZhS32, a nickel-based superalloy, is one of the traditional alloys used for producing aircraft gas turbine engine blades. It is a cast alloy with directional crystallization and intermetallic and carbide strengthening. The alloy can operate at temperature up to 1100-1150 ºC. Its dendritic structure consists of a γ - solid solution that is strengthened by the γ′- phase, MeC-type carbides, and a non-equilibrium eutectic (γ+γ′) structural component. The superalloy is then subjected to homogenization, aging, and various technological annealing as a part of the serial repair of working blades of modern aircraft gas turbine engines. As a result, the strength characteristics become more stable due to optimal structural parameters.

Attempts are being made to use additive manufacturing and repair technologies due to the high cost of manufacturing parts and the specific nature of damage incurred during operation [1-6]. Until recently, various types of additive manufacturing were mainly applied to weldable alloys, including directed-energy deposition (DED) [1], selective electron beam melting (SEBM) [2], selective laser melting (SLM) [3], and their combinations [4]. The industrial application of the arc process of multilayer microplasma powder deposition (MWPD) is also well-known, particularly in the context of additive technologies [6].

ZhS32 alloys belong to a class of nickel-based superalloys that are limited weldable. They tend to form several types of cracks and metallurgical defects [7,8], and have limited deformation capacity. The thermal deformation mode of crystallization in deposition processes differs greatly from the directional crystallization process of the base metal in vacuum induction melting. It is necessary to investigate the differences in structure and the tendency towards hot cracking or the formation of a low-plastic state with critical stresses. Understanding the processes of structure and crack formation in additive manufacturing should provide a basis for future research into these classes of materials.

This study aims to investigate the structure formation process and phase composition of multi-pass deposited metal of the ZhS32 nickel superalloy, obtained by the MWPD process. The study will assess the short-term strength and plasticity (ductility) of the metal, depending on the influence of different heat treatment modes. The microstructures and short-term mechanical properties of the base metal (BM) and deposited metal (DM) will be compared to understand the conditions and causes of hot cracking in ZhS32 alloy welded joints.

2. EXPERIMENTAL SETUP

Vertical wall type welding deposition sample (70-75x30-35 mm), obtained by multilayer MPWD with interpass cooling to room temperature and mechanical processing after every layer's deposition. Spherical-shaped ZhS32 superalloy powder with a 63–160 µm particle size was used as the additive material. Spectral analysis data **(Table 1)** showed that the chemical composition of the 'vertical wall' samples corresponded to that of the cast ZhS32 metal with directional crystallization. The general scheme of the MPWD process is shown in Figure 1. After deposition, the side surfaces of the 'vertical wall'-type (DM) ZhS32 samples were ground down to a thickness of 2.5–3.5 mm. After grinding, the side surfaces were subjected to a first liquid penetrant test (LPT), confirming the absence of any defects. Since preserving short-term strength characteristics is a key approach to selecting materials for manufacturing and repairing parts and structural assemblies, evaluating the mechanical properties and deformability of the metal is essential. Tensile tests were conducted on an MTS-810 machine at temperatures ranging from 20 to 1100 °C. These tests evaluated short-term strength parameters, including ultimate tensile strength (UTS) and tensile strength Rm, as defined in [9], as well as critical fracture strain (εcr) and percentage total extension at fracture, also as defined in [9].

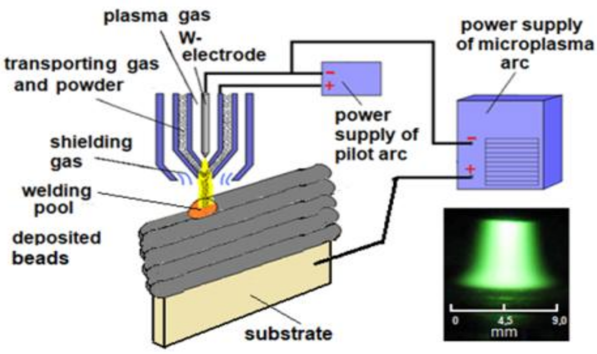


Figure 1 Scheme of multi-layer MPWD process

Table 1 Chemical composition of ZhS32 nickel-based superalloy (in wt%)

Alloy	C	Cr	Ti	Al	Ni	Mo	W	Co	Re	Ta	Nb	V	Fe
directional crystallized ZhS32-VI (BM)	0.12-0.18	4.3-5.6	---	5.6-6.3	Bal.	0.8-1.4	7.8-9.5	8.0-10.0	3.5-4.5	3.5-4.5	1.4-1.8	≤0.15	≤0.5
MPWD metal (DM)	0.12	5.0	---	6.2	Bal.	2.0	9.2	10.2	3.5	3.5	2.0	---	---

Miniature samples for mechanical and deformation capacity tests, as well as microsections for metallographic analysis, were produced from plates obtained directly after MPWD 'as-built' using electric discharge cutting. Some of the manufactured samples were subjected to heat treatment (HT) to obtain more stable and increased strength characteristics. The HT modes were selected based on those typically employed for cast ZhS32 metal with directional crystallization [10]. HT procedures improve the dispersion of the γ′ phase, reduce the amount of γ/γ′ eutectic and reduce element segregation. Carbide precipitates are also redistributed during HT, redepositing in the grain body and boundaries.

HT was carried out at 1280 °C for 1.5 hours to stabilize the structural state and increase strength at both room temperature and 1000 °C. For cast alloys with directional crystallization, homogenization is usually followed by two-stage ageing. To study the technological heritability of the DM samples after homogenization (1280 °C for 1.5 hours), one-stage (1280 °C for 1.5 hours + 1050 °C for 5 hours) and two-stage (1280 °C for 1.5 hours + 1050 °C for 5 hours + 870 °C for 20 hours) ageing was performed. The first high-temperature ageing process is usually close to the operating temperatures of the ZhS32 alloy. Consequently, the redistribution of γ-phase particles becomes bimodal. During the second stage of ageing, the ultra-dispersed γ′-phase particles dissolve and the undissolved particles are cuboidal with an optimal size of 0.3–0.4 µm. The 1050 °C for 2.5 h aging mode was chosen as an option for the industrial heat treatment of HPT working blades made of ZhS32 superalloy [11] for the D18-T aircraft GTE, restored by the MPWD process.

The BM samples were heat treated in three stages: homogenization at 1280 °C for 1.5 hours, followed by two-stage ageing at 1050 °C for 5 hours and then at 870 °C for 20 hours. The heat treatment (HT) was performed in a SShVE-1.2.5/25I2 vacuum furnace, with temperature and vacuum parameters monitored throughout. Metallographic analysis was performed using a Tescan Mira 3 LMU scanning electron microscope (SEM). Image analysis and measurement of structural object sizes were performed using SEM visualization in combination with the SEOImageLab metallographic image processing program. Four SEM images, taken at magnifications of 5.06 kx (field of view: 150 µm), 12.6 kx (field of view: 15 µm) and 37.9 kx (field of view: 5 µm), were used for each heat treatment mode. The total length of the analysed grain boundaries was 600 µm for each heat treatment mode. The length of the edge of a cubic particle was taken as the size of the γ′-phase particles. If the particle was elongated at the grain boundary, the average length between the long and short sides was chosen. The optimal particle size is 0.4 µm [10]. The number of particles falling into the field of view was measured.

3. EXPERIMENTAL AND RESULTS

In contrast to the directional crystallization of the BM (**Figure 2**), the microstructure of DM is polycrystalline. There are significant differences in the size of the dendrite cells and interdendritic distances. After undergoing complete HT (1280°C for 1.5 hours, then 1050°C for 5 hours, then 870°C for 20 hours), the base metal's structure is dendritic-cellular, with cell diameters of 30-40 x 80-100 µm and no grains. The carbides are in a font shape. Particles of the cubic γ′ phase are evenly distributed with a size of 0.2–0.4 µm **(Figure 3f)**. After deposition ('as-built'), the DM structure is polycrystalline. The grains are elongated (200...300 x 800x1000 µm). A dendritic-cellular microstructure is present inside the grains, with cell diameters of 20–30 × 20–50 µm. The carbides are either elongated and needle-shaped (0.1 × 1–5 µm) or round with a diameter of 0.1–3 µm. Particles of the γ-phase in a cubic shape measuring approximately 0.2 µm are present in the grain body. The γ′ phase size is up to 2 µm along the boundaries in eutectic form **(Figures 3a** and **4** in the “as built” state).

HT does not change the grain sizes, but it modifies their boundaries. After homogenization at 1280 °C for 1.5 hours, the grain boundaries are thin and free of eutectics, and the γ′-phase particles are cuboid and up to 0.7 µm in size. Cells in the grain body practically disappear after homogenization. The particles of the γ′-phase inside the grain bodies are cubic in shape and range in size from 0.05 to 0.5 µm (**Figure 3b** and **Figure 4** – “HT 1280 °C 1.5 h”). After further ageing at 1280 °C for 1.5 hours, the particles of the γ′-phase are uniform in the grain body and cubic in shape, measuring 0.3–0.5 µm. + 1050 °C for 5 hours, the particles of the γ′-phase are uniform in the grain body and are cubic in shape, measuring 0.3–0.5 µm. **(Figure 3d** and **Figure 4**, “HT 1280 °C 1.5 h + 1050 °C 5 h”). Full heat treatment finally perfects the size and location of the γ′-phase **(Figure 3e** and **Figure 4**, "HT 1280 °C 1.5 h + 1050 °C 5 h + 870 °C 20 h”). Annealing at 1050 °C for 2.5 hours, one of the industrial heat treatment modes for restored ZhS32 impeller blades, does not completely remove the cellular structure. However, it makes the dispersion in particle size of the γ′-phase less noticeable, with an average size close to the optimal 0.4 µm **(Figure 3c)**. **Figure 4** shows the evolution of the γ′ phase along the boundaries and in the grain body. The carbides that separated after deposition and homogenization HT have a combined composition and undergo slight growth and conglomeration of up to two or more particles after HT.

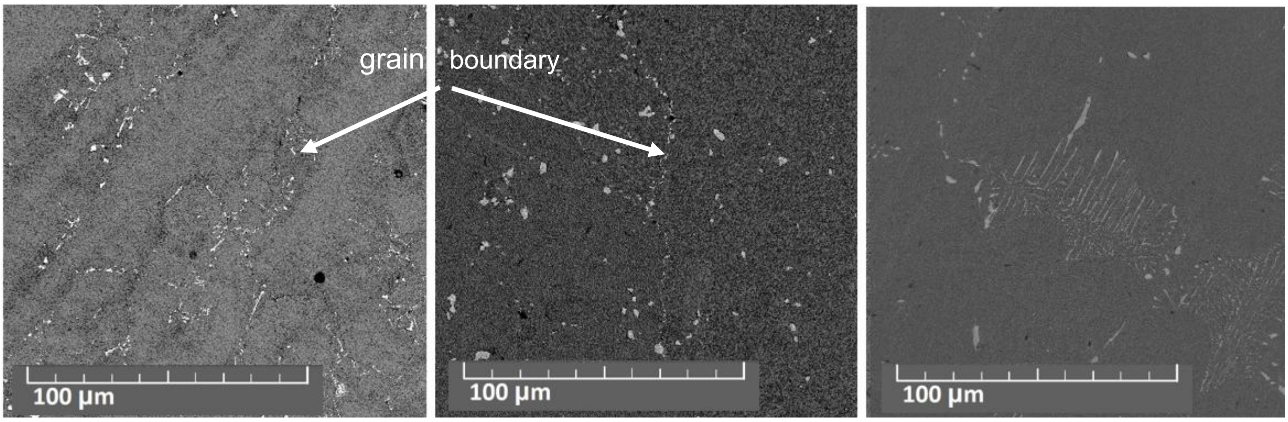


Figure 2 Structure of the polycrystalline DM (a, b) and directional crystallized BM (c) ZhS32: a - DM without HT, b - DM with HT 1280 °C-1.5 h + 1050 °C-5 h + 870 °C-20 h; c - BM with HT 1280 °C-1.5 h + 1050 °C-5 h + 870 °C-20 h, Scanning microscope, BSE - phase contrast, back scattering electrons

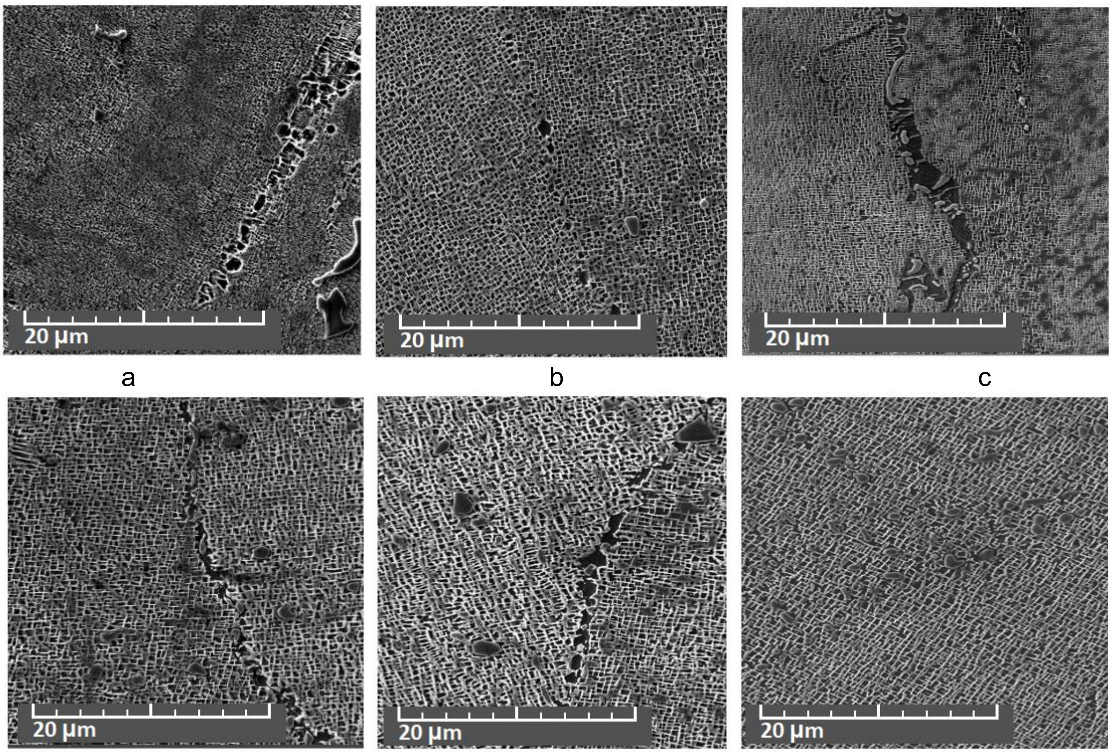
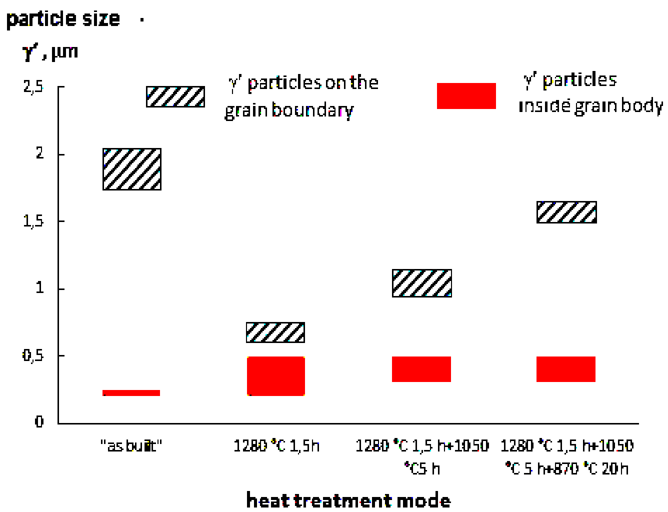


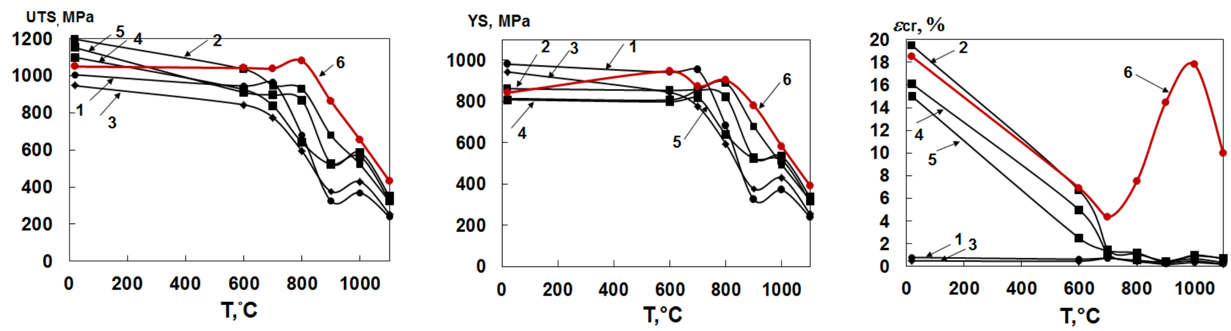
Figure 3 Microstructure of DM “as built” (a), deposited metal with HT at 1280 °C-1.5 h (b); DM with HT at 1050 °C-5 h (c); DM with HT at 1280 °C-1.5 h + 1050 °C-5 h (d); DM with HT at 1280 °C-1.5 h + 1050 °C-5 h + 870 °C-20 h (e) and BM with HT at 1280 °C-1.5 h + 1050 °C-5 h + 870 °C-20 h (f) ZhS32. Scanning microscope, SE - morphological contrast, secondary electrons



*particle size refers to the length of the edge of a cubic γ′ particle

Figure 4 The effect of HT on the γ′-phase particle size in DM ZhS32

The process of determining the short-term mechanical properties revealed that the DM in the 'as built' structural state at = 800 °C exhibits a 30-60% decrease in UTS compared to cast metal with BM. This decrease in UTS, as well as the low values of ε_{cr} ≤1% across all temperature ranges **(Figure 5a**, curve 1), may /be attributed to the non-optimal size of the γ′-phase particles within the grain body, as well as the γ′ phase eutectics at the grain boundaries **(Figures 3a** and **4,** "as built"). Following HT in the ageing mode (1050 °C for 2.5 hours) on the DM ZhS32, the situation remains largely unchanged, with only a slight increase in the UTS value observed at 1000 °C. **(Figure 5a**, curve 3). Homogenisation at 1280 °C for 1.5 hours increases the UTS value of the DM ZhS32, which is close to the corresponding values of the homogenised cast BM ZhS32 with directional crystallisation at T = 600-900 °C **(Figure 5a**, curve 2). The HT of the DM ZhS32, according to the homogenisation modes of 1280 °C for 1.5 hours and then ageing at 1050 °C for 5 hours, or 1280 °C for 1.5 hours and then two-stage ageing at 1050 °C for 5 hours and then 870 °C for 20 hours, only slightly increases the UTS and YS strength values compared to the homogenisation mode of 1280 °C for 1.5 hours **(Figure 5a** and **5b**, curves 4 and 5). According to the ductility characteristics, the mechanical tests **(Figure 5c)** showed that the DM 'as-built' has the lowest εcr of 0.4–1.0% across the entire temperature range of 20–1100 °C. A significant decrease in ductility was observed for both the BM ZhS32-VI superalloy with a directed crystalized structure and the DM ZhS32 after homogenisation and ageing HT, with values decreasing from ε_{cr} ≈ 20% at 20 °C to ε_{cr} = 4.35% at 700 °C for the BM structure and from εcr = 15-18.5% at 20 °C to ε_{cr} = 1.1-1.4% at 700 °C for the DM. However, at T > 700 °C, a difference in the dependence of ε_{cr} on temperature is observed for the BM ZhS32-VI and the DM ZhS32. For the BM ZhS32-VI after full HT, there is an increase in high-temperature ductility, with the value of ε_{cr} increasing to 7.5–17.8%. For the DM, however, high-temperature ductility decreases after HT in the homogenisation and ageing modes, with ε_{cr} = 0.4-1.0%.



a b c

Figure 5 Short-term mechanical properties of ZhS32 superalloy: 1 – DM, "as built"; 2 – DM, after homogenization HT 1280 °C-1.5 h; 3 – DM, after aging HT 1050 °C-5 h; 4 – DM after HT homogenization 1280 °C-1.5 h + aging 1050 °C-5 h; 5 – DM, after HT homogenization 1280 °C-1.5 h + aging 1050 °C-5 h + aging 870 °C-20 h; 6 – BM after HT homogenization 1280 °C-1.5 h + aging 1050 °C-5 h + aging 870 °C-20 h. Notes: UTS – ultimate tensile strength; YS – yield strength; ε_{cr} – the critical fracture strain

The significant reduction in ε_{cr} at temperatures above 700°C is attributed to the presence of a multi-level disclination-dislocation substructure within the deposited metal. As the temperature increases, defects in such a structure activate diffusion processes that weaken the strength of the grain boundaries. Fracture during testing of the DM, for both samples immediately after deposition and samples after all HT modes, occurs along the grain boundaries.

4. CONCLUSION

Microstructural analysis combined with experimental data on the short-term mechanical properties showed that the standard HT treatment of the cast nickel superalloy ZhS32-VI (1280 °C for 1.5 hours, followed by 1050 °C for 5 hours and then 870 °C for 20 hours) was ineffective in improving the corresponding properties of the deposited metal ZhS32. The properties of the homogenized deposited metal ZhS32 after the first and second ageing processes are characterized by reduced ultimate strength (UTS), yield strength (YS) and critical fracture strain (ε_{cr}) values in the temperature range of 20-900 °C compared to the homogenized deposited metal ZhS32 alone. However, the critical fracture strain (ε_{cr}) values are saved at T≥700 °C.

The experimental data showed that the deposited metal ZhS32 has the highest level of heat resistance and deformability after HT in the homogenization mode (1280 °C for 1.5 hours). Subsequent two-stage ageing (1050 °C for 5 hours, followed by 870 °C for 20 hours) only slightly increased the ultimate strength (UTS), the yield strength limit (YS) and the critical fracture strain (ε_{cr}) at temperatures of 1000 and 1100 °C.

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