Hybrid additive technologies in the production of equipment for the food industry

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Abstract. The article explores the application of hybrid additive technology using WAAM synthesis in combination with wave strain hardening and machining for the production of food processing equipment. Despite the widespread use of additive technologies in the aerospace and automotive industries, their potential in the food industry remains underestimated due to high demands on surface quality, corrosion resistance, and compliance with Hygienic Design standards. The proposed combined approach makes it possible to eliminate key disadvantages of WAAM synthesis, such as surface roughness, porosity, and structural heterogeneity. Experimental studies conducted on 309LSi stainless steel demonstrate the formation of a finely dispersed microstructure with an increase in hardness of up to 70%. The technology ensures the creation of monolithic products with improved mechanical properties and compliance with strict hygienic requirements. The results of the work open up opportunities for the production of complex parts of food processing equipment: augers, reactor housings, agitator blades, nozzles with internal channels and non-standard elements. The proposed method is a cost-effective solution for small-scale production and repair of equipment using standard materials certified for the food industry.

1 Introduction

Currently, additive technologies (AT) are widely used in such high-tech industries as the aerospace and automotive industries, as well as the energy sector [1-6]. However, their potential remains insufficiently realized in the field of production of food processing equipment, and to date, only approaches to its application have been identified in the AT industry [7, 8]. The use of WAAM synthesis (Wire Arc Additive Manufacturing) for the production of food processing equipment is a promising area that combines the advantages of 3D printing of large metal objects with the stringent requirements of the food industry. WAAM synthesis is ideally suited for creating large-scale, often piece-by-piece or small-scale equipment where traditional manufacturing methods are economically impractical [9, 10].

The use of WAAM synthesis in the creation of equipment for the food industry has a number of advantages. WAAM installations (often based on industrial robots) allow you to

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print products several meters in size, which is important enough to create large-sized parts such as reactor vessels, tanks, bunkers, etc. WAAM technology allows you to create a part directly from a digital model, minimizing pre-production costs, as well as easily making changes to the digital model. The rate of metal deposition is significantly higher than that of laser or electron beam systems, which speeds up the process of product synthesis. It is possible to create parts with complex internal geometry (for example, integrated cooling/heating channels). The method is also ideal for restoring and repairing worn-out parts of equipment (for example, augers, agitator blades, etc.). Standard welding wires certified for the food industry can be used: stainless steels [11, 12], as well as nickel alloys resistant to corrosion and aggressive environments.

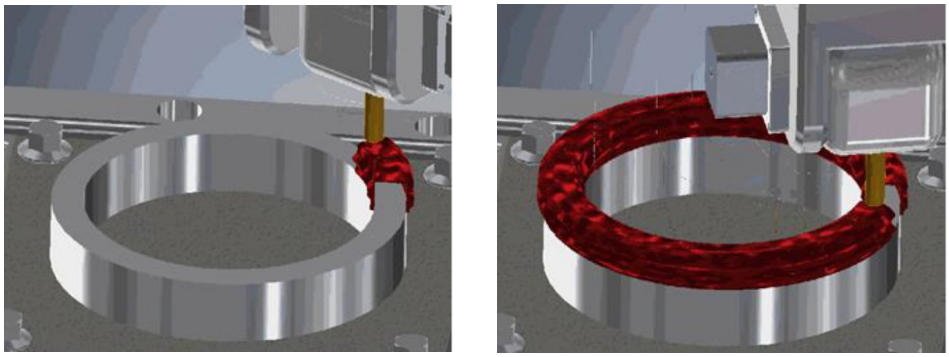
When using WAAM synthesis for food processing equipment, it is necessary to take into account the specific features associated with its operation. Any equipment that comes into contact with food must comply with strict standards. The material must have high corrosion resistance, withstanding the effects of water, salts, acids, alkalis, detergents and disinfectants. When manufacturing products for the food industry, it is necessary to follow the principles of Hygienic Design, i.e. products should have a smooth surface, no pores, cracks, micro traps where product particles can get stuck and bacteria multiply, all internal corners should have a radius of curvature and allow effective cleaning and disinfection [13-15]. In addition, the design of the products must be resistant to loads, wear, and vibrations.

These requirements significantly hindered the use of WAAM synthesis for production for food equipment, since its main disadvantages are surface roughness, the presence of pores and the structural heterogeneity of the resulting material. To solve these problems, it is proposed to use a hybrid technology including surfacing, periodic hardening treatment by surface plastic deformation (SPD) and mechanical cutting treatment – subtractive processing (SP).

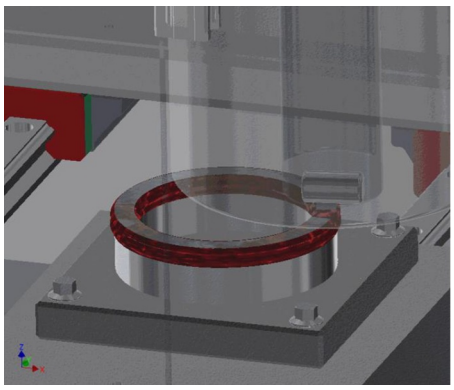
2 Materials and methods

To harden the PPD of deposited materials, it is quite effective to use wave deformation hardening (WDH), in which controlled shock pulses are applied to the hardened surface. The shape of the shock pulses determines the transmitted impact energy and is regulated by the geometry of the shock system, consisting of a striker and a waveguide. During hardening, the firing pin strikes the waveguide with the tool statically pressed to the surface of the part, as a result of which flat acoustic waves arise in the shock system, which form shock pulses of the required shape in the contact spot of the tool and the surface of the part. For each reinforced material and its hardening conditions, the shape of the shock pulses is selected, maximizing the transmission of impact energy, thereby increasing the efficiency of the process.

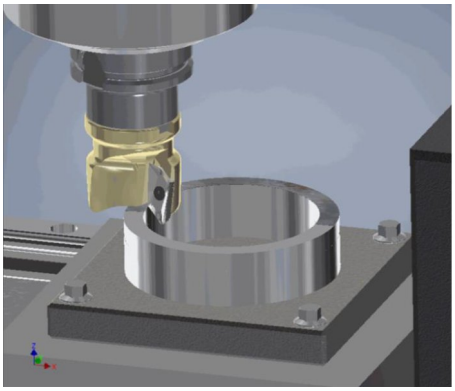
The technological process of synthesis of WAAM+WDH+SP is carried out as follows. At the first stage, the initial layer of the material is deposited on a specialized substrate (Figure 1a), the chemical composition of which is close to that of the deposited material. At the second stage, the hardening of the non–cooled deposited layer is carried out using a deforming roller tool, which is pressed with a given static force and performs rolling movements. At the same time, the shock effects of the striker are transmitted through the waveguide to the roller (Figure 1b). The cycle of surfacing and subsequent hardening is repeated for each new layer. If it is necessary to correct the geometric parameters of the part, mechanical processing is applied at the final stage (Figure 1c-f).



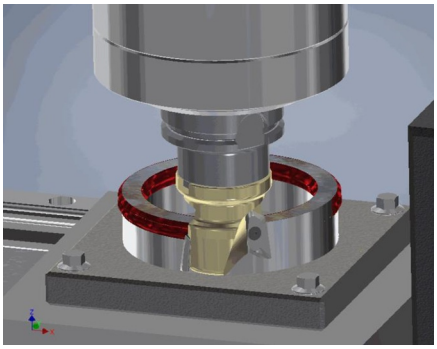
(a) WAAM synthesis



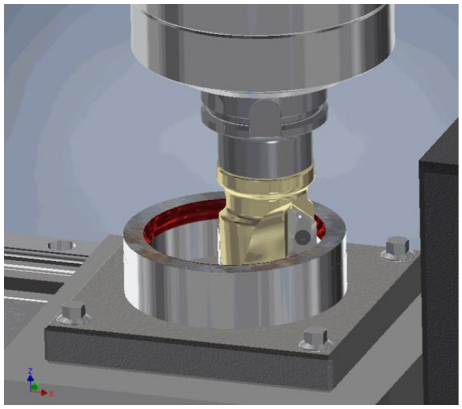
(b) WDH of the deposited layer



(c) SP of the end of the product



(d) SP of the outer surface of the product



(f) SP of the inner surface of the product

Fig. 1. Stages of synthesis using the WAAM+WDH+SP hybrid technology.

When implementing the proposed hybrid technology, the molten material is initially applied to the surface of the substrate. The main heat exchange occurs between the hot deposited layer and the cooler substrate, which initiates active crystallization in the material. The formed dendritic structure, which retains an elevated temperature, is subjected to WDH treatment.

The impact of shock waves leads to the crushing of large dendrites and the creation of a riveting effect in the surface layer. The increased plasticity of the heated metal helps to seal

the microstructure, close the pores and reduce internal defects in the coating. The subsequent thermal effect of applying a new layer causes partial softening of the previously hardened layer, however, the subsequent WDH of the new layer ensures not only its hardening, but also the re-hardening of the lower layers due to the action of controlled shock pulses.

When hardening the main layers applied to preheated and hardened layers, the crystallization and hardening processes occur almost simultaneously. This makes it possible to achieve the effect of surface riveting while simultaneously grinding the formed dendritic structures.

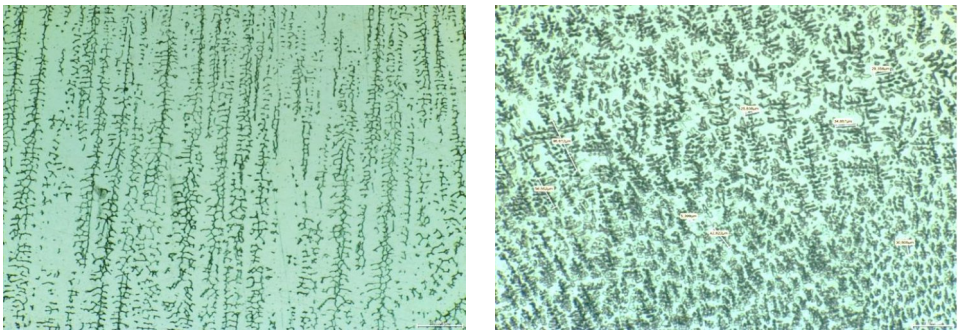
Comparative studies of the WAAM synthesis process were performed: in one case without the stages of WDH and mechanical processing, in the other – with their application. A 309LSi stainless steel wire was used for the research. Such steel is widely used in the manufacture of technological equipment for the food and chemical industries (Table 1). The obtained samples were used to manufacture grinders in order to study the microstructure and measure Vickers hardness in cross section.

Table 1. Chemical composition of 309LSi wire.

C	Si	Mn	P	S	Cr	Ni	Cu	Mo
<0.03	0.65-1.0	1.0-2.5	<0.03	<0.03	23.0-25.0	12.0-14.0	<0.75	<0.75

3 Results and discussion

The study of the microstructure of the obtained samples showed the absence of pores and the solidity of the samples obtained using WAAM+WDH+SP technology. As can be seen from Figure 2, the redistribution of microstructure components into a more cellular form is clearly expressed in the hardened sample. Unlike non-hardened samples with a transcrystalline coarse dendritic structure, the samples obtained with WDH in all layers have a finely dispersed microstructure of fragmented dendrites, with more than 8-10 times smaller characteristic size of phase particles.



(a) (b)

Fig 2. Microstructure of 309LSi steel samples obtained using the following technology: WAAM without hardening (a) and WAAM+WDH+SP (b).

The redistribution of microstructure components affects the microhardness (Figure 3). The average microhardness of the non-hardened sample is 174 HV. It was found that the degree of hardening ($\Delta HV=((HV-HV_0)/HV_0\times100\%)$, where HV is the hardness of the sample synthesized using WAAM+WDH+SP technology, HV0 is the hardness of the sample synthesized using WAAM technology) varies with the depth of the hardened

surface layer of the synthesized sample. The maximum degree of hardening is 65-71% and extends to a depth of 4 mm.

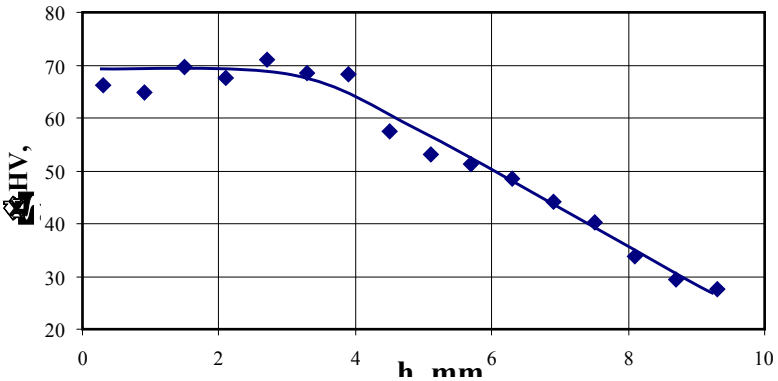


Fig 3. Change in the degree of hardening in depth of a sample of 309LSi steel synthesized using WAAM+WDH+SP technology.

4 Conclusions

A hybrid technology combining additive synthesis, wave strain hardening and mechanical processing (WAAM+WDH+SP) for the production of food processing equipment has been proposed and experimentally substantiated. This technology effectively eliminates the key disadvantages of WAAM synthesis: surface roughness, porosity, and structural heterogeneity, which is necessary to meet Hygienic Design standards. In addition, the proposed technology increases the hardness of the synthesized 309LSi stainless steel material by up to 70%, which can increase the wear resistance and durability of food processing equipment.

The obtained research results make it possible for the first time to apply WAAM synthesis for the manufacture of food equipment:

- complex parts with a screw surface that are expensive to manufacture using classical methods, for example, screws and working bodies of extruders;
- large-sized parts of complex shape with integrated heating/cooling jackets, such as reactor housings and covers, mixers;
- blades of large length and complex geometry, such as agitator blades;
- nozzles and spray heads with internal channels of complex shape for spraying liquids or drying;
- non-standard adapters, tees, and contours that are not mass-produced.

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