Porosity reduction in metal with hybrid wire and arc additive manufacturing technology (WAAM)

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Among different additive manufacturing (AM) methods, wire and arc additive manufacturing (WAAM) is the most suitable for manufacture of large-size metal components due to high deposition rates, which are rather higher than that for a powder laser and electron beam technology. AM processes are connected with high residual stresses and deformations due to excessive heat supply and high deposition rate. Influence of the process conditions, such as supplied energy, wire feed rate, welding speed, features and sequence of deposition etc., on thermal prehistory and resulting residual stresses in machine components (which were processed via additive-modular treatment), requires additional understanding. Additionally, low accuracy and surface cleanness during the process restricts use of AM technology with wire addition. This paper describes a hybrid (additive + subtractive) manufacturing approach for a steel component based on wire and arc additive manufacturing. The hybrid wire and arc additive manufacturing (WAAM) is used to describe a sequence of manufacturing steps. The main idea of the suggested approach is minimization of porosity in WAAM production process of machine components; as a result, quality of deposed metal layer improves. A steel wall was produced by hybrid (additive + subtractive) manufacturing. The non-destructive testing methods (penetrant inspection, ultrasound inspection, and X-ray inspection) were used to confirm high quality of metals.

Key words: hybrid manufacturing, wire and arc additive manufacturing (WAAM), grinding, defects, ultrasound, X-ray.
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Introduction

In industries, wire and arc additive manufacturing (WAAM) has been widely used due to the high surfacing rate and low cost of equipment used in the manufacture of large machine components and mechanisms [1–8]. In [6], a number of welding methods such as gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) have been described; five disadvantages of WAAM have been revealed, and features of the wire feeding process affecting the quality of metals and accuracy of finished products have been examined. All welding and surfacing defects have been classified following the national and international standards. It has been established that porosity, no fusion appearances between rollers, cracks such as delamination are common welding and deposition defects that need to be reduced by WAAM treatment. Recognizing this problem, most researchers have focused on mastering of WAAM parameters and use of additional equipment for monitoring. In [1], a relationship between motion speed, arc power and surfacing rate in GMAW, CMT and GTAW processes and its influence on forming has been studied. In [9], a system with passive video sensors designed to ensure the WAAM stability and control the distance from the nozzle to the upper surface of the metal has been described. In [10], the authors have described a new local protection system for the surfacing zone, which creates a laminar flow of protective gas. Hybrid additive manufacturing has been defined as a cyclical chain of processes (surfacing + machining). In [11], WAAM and milling have been described as auxiliary techniques allowing to use advantages of both processes. According to [12], hybrid systems (AM) are created by upgrading three-axis platforms in a CNC machining center by adding a surfacing head. The additive method interchanges with the subtractive one after every few layers to provide hybrid production. The iterative hybrid method [13] involves operations such as addition and subtraction performed in several stages rather than sequentially. In [14], a hot-forging-based WAAM technology has been described as the new hybrid technology. The material is locally forged immediately after deposition, and in-situ viscous-plastic deformation occurs at high temperatures.

The large additive subtraction integrated modular machine (LASIMM) has been developed as part of the European LASIMM project [15]. High quality can be ensured by non-destructive testing and layer-by-layer machining which makes it possible to eliminate defects. However, an integration of a welding head with a CNC machine creates numerous technical problems [12] and increases the equipment and operating costs. At the same time, according to the principle of alignment [14], instead of forging a hybrid technology (grinding and WAAM) can be used.

Taking into account the requirements to AM, especially WAAM, which is no longer a simple laboratorial prototyping technology, it is necessary to pay the main attention to its transformation in well-operating and profitable production. Such transformation is connected with necessity to solve several problems concerning accuracy and efficiency of manufactured components. Thereby the problems of quality, dimension accuracy and surface cleanness in WAAM should be emphasized.

The aim of this work is to examine quality of forming of surfacing metal from the point of view of macro-roughness, pores formation, non-fusion during WAAM process of hybrid additive growing with use of conventional control methods.

Materials and methods

This hybrid WAAM technology (**Fig. 1**) can occur during WAAM forming or processed after WAAM forming, what allows to eliminate surface oxidation, surface defects and pores in the surface layer of the deposited metal and to improve forming conditions during the subsequent roller application. The equipment set for WAAM process included KUKA KR210 R2700 extra manipulating robot with energy source, as well as wire falling mechanism and gas balloons [16, 17].

For wire melting during WAAM process, the Lorch SpeedPulse S3 mobil XT welding machine was used as an energy source. CO_2 shielding gas was used for wire gas protection. The OK Autrod 12.51 (ESAB) welding wire (0.8 mm in diameter) was used. This universal coppered wire was intended for semi-automatic welding of structures made from non-alloy and low-alloy steels with yield strength up to 420 MPa; it is an analogue to Sv-08G2S wire and is used in shipbuilding, welding of metal structures, machine-building and other industries. To grind the weld bead surface, the abrasive BOSCH wheel with 125 mm diameter and 120 grain size was used.

At the first stage, optimal parameters of welding voltage U, welding current I and welding speed v_s on the deposition of individual weld beads were determined, with no visual surface defects (pores) [17, 18]. Autodesk Fusion 36 was used to create 3D models. Ultimaker Cura slicing software was used to separate the model to layers and to set printing parameters. RoboDK was then used to simulate the printing process and programming the KUKA industrial robot. To study the metal produced via the standard method and hybrid WAAM method, two samples (150 × 17 × 35 mm) with 8 layers were fabricated. To control the deposited sample, its top and sides were subjected to milling. The deposited sample was then subjected to non-destructive testing by the following

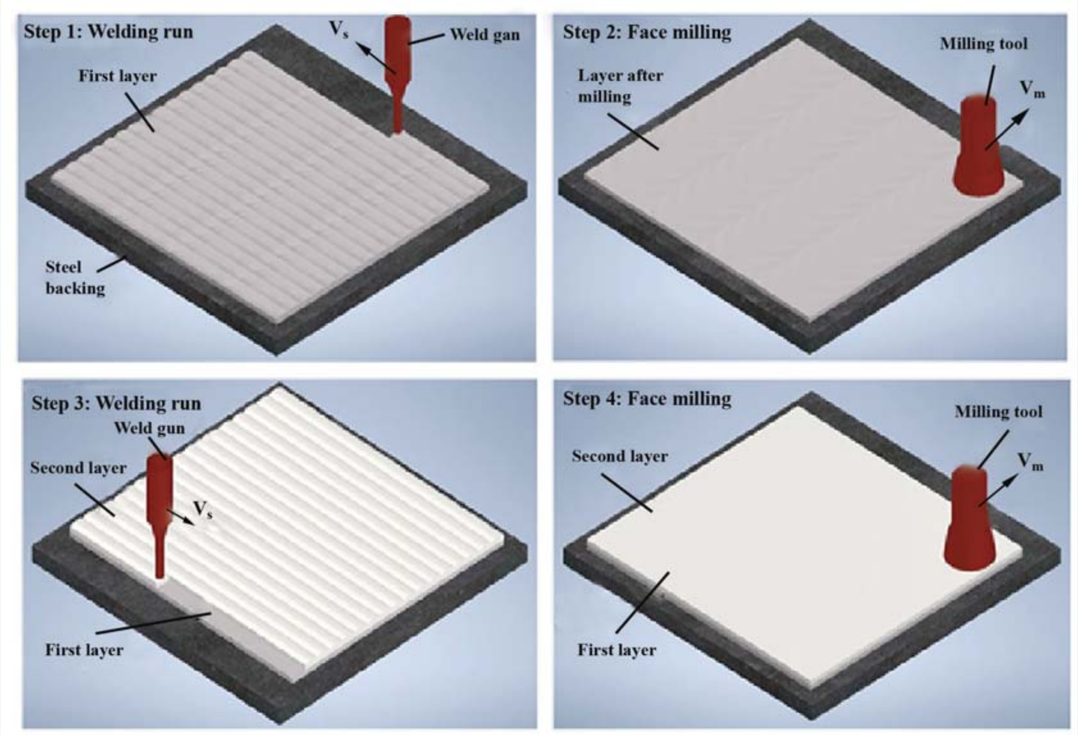

Fig. 1. WAAM combined with layer-by-layer grinding

techniques: visual inspection, magnetic particle inspection, surface inspection by penetrating substances (the NORD-TEST penetrant system) as well as ultrasonic and X-ray inspection. Arina 2 device and digital radiographic software complex "BeRKUT" were also used. The A1214 EXPERT ultrasonic flaw detector was used to assess the metal quality. In the tensile testing, the Instron 3369 electromechanical testing machine with a permissible load of 50 kN (5000 kgf) was used. The tests were conducted in compliance with GOST 1497-84 "Metals. Tensile test methods" (Russia).

Results and Discussion

After the samples with size 150 × 17 × 35 mm (8 layers) were fabricated via the standard and hybrid WAAM methods, the metal quality was assessed using non-destructive testing. With standard WAAM technology, it was not possible to control the pore formation process during weld bead application, because visual inspection was performed only after the process is finished. With hybrid WAAM technology accompanied by layer-by-layer grinding, the surface of each subsequent weld bead was smooth, and their width was uniform. After machining, steel walls, which were fabricated via standard and hybrid WAAM technologies, were visually inspected using a 5X Magnifier. With hybrid WAAM technology, metal quality was high, while with standard one, single defective surface defects (discontinuities) were observed. Ultrasonic testing showed that with hybrid WAAM technology, only the bottom signal was visible on the flaw detector screen (**Fig. 2, *a***). The sample, which was fabricated via standard WAAM technology, had defects detected by the ultrasound method (**Fig. 2, *b***). When the defects were detected, the bottom signal amplitude decreased and one more signal located to the left of the bottom signal became visible on the flaw detector screen (see Fig. 2, *b*).

Defects 1–5 (discontinuities) were revealed at the depth 10.1 mm, 8.2 mm, 9.6 mm, 8.4 mm and 17.1 mm respectively; an excess amplitude was 3.2 dB, 3.5 dB, 2.7 dB, 5.4 dB and 7.5 dB respectively, in comparison with the rejecting sensitive level. To check the ultrasonic testing results, a mechanical cut was made in the controlled sample in the area of the defect 5. A visual inspection detected an area of pore accumulation (see Fig. 2, *b*). Then visual and penetrating inspections were also performed (**Fig. 3**). The penetrating control showed pores not only in the deposited metal with standard WAAM, but also at the initial layer formation stage at substrate.

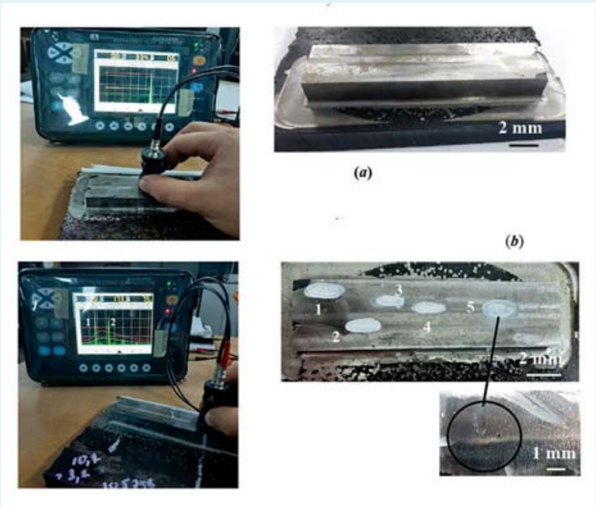

Fig. 2. Ultrasonic inspection with hybrid (*a*) and standard (*b*) types of WAAM

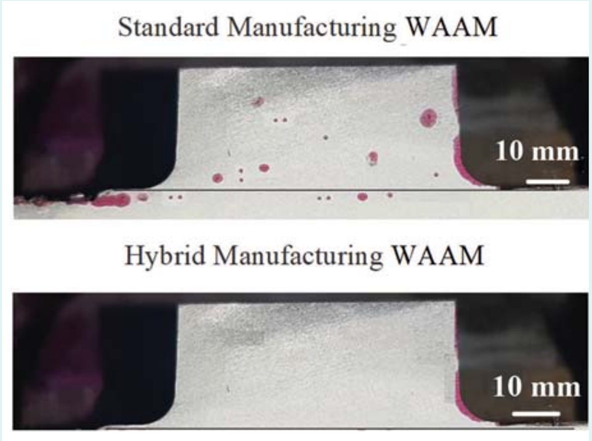

Fig. 3. Comparison of metal quality using the penetrant inspection method with standard and hybrid types of WAAM

To determine the static tension mechanical properties according to the GOST 1497-84, three flat samples of the type 1 were cut from the walls fabricated via standard and hybrid types of WAAM technology were prepared (**Table**). These samples were cut from the plane *x*. The confidence level during testing was accepted equal to 0.95 %, based on the law of normal distribution, meeting the requirements of the GOST 1497-84. The testing results showed that mechanical properties (elongation to fracture, yield and ultimate tensile strength) of deposited metal 08G2S were different.

It was established that mechanical properties are rather better for the hybrid technology of wall forming. Surfaced walls were tested visually and using X-ray inspection before machining to check quality of weld beads forming (**Fig. 4**). It can be seen that conventional method of weld beads forming is characterized by defects such as metal flow and incomplete melting between weld beads (Fig. 4, *a*). It explains low metal mechanical properties in comparison with the hybrid technology of wall forming.

After tension test, the samples were inspected via X-ray method (**Fig. 5**). This figure displays usual magnification, typical for film photographs. Internal defects (pores) were revealed, which could not be found by visual control.

It is shown from the works [9–23] that WAAM process has influence on size and accuracy of the components. WAAM technology includes wire arc melting, transfer of molten metal in a melt bath, convective flow of liquid metal in a melt bath, which is stipulated by the surface tension gradient, as well as deformation of bath surface under arc pressure and solidification of a melt bath.

Mechanical properties of the samples after hybrid and standard types of WAAM

Mark (number) of sample	Testing temperature, °C	Yield strength, $\sigma_{0,2}$, MPa	Tensile strength, σ_B, MPa	Relative elongation, δ_{10}, %
1, hybrid	20	364, 362, 362	474, 469, 472	29.75
2, hybrid	20	404, 408, 407	513, 510, 518	33.25
3, hybrid	20	370, 369, 372	445, 443, 448	33.71
4, standard	20	275, 274, 276	401, 400, 404	21.65
5, standard	20	295, 292, 294	415, 410, 412	22.15
6, standard	20	286, 286, 288	396, 390, 395	23.45

Manufacture of high-strength and defect-free WAAM components with required geometrical accuracy and surface cleanness needs corresponding selection of technological parameters, such as welding parameters (including current *I*, voltage *V* and surfacing rate, which influence on WAAM thermal profile and, respectively, on material properties, dimensions stability and substrate wetting ability. WAAM interlayer temperature reflects the temperature of the previous layer, which was deposited lately before the new layers [21–23] and has the effect on cooling rate as well as on mechanical properties and microstructure.

Selection of interlayer temperature influence finally on quality and productivity. Continuous deposition without intermediate cooling can lead to excessive heat input in a local area, what will finalize in high temperatures and wide secondary melting and, respectively, to low dimensions accuracy and surface cleanness [20–23]. From one side, wetting ability of a melt bath can be improved when the temperature between passes is high; it also causes additional temperature rise in small sections and outstanding components. It leads to melting of previously deposited layers and can cause forming of strong metal flows and even to destruction of the wall [23]. Termination of the process until the temperature will decrease below 100–170 °C is considered as the conventional method of solving the problem with interlayer temperature [17, 18, 21–23]. Use of hybrid approach allows to solve the problem of temporary downtime due to conduction of machining within this temperature range.

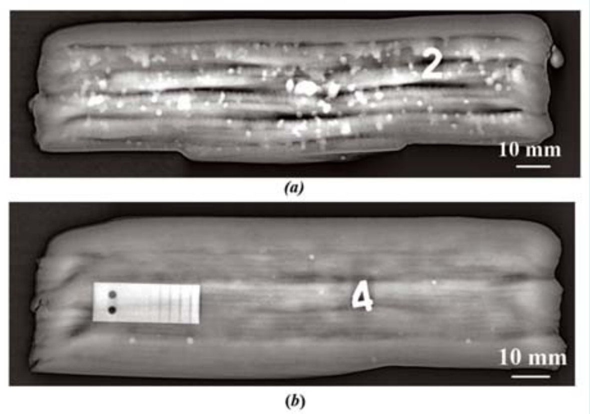

Fig. 4. Comparison of metal quality of the formed wall using the X-ray inspection method with standard (*a*) and hybrid (*b*) types of WAAM

WAAM technology uses protective environment with the main purpose to protect melting area and its adjacent areas from oxidation. Thereby, protective gas is an important parameter, because it has the effect on heat transfer procedure [20], process stability [21], geometry and appearance of weld beads, surface waviness and deposition efficiency [22], in addition to influence on mechanical properties [23].

According to [1–8], pores in welded seams are usually forming within a primary metal crystallization in a weld bath as a result of gas evolution. The pores are cavities in seams filled with gas, they can be spherical, elongated or have more complex shapes. They can also be hidden in the metal or located on the surface, arranged in chains or in separate groups, be microscopic or large (up to 4–6 mm in diameter). The pores observed in the layers after standard WAAM form as a result of gas evolution in macro- and micro-volumes.

The volumetric supersaturation of the weld bath metal with gases due to a decrease in solubility caused by metal temperature lowering, contributes to the macropore formation process. Gas bubbles grow takes place as a result of convective gas diffusion from the surrounding metal volumes. The bubble growth rate depends in this case on the degree of bath supersaturation with gases and on the rate of gas desorption into a nucleus. With local supersaturation of the liquid metal near the crystallization front, the bubbles develop most probably when the crystals stop growing. The bubbles develop mainly due to the diffusion of gas atoms (ions) from the adjacent metal micro-volumes. Their size is determined by duration of stops in the growth of crystals. With a crystallization of the first layers and stops duration 0.1–0.2 s, which are typical for the most common growth procedures [1–17], the smallest pores may form at the

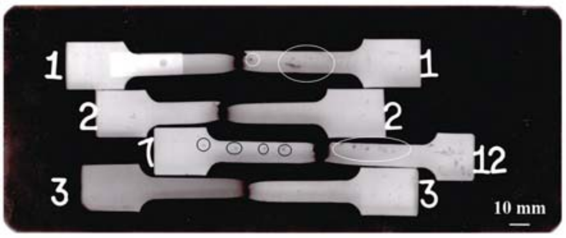

Fig. 5. Comparison of metal quality using the X-ray inspection method with standard (1, 12) and hybrid (2, 3) types of WAAM

fusion line. There is a type of porosity during technological process, which is caused by changes in current fluctuations, voltage and wire feed rate. This type of porosity is usually non-spherical and often caused by poor wire path planning or unstable deposition. The second type of porosity is associated with the material (wire, substrate, shielding gas) that contains contaminants (moisture, grease, lubricant). These contaminants can quickly enter the weld bath and porosity is forming after hardening. Thus, layer-by-layer grinding is used to detect areas with both single pores and a chain of pores in the case of hybrid technology. With the subsequent application of the weld bead, these pores will close, which will improve the product quality.

Conclusion

1. An eight-layer sample from Sv-08G2S steel wire with dimensions of 150 × 17 × 35 mm was successfully fabricated via standard and hybrid WAAM technology, using layer-by-layer grinding, was assessed using the conventional non-destructive testing methods. The study revealed that the hybrid technology (WAAM and layer-by-layer grinding) provided 100 % melting of layers and reduced porosity in the deposited metal.

2. The tensile properties of the samples fabricated via the hybrid technology (WAAM and layer-by-layer grinding) improved by 30–50 % in comparison with the samples obtained via the standard WAAM technology.

3. The hybrid WAAM technology with layer-by-layer grinding will allow design engineers and technologists to get more freedom and confidence to obtain high-quality layers and to develop and manufacture next-generation parts.

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