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Теоретические исследования и практическое использование вибрационных процессов в технике и технологиях, задачи управления и автоматизации в мехатронике и робототехнике являются актуальной сферой деятельности и научных интересов многих ученых в России и за рубежом.

Результаты этих работ нашли свое отражение в программе XII Международной научно-технической конференции «Вибрация-2016. Вибрационные технологии, мехатроника и управляемые машины».

Проведение конференции в Юго-Западном государственном университете стало уже хорошей традицией и закономерностью, подтверждающей успешное развитие научной школы по вибрационной механике, заложенной заслуженным деятелем науки и техники России, профессором П.М. Алабужевым. В сборнике, публикуемом по итогам ее работы, представлены результаты исследований ведущих ученых России, Германии, Латвии, Украины, Белоруссии, Казахстана, Эквадора, Зимбабве.

Тематика представленных на конференции научных работ весьма широка и многогранна: вибрационные технологии и машины; управление вибрацией и виброзащита; вибрационная диагностика; мехатроника и робототехника; история машиноведения; моделирование динамических процессов; биомеханические системы и технологии; электромеханические системы; нано- и микросистемы.

Сборник будет полезен научным работникам, инженерно-техническим специалистам, аспирантам и студентам, занимающимся проблемами исследований в области машиноведения, мехатроники, робототехники, автоматизации и микросистемной техники.

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ADDITIVE MANUFACTURING TECHNOLOGY USING METAL WIRE AND ELECTRIC ARC

This paper presents a general view of the technology intended for manufacturing of machine metal structural parts from a computer generated CAD drawings using an electric arc and filler wire. The proposed approach would make an alternative method of producing metal structures, with the benefit of large part size and high deposition rates. Concerned aspects that contribute to the geometry and structure of a finished part are observed. The welding inverter determines the arc energy and the deposition rate; therefore the differences between gas metal and gas tungsten arc welding are shown. Alongside the arc energy, factors like shielding gas type and torch angle contribute significantly to the size and shape of a bead. The general examination of the process of metal buildup is made using computer generated part geometry. In order to use a built part, it is very important to create a solid bond without any impurities. For testing purposes a small positioning apparatus is developed. This apparatus enables three axial movements to establish simple beads, besides an isolated environment and visibility of the process are provided.

Introduction

Additive technology, where a mechanical or structural component is created by adding layer by layer of material to form the end part, has been used for several decades but only by large corporations. The reasoning behind this is the fact that the technology and the process is very costly. The machine itself incorporates a high energy heat source, typically a laser beam or an electron beam, and various ways of delivering the fill material which usually is in the form of fine equally sized particles. Either the particles are laid in a special chamber in small layers, where the heat source fuses the particles together creating a solid bond. Then the next layer is laid, or is applied directly on the heated area of the part via a stream of particles that are blown in a spray like formation, hitting the heated area and fusing with the parent part. The high cost of the end product makes the process suitable only for special applications. For a small company or private users this is a costly way to create parts, and usually traditional methods of manufacturing are used.

Similarly layers may be built using an electric arc as a heat source and metal wire or powder to build up the part. The process is not new, material buildup and cladding is a well know technology where a part is restored applying layers of metal beads overlapping each other on worn areas. Fields of application are connected with the restoration of rail wheels, different agricultural or earthwork equipment where contact with other materials degrades tools. This technology allows reducing the cost of the replacement part. Building the weld bead on top of each other in a wall-like manner would allow construction of unique parts with a geometry that is near the finished product, the outer shape can be machined to a suitable finish. Some aspects of this technology concerned with the geometry and structure of a finished part are considered in this paper.

Materials and methods

The concept of the technology is purely based on the welding procedure. Fig. 1a shows the main principle of the gas metal arc welding (GMAW) or metal inert gas (MIG) process. The added filament is fed directly through the welding gun nozzle which also serves as the electrode which is consumed after the process. To maintain a clean weld, shielding gas is used to purify the welding zone, so that contamination from air or other sources may not protrude the molten metal; the gas is delivered via the torch. There are various metal transfer methods for this type of welder and each has its own specific properties:

- Short circuit

This is the most used method for manual welding. It may cause impurities if not properly tuned, filler wire touches the surface of the material and closes the circuit. Depending on the stick out of the wire it heats up and melts with the molten puddle, process repeats 20-200 times per second.

- Globular transfer

This method uses low current and is applied where less heat is needed. The filler wire end forms a ball like shape, which eventually drops in the molten puddle; this transfer type is very inaccurate.

- Spray metal transfer

In this case argon rich shielding gas is used, and the polarity of the inverter is set to DCEP (Direct current electrode positive) with high current settings depending on filler wire diameter. The metal wire goes from globular to spray type. This method produces a lot of heat and is nearly spatter free.

- Pulsed arc metal transfer (GMAW-P)

Transfer cycle consists of two parts – a high current phase and a low current phase. At the high current phase the filler wire is transferred via spray, and on the other cycle the weld is cooled. This allows better control of the weld and good penetration. The high current provides good welding characteristics for aluminum without pre heat, because it overcomes the high conductivity. This type of transfer is only possible with special inverters that are more expensive because of the complexity of the settings.

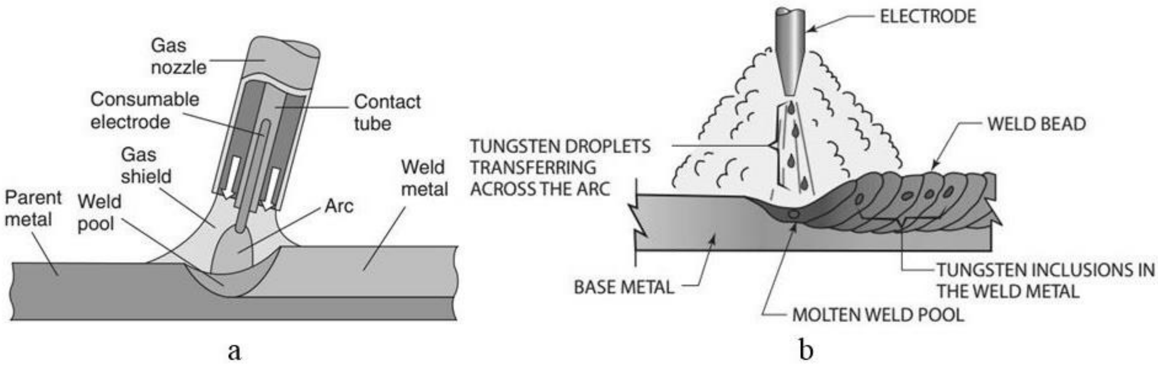

Fig. 1. Welding methods: a – GMAW process; b – GTAW process

The compact torch with filler as an electrode is very suitable for automation where only positioning needs to be supplied. The deposition rate can reach up to 3.73 kg/h with a current of 270A and filler wire size of 1.2mm [1; 2].

The gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding process supplies a more accurate arc with a much narrower heat affected zone that causes less distortion. A non-consumable tungsten electrode shown in Fig. 1b initiates a stable arc that gives more control and penetration than the MIG process. The filler material is delivered externally, dipping the welding wire in the molten puddle. The deposition rate is slower than the MIG, but with a higher quality, and if tuned properly won't generate spatter. To automate, the filler wire must be delivered to the molten metal puddle at a given angle and direction. Most TIG inverters have a built in arc control, where settings like pulse frequency. Initiation and shutoff of the arc and gas flow can be manipulated. To achieve high duty cycles machines are equipped with cooling that maintain a stable temperature at the electrode. The mean deposition rate of GTAW is 0.216 kg/h when working with stainless steel [1–3].

Three types of currents are used either for MIG and TIG:

- DCEN (Direct current electrode negative)

This method gives more penetration in welds because 2/3 of the heat is generated in the material, leaving 1/3 on the electrode. For TIG welding, this reduces erosion of the tungsten and smaller electrodes can be used.

- DCEP (Direct current electrode positive)

DCEP has an opposite heat effect from DCEN, the weld is much wider and shallow; the arc however may be erratic and hard to control. The DCEP has great cleaning properties, which makes it suitable for thin and oxidized materials.

- AC (Alternating current)

This type combines the DCEN and DCEP. The periodic direction switching of the current cleans the surface from oxidation and other impurities, but alongside gives good penetration; this is mostly used welding aluminium [1; 2].

Other welding methods or modifications exist as the twin arc welding method for MIG where the molten metal puddle is created by two separate electrodes. In this case a more accurate weld under the much higher deposition rate can be made. Alternatively Plasma-TIG and Plasma-MIG welding may be used as a heat source which allows creating a stable arc with low current settings, low as 0.1A. To achieve higher deposition rates the hot-wire method can be introduced in the molten puddle [4].

During welding of carbon steel metals, a small area is heated to a temperature that is above 1600°C, and a liquid metal puddle is formed. After removing the arc, the surrounding metal and air draw the heat, and within a second a metal weld returns to a solid state. The molten metal, solidifies, creating a new structure, which begins from the parent metal inwards to the center of the pool; the grain size is mimicked from the fusion boundary, and continues to grow in a columnar form. Understandably the region around the prior liquid puddle will also be affected. This region is called HAZ (Heat affected zone). Areas that heat above 723°C are changed to an austenitic phase where the carbon content is dissolved. In the case of slow cooling soft ferrite and pearlite are formed, but in cooling at a faster pace – strong but brittle, bainite and martensite are produced. The critical range of temperature lies within the interval from 800º till 500°C; the cooling rate determines the final microstructure [5].

Results and discussion

One can imagine that for a buildup of a vertical wall the welding gun travels along a trajectory and after each pass slightly raises the height and continues building the next layer after the previous one is solidified. Either of the two methods in the previous chapter can be used for creating metal objects. For better control the MIG process would need a separate wire speed control. Whereas for the TIG the wire needs to be fed externally with a delivery system that can be manipulated changing angle and feed direction to the puddle because the torch does not deliver the filler wire as the MIG. For optimization of the settings, the feed rate of the metal wire should be controlled directly with the processor, due to the wire speed being proportional to the travel speed. If using the MIG inverter, care should be taken to maintain a stable transfer of the filler. Accurate result may be achieved with spray and short-circuit method; the pulsed method would enable more optimization, however it is more expensive [1].

The most aspects that influence the bead characteristics are the following:

- Arc energy

The arc energy is derived from current settings, voltage and travel speed by the formula

$$E_t = \frac{VA}{S}, \qquad (1)$$

where E_t is the total arc energy input, V – arc voltage, A – arc current, S – travel speed of the arc source.

The amount of current to be used is dependent on wire diameter when using the MIG process. Smaller diameter wire will overheat if the current is set too high and spatter. Larger diameter wire will draw heat from the weld puddle which then needs to be compensated with higher arc settings.

R. Scott Funderburk [6] used Rosenthal’s calculations of the heating cycle for the most common welding cases in a semi-infinite object [7]. Tests were made with different settings with a 4 mm conical tipped electrode using an automated GTAW on mild steel. Argon rich shielding gases were mostly used in tests. Efficiency of the process and melting was evaluated using Rosenthal’s equations. It was concluded that the process efficiency improves if travel speed is increased from 2.1 mm/s to 6.2 mm/s, but decreases if current level is increased from 125 A to 225 A. If the current is increased the weld nugget sizes also become bigger.

- Shielding gas type

The type of gas used is dependent on the type of metal that is being welded, how the different molecules interact with the metal compound. Usually the gas is a mixture of different types to combine the positive effects of each type. One must note that mixtures with helium or similar are lighter than air and may escape the welding zone if drafts or insufficient gas flow is present. CO_2 shielding gas is often used because of its low price, but may cause spatter, therefore a mixture with argon increases quality. J. Lozano, P. Moreda et al [8] have done multiple tests with different gas mixtures on the bead formation of stainless steel. It was shown, that mixtures with the compositions Ar-43% + HE-55% + CO_2-2% and Ar-95% + He-5% allow to form proportional beads with deep penetration and cover a wide area. However mixture with Ar-98% + O_2-2% forms a high reinforcement area, which is suitable for creating high and narrow wall sections. Argon maintains a better process efficiency on carbon steel welds under the increasing current settings on a given travel speed, but the melting efficiency is improved when using helium.

- Angle of torch

In general, pushing the torch with an angle toward the path creates a wide and low weld. Perpendicular positioning of the torch results in deep penetration and similar shape as from the push angle. And an angle opposite the direction of welding (called drag angle) creates deep penetration and a narrow – high weld. In accordance with [8], changing of arc angles has no influence on the overall efficiency of the GTAW process on mild steel. But with the increasing of the angle from 30° to 120° the rise in the ratio of weld nugget to the HAZ occurs, and the melting efficiency is also improved [1].

When higher deposition rates are of interest, the bead may be made narrow and high or if the pass is to be made wide, the height is lower. The interaction of the heat source with the weld area is a complex process, where different factors (pressure from the arc, surface tension, molten metal, and viscosity) influence the geometry of the final bead shape. An extensive analysis of different modeling methods are described in [7] using the previously mentioned Rosenthal equations. Gaussian flux distribution plotted by the equation (2) is shown in Fig. 2. Surface Gaussian flux distribution

$$q(r) = q(0)e^{-Cr^2}, \tag{2}$$

where $q(r)$ is a surface flux at the radius r, $q(0)$ is maximal flux at the center of the heat source, C is the distribution width coefficient, and r is a radial distance from the center of the heat source.

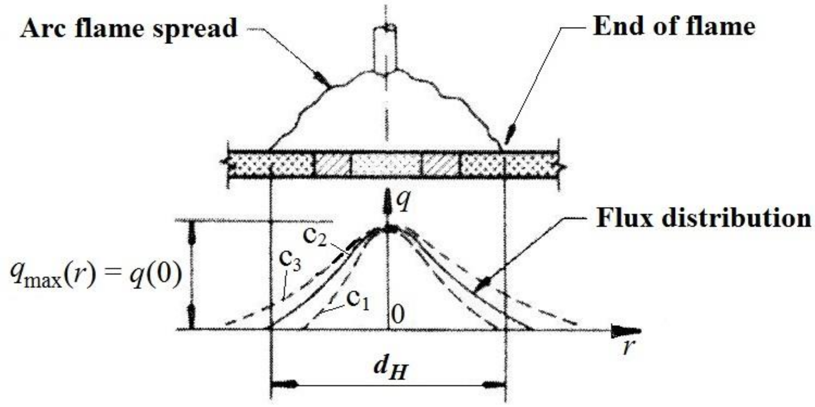

Fig. 2. Gaussian flux distribution

The flux distribution at the toes of a weld (Fig. 2) may be insufficient to fuse the new layer. To illustrate the lack of fusion in a wall type structure using FEA (Finite element analysis), multiple layers of buildup are stressed vertically across the beads in opposite directions (Fig. 3a). For this analysis SolidWorks Simulation is used. An equal load of 100 N is exerted on both ends, and inertial relief is used to stabilize an unrestrained model with applied balanced load. To highlight the effect of fatigue, an artificial notch is created protruding 14.6% of the total net width of 4.8 mm, the height of each layer is 1.5 mm. The size and geometry are taken from test results described in [9].

According to the flux distribution an approximate weld section is shown in Fig. 3a. The forming of each sequent weld creates an overhang in the wall section, this is important to ensure that the fusion is complete to form a straight vertical wall. If, however the fusion is incomplete by wrong settings as high speeds or insufficient arc energy, high concentrated stresses may occur - these are called stress points (Fig.3c). In this case the current structure undergoes 24% more stress with the notch. To minimize the stresses caused by the narrow sections of the weld, machining of the overhang may be used (by this method stresses can be reduced by 17%, see Fig. 3b). However if the stress point is located beyond the milled surface shown in Fig. 3d, upon dynamic loads the area may continue to fracture. This type of fault is difficult to detect until the surface is machined.

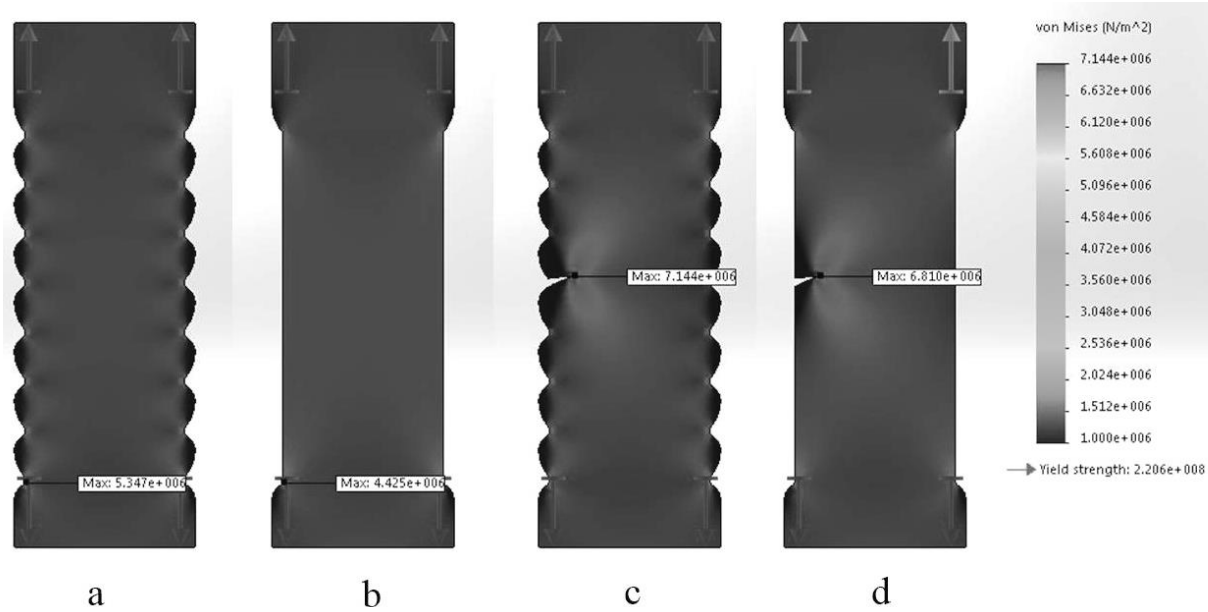

Fig. 3. Cross section of a welded wall: *a* – Regular weld buildup; *b* – The overhang is machined to a nominal thickness; *c* – Insufficient fusion along weld boundary; *d* – Machined to a nominal width, with the crack still present

The forming of unfused areas along the boundary of sequent beads, may lead to labor intense operations where the area needs to be repaired. For small fractures shot peening can significantly help to maintain even distribution of stresses along the outside faces. For deeper unfused areas additional quality tests need to be done to identify good weld settings. To examine the interior quality, a nondestructive test may be performed (e.g. ultrasound testing [10]).

As mentioned before, the HAZ plays a great role in material microstructure. For welded structures heat treatment is used to reduce residual stresses, when multiple welds or long uninterrupted welds are made. But when forming a part with weld buildup, heat is added and the material stays hot, and undergoes self – tempering, where internal stresses are relieved and hardness and strength is decreased, but ductility is increased. If areas are exposed to temperatures above 723°C for a longer period of time, the grains may grow to a size which is not desirable. Machinability with the decrease of hardness is improved. In an unsymmetrical part some areas may undergo more tempering, causing uneven mechanical properties throughout the model [11].

Depending on the geometry of the part it can occur that upon heating, some areas with a larger mass may cool slower, than thin-walled areas with less mass. In this case, if a weld is made at a boundary of such area, the molten puddle begins to solidify, dendrites form at an unequal pace, because the smaller section cools faster and shrinks resulting in stresses in the puddle and creating cracks at boundaries of the grains from each side. Preheating of the base metal can be done to prevent uniform cooling or controlling the environment to maintain temperature [1].

After the general examination of the process of metal buildup using a computer generated part geometry, more thorough research should be made to examine the heat effect of the structure while the part is being processed. And studies are necessary to determine the overall quality of the structure, so that the part may guarantee stability. For testing purposes a small positioning apparatus is developed (Fig. 4).

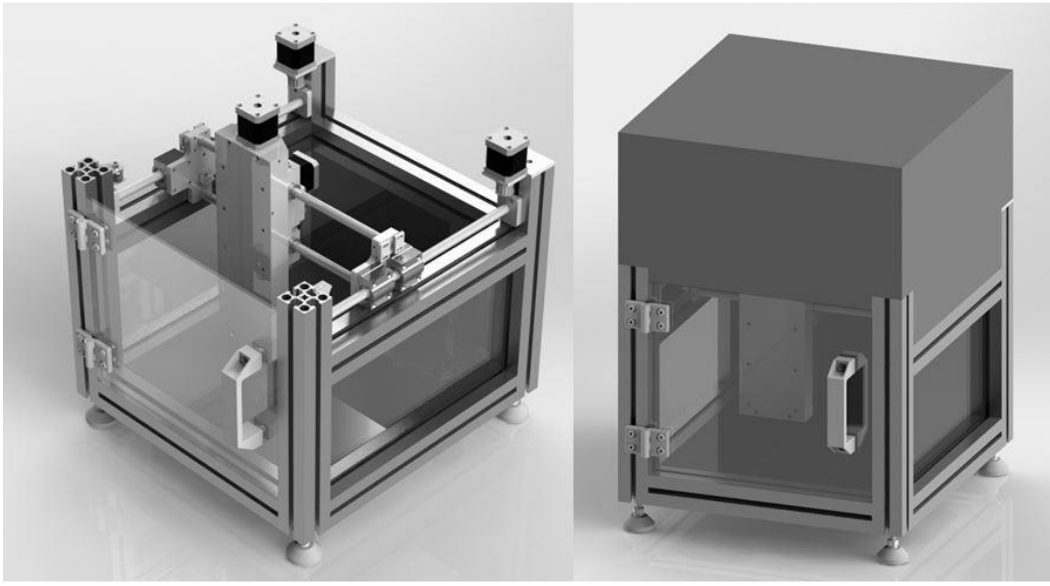

Fig. 4. Enclosed positioning apparatus

Three axial movement of the working head allows to establish simple beads. Additionally the fixture for the torch is made so that it becomes possible to adjust the angle of the electrode. A closed environment allows removal of weld gases and with a fan on the exhaust exit air flow can be slightly controlled. Transparent walls provide a clear view of the process, adding a sliding UV protection glass could allow visual inspection without wearing protective goggles. The construction is lightweight and easy to transport, the control components can be fixed to the positioning frame. But to reduce interference due to the magnetic effects from the welding process, electrical components can be mounted in a separate enclosure that isolates from the influence of magnetic field. Detailed experimental analysis of the process would be critical in the future.

Conclusions

1. The proposed method of additive manufacturing promises high deposition rates: for GMAW up to 3.7 kg/h, for GTAW – average of 0.28 kg/h. Deposition rate for a laser sintered part is from 0.04 to 0.16 kg/h.

2. Manufactured structural part undergoes heat tempering from the sequent buildup of layers; this lowers the residual stresses and hardness, increases ductility.

3. Shielding gas, arc energy and torch angle play a substantial role in weld geometry.

4. Machining layer in a manufactured product is relatively small.

5. Overall part cost of final product includes filler material, welding apparatus, positioning, and additional machining costs.

6. Wrong settings may cause insufficient fusion, resulting in poor bonding with layers. Outer bead region can cause formation of cracks.

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