Research on Microstructure and Properties of Medium Carbon Steel Parts Manufactured by HDMR Technology

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Abstract

A new study on manufacturing medium carbon steel parts by HDMR (Hybrid Deposition and Micro Rolling) technology was carried out, and the microstructures and mechanical properties obtained by HDMR process and freeform arc deposition process respectively were tested and compared in this paper. The experiment results show that: compared with the freeform arc deposition process, the grain size number obtained by HDMR process，increased from 3.0 to 9.0；the tensile strength and yield strength were increased by 37.1%, 68.6%， in contrast to the investment casting, increased by 65.4% and 107.7%; compared with the forging, the tensile strength and yield strength were increased by 12.9% and 31.4% respectively. Finally, a medium carbon 45 steel aeronautical part difficult to overlay was manufactured successfully by HDMR technology, thus a new efficient way for additive manufacturing of hard-shaping metal parts at high-quality with low-cost was provided.

Introduction

Direct manufacturing metal parts is one of the foreland fields of present addictive metal manufacturing technology and has been received considerable attention around the world. Generally, lasers, electron beams and arc energy are used for melting the metal powder or wire to achieve rapid prototyping, such as LENS (Laser Engineered Net Shaping), EBM (Electron Beam Melting), ADM (Arc Deposition Manufacturing), etc. [1]. LENS needs to use high power laser beam with good controllability but is suffering for its low energy utilization, material utilization and shaping efficiency; EBM is favored and admired by NASA and Lockheed Martin Space Systems Company on account of high energy efficiency, but it’s only available for titanium alloy powder and the shaping size is limited by the expensive vacuum chamber volume. Both of them need high investment in equipment and operating costs [2].

ADM using arc as the energy source has drawn a significant research interest owing to its low cost, high efficiency and simple equipment [3, 4]. Generally, the arc-based additive manufacturing process is composed of several procedures including establishing the part 3D model, deposition path planning for each layer, and stacking up of beads layer by layer[5]. Although the shaping precision of ADM is lower than two above, however its wider range of materials, high shaping efficiency, low cost, compact structure, and thus receiving the attention of Airbus, Rolls-Royce and other companies. But because of some defects like coarse grains, lower mechanical performance than forgings, etc., its application range is limited.

As carbon structural steel with good mechanical properties, medium carbon 45 steel can be incredibly valuable if used for manufacturing high-quality and low cost parts by AM (Add Manufacture).

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But because of its poor weldability, it has the tendencies to generate cracks and holes in AM processing. According to rolling theory, the compressed semi-solid metal has compact microstructure inner, fine grains and less holes and cracks in hot rolling under the high temperature and multi-directional pressure[6], therefore, the semi-solid metal gets compressed while AM processing, so that the shaping ability and comprehensive mechanical properties of the parts manufactured by HDMR technology and the equipment developed in our laboratory[7] were improved significantly. Finally a 45 steel aeronautical part difficult to overlay was manufactured based on the HDMR method in this paper.

Experiment condition

2.1 Experiment matiral and equipment

Substrate: Q235 steel plate (160 mm × 60 mm ×12 mm); welding wire: 45 steel wire (1.2mm). Experiment equipment: HDMR (Hybrid Deposition and Micro Rolling) equipment developed by our laboratory, the infrared thermal imager, DX70 metallographic microscope, Wilson Hardness ck - AH micro Hardness tester, universal tensile testing machine, etc.

2.2 Experiment method

Table 1 Process parameters

Wire Feed Rate /（m min^{-1}）	Welding Speed /（m min^{-1}）	U /V	I /A	Gas Flow /(L/min)
10.0	600	29.0	74	17

Test parameters are shown in Table 1, under multi-channel and multi-layer welding, micro rolling composite process of micro zone rolling down at a rate of 30%. HDMR process and free arc-based deposition process were used for manufacturing sample respectively. Figure 1 shows the infrared thermal image in the test processing. The highest temperature of the welding bead is 1302.6℃.

L is the torch moving direction and H is the laminated orientation during deposition in Figure1. The size of the blank is 140mm ×40mm ×40mm. The block samples with the size of 20 mm ×10 mm ×15 mm were taken to compare with metallographic and test the hardness of the block samples along the H direction. According to "Metallic Materials Tensile at the Preparation" in GB/T228-2002[8], the tests were made on the rectangular non-proportional flake samples on the right side of the block.

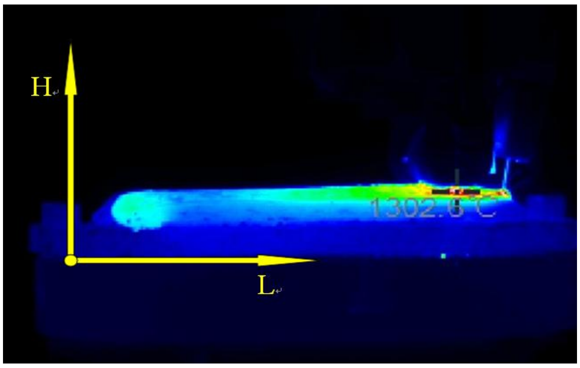
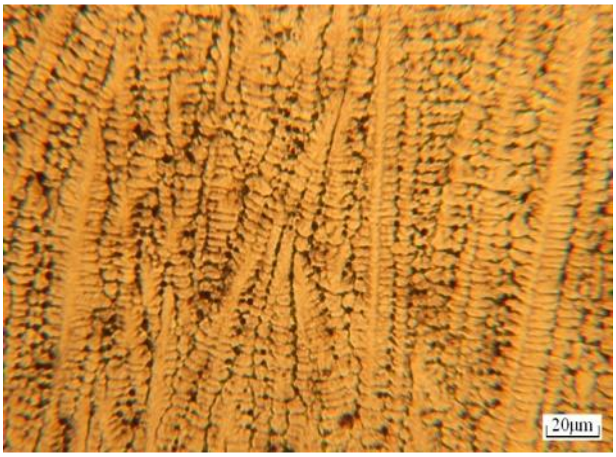


Figure 1 Infrared thermometry in HDMR processing

Experimental results and analysis

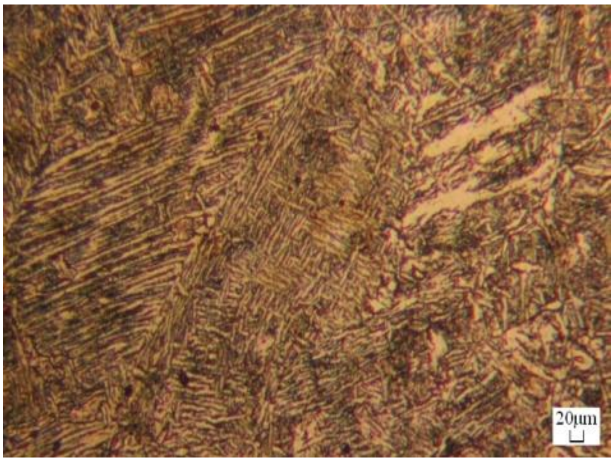
3.1 Metallurgical results

After sample grinding and polishing, the samples were corroded in the 80℃ water with saturated picric acid solution and sodium dodecyl benzene sulfonate (SDBS). Figure 2 (a) and (b) show the observation of the grain size under an optical microscope at a magnification of 50X; Figure 2(c) and (d) show the metallurgical structure corroded by alcohol with 4% nitric acid and observed under the optical microscope at a magnification of 500X.

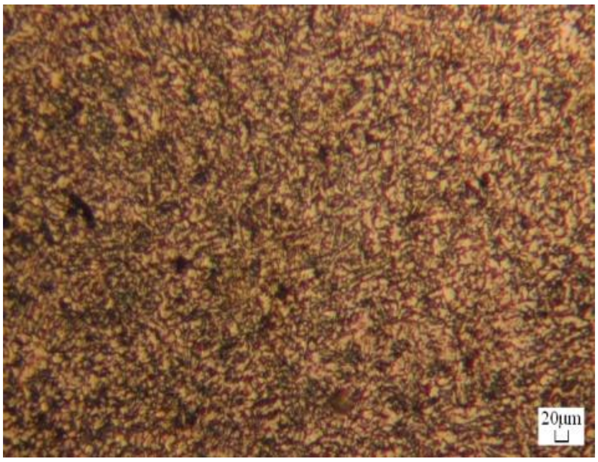


(a) Freedom arc deposition grain

(b) HDMR grain



(c) Freedom arc deposition metallographic phase



(d) HDMR metallographic phase

Figure 2 Comparison of grains and structures between freedom arc deposition process and HDMR process

According to the standard test method for metal average grain size by measurement method in GB 6394-2002, the average diameter for grain of the freedom arc deposition sample is 48.83μm with the metallographic assessment level of 3.0; and the HDMR sample is 5.22μm with the level of 9.0. Figure 2(a) shows the oversize and powerful columnar grain of freedom arc deposition zone. The micro-region nucleation increasing as the plastic deformation caused by micro-region rolling could break down dendrites and turn into dynamic recrystallization. Figure 2 (b) shows the overall grain refined.

Metallographic phase of the freedom arc deposition sample was shown in Figure 2(c): There exists a flake ferrite of multiple sets of parallel needles and sheet along the grain boundaries; the grains are arranged in several different directions with perpendicular to each other in the middle of the ferrite and the right side was mixed form. The results show an overall Widmanstatten structure characteristic representing an overheating defect. That the role in dividing coarse ferrite or cementite in the matrix reduces the steel strength but increasing the brittleness. The HDMR metallographic phase shown in Figure 2(d) represents uniform orientation of equiaxed grain and uniformly overall distribution with white ferrite and black pearlite.

Grain refinement is considered as the most effective way to improve the strength and toughness of the steel material; the finer grain, the higher strength of the material [9, 10]. According to the theory of controlled rolling, the deformation band density with increasing pressure and rapid increase in the amount of deformation with ferrite core will become favorable position when the reduction ratio approaches to a certain extent, after the phase transition, the α-grains becomes fine as the increasing of total rolling reduction ratio of the non-recrystallization region in austenite [10]. The ferrite grain refinement of phase transition will play an important role in improving the strength and toughness of the metal parts [11].

3.2 Hardness distribution results

Using Wilson Hardness ck-AH type hardness tester, respectively, along the H direction of freedom arc deposition sample and HDMR sample, compared the results with measuring points for every 2mm, load of 48.9N, pressure dwell of 10s and both 10 dots. The Vickers hardness distribution is shown in Figure 3.

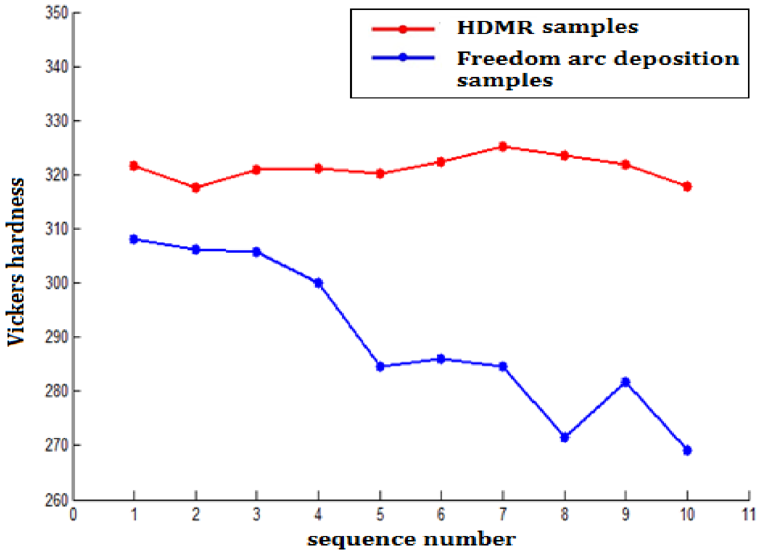


Figure 3 Hardness distributions between freedom arc deposition samples and HDMR samples

The Vickers hardness of the freedom arc deposition sample is 289.75 with the standard deviation of 14.35; the Vickers hardness of the HDMR sample is 321.26 with the standard deviation of 2.33.

The average hardness of HDMR sample is increased by 10.9% compared to freedom arc deposition sample. It's clearly that the hardness of the latter is not distributed uniformly compared to former. There are both coarse dendrites and local small vertical dendrites, resulting in different hardness in the freedom arc deposition samples, while HDMR sample represents fine and uniform equiaxed grains resulting in more uniform hardness.

3.3 Tensile test results

Tensile test results are shown in Table 2, the tensile specimen displacement - load curve is shown in Figure 4.

Table.2 Tensile property of 45 steel shaping by different methods

	Tensile strength /MPa	Yield strength /MPa	Elongation /%
Investment casting	570	310	15
Forging	835	490	17
Freedom arc deposition	688	382	13
HDMR	943	644	18

Compared with the freedom arc deposition sample, tensile strength of the HDMR reached by 37.1%, yield strength increased by 68.6% and the elongation rate increased by 38.5%; compared with 45 steel(casting), tensile strength of the HDMR improved by 65.4%, yield strength increased by 107.7% and the elongation rate increased by 20%; compared with 45 steel(forging), tensile strength of the HDMR(hybrid deposition and micro rolling) improved by 12.9%, the yield strength increased by 31.4% and the elongation rate increased by 5.9%. High temperature plastic deformation pressure can make metal organization homogenize and the grain size be refined, thus improving the mechanical properties significantly.

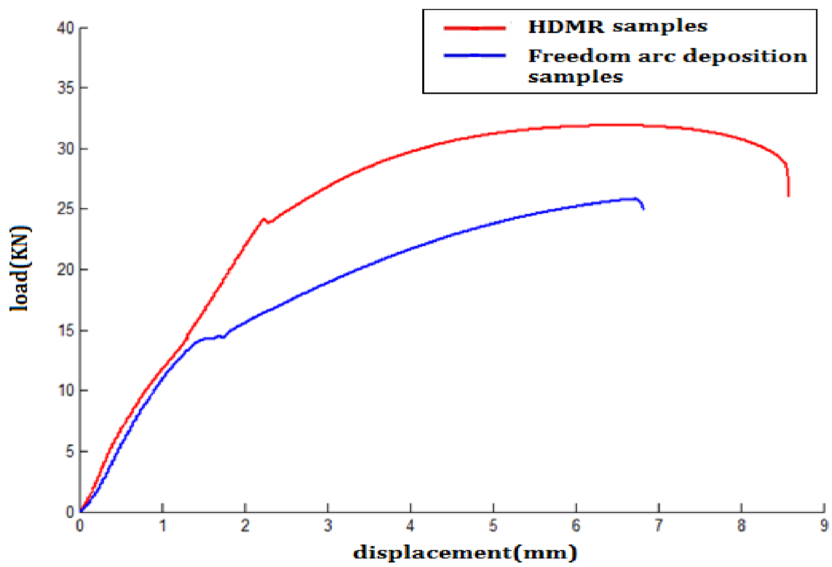


Figure 4 Tensile displacement-load curves between freedom arc deposition process and HDMR process

3.4 Trial manufacturing result

Finally, a 45 steel (difficult to overlay) aeronautical part shown in Figure 5 was manufactured by the HDMR method.

Figure 5 a 45 steel aeronautical part manufactured by the HDMR method (after milling)

Conclusions

1. In the freedom arc deposition processing, it's easy to form coarse austenite grains and Widmanstatten structure, while HDMR processing, the grain diameter can be refined to 5.22μm, and the metallographic structure are uniformly equiaxed ferrites and pearlites to play a very effective role in fine grain strengthening.

2. Compared with the freedom arc deposition, the HDMR process can improve the hardness by 10.9%, the tensile strength by 37.1% and the elongation by 38.5%.

3. Compared with the investment casting, the HDMR can improve the tensile strength by 65.4% and the elongation by 107.7%.

4. Compared with the forging, the 45 steel parts manufactured by HDMR method reach the improvement with the tensile strength of 12.9% and the elongation of 5.9%, thus the performance of traditional materials can be improved significantly by the HDMR process

5. Finally, a 45 steel (difficult to overlay) aeronautical part was successfully manufactured by the HDMR method, thereby a new none foundry and forging method for green manufacturing metal parts at low-cost with high performance was established.

Acknowledgments

The authors would like to give their gratitude to Yanzhao Peng and Pan Yun for their supports. This work was financially supported by the National Natural Science Foundation of China under Project No. 51175203.

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