3D Welding and Milling for Direct Prototyping of Metallic Parts

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Abstract:

Welding has been used for the direct fabrication of metallic prototypes and prototype tools by several research institutes. Since welding alone is not able to deliver the accuracy and the surface quality needed for prototype tools, especially for injection molds, a combination with conventional machining is necessary. In this paper, welding and 5-axis milling are combined together for the direct fabrication of metallic parts. For welding, conventional CO_2 arc welding is used. Test parts with conformal cooling channels and undercuts demonstrate the technological potential of this process combination for rapid tooling applications.

1. Introduction

With an increasing demand to the prototype tools in regard to dimensional accuracy as well as to mechanical strength, several rapid tooling techniques have been developed and applied in industrial application [1, 2]. Although they seem quite promising, the critical issue of dimensional accuracy remains for the currently used rapid tooling techniques. Usually, each extra step required for the conversion process towards the final part implies a deterioration of its dimensional accuracy. As matter of fact, it would be best if the prototype tool can be manufactured directly without any secondary process.

For this purpose, several approaches for the direct prototyping of metallic tools are being developed. The common feature of the processes consists in direct melting of metal with a focussed laser beam, an arc or a plasma. The material used is normally supplied either in form of powder or wire. Because of the complete melting, however, the obtained accuracy as well as the surface quality of parts are generally lower than that of machined parts.

To overcome this difficulty, the process combination with a substractive technique such as conventional milling can be an appropriate solution. This kind of process combination has been already successfully implemented in shape deposition manufacturing [3,4] and laser generating [5]. In this investigation, it is aimed to discuss some fundamental technological aspects of the process combination for its further development.

2. Experimental Procedure

The test facility consists of a 5-axis vertical milling machine and an arc welding equipment, **Fig. 1**. The welding gun attached to the spindle can be moved in z direction. The substrate plate is fixed on a rotary table mounted on the linear x-y table of the machine tool.

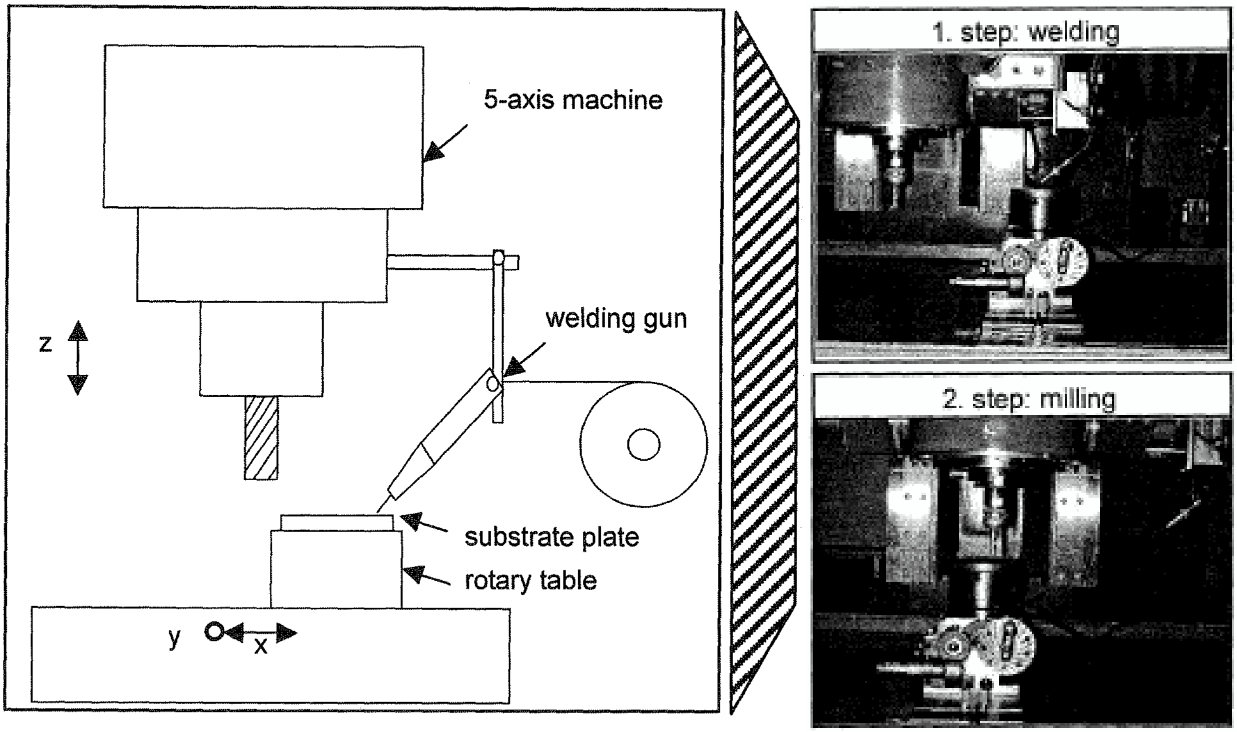


Fig. 1: View of the test facility

As shown on the right side of Fig. 1, the substrate plate is placed directly beneath the welding gun at first, and then moved to the milling tool after welding operation is completed. In milling operation, the top as well as the sides of the bead are machined to a specified height and width before depositing a new layer upon the previous one. This procedure repeats until part is completed.

Among the significant process parameters of 3D welding and milling are voltage and current as well as travelling speed of the substrate plate. Prior to the experiment, the relative position between the welding gun and the substrate plate and the flow rate of shielding gas were set according to the result of the previous investigation and kept constant during the experiment. For welding operation, a carbon steel wire (AWS A5.18) with a diameter of 0.9 mm was used. The substrate plate was also made of a carbon steel.

As an alternative to arc welding, laser beam welding can be used in the experiment. Since laser beam can be more precisely focussed than welding arc, more accurate parts can be built. In addition, focussed laser beam allows a less heat input into the part, thus making the part less susceptible to distortion. However, the deposition rate of laser beam welding is generally lower than that of arc welding. Besides, the utilization of laser requires a more complicated beam delivery mechanism and a more precise wire feeding system. Considering these features, laser beam welding is more suitable for manufacturing small and precise parts rather than large and bulky parts. A selection between arc and laser beam welding should be made depending on the geometrical complexity and the size of part.

3. Results and Discussion

3.1 Single layer experiment

Starting from the single bead experiment, the influence of voltage, current and travelling speed on the formation of welding beads was investigated. Voltage and current were varied in ranges of 16V-36V and 60A-140A, respectively. Optimizing the parameters in the ranges above at a constant travelling speed allowed to deposit single connected beads instead of loose spheres. It was shown that the bead size heavily depends on the travelling speed of the substrate plate, **Fig. 2**. When the travelling speed exceeds v_S= 600 mm/s, however, the height decreases only slightly down to 0.5 mm, whereas the width linearly decreases to 1.8 mm.

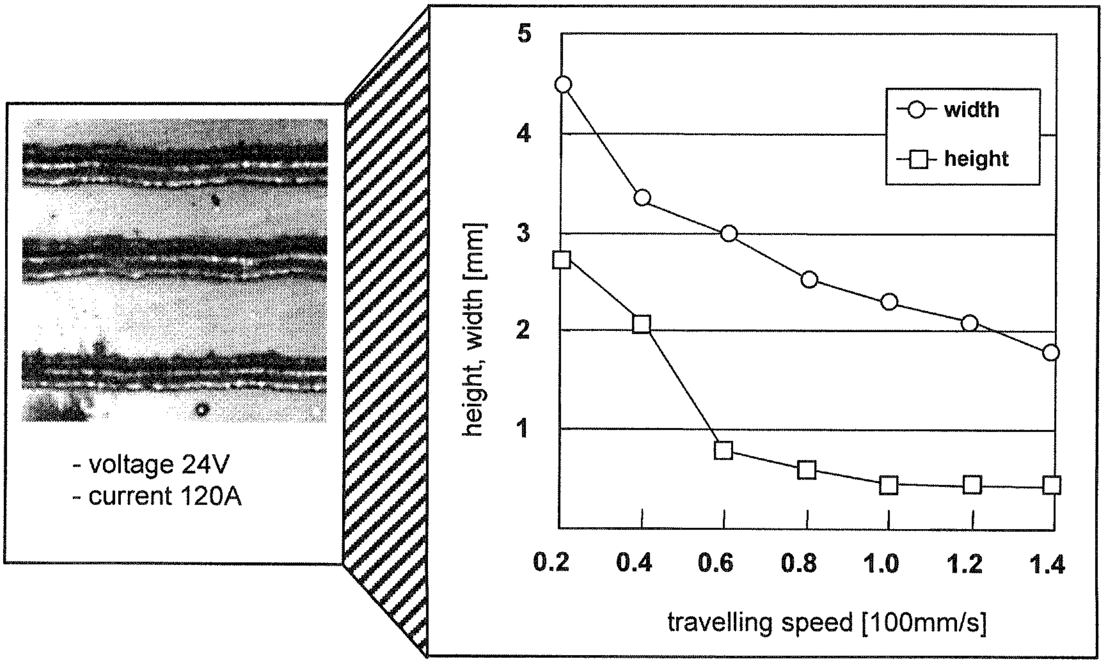


Fig. 2: Height and width of single beads at different travelling speeds

The result in Fig. 2 also shows that varying the travelling speed between v_S = 200 mm/s and 1200 mm/s constitutes an effective method to control the size of beads. Compared to the other process parameters such as voltage and current, the travelling speed is relatively easy to change during the process. For this reason, if the bead size is required to be changed during the process, the travelling speed should be varied.

3.2 Multiple layer experiment

The fundamental difference between a single layer and a multiple layer is the condition of heat conduction from the processing area. In case of the single layer, the heat can dissipate relatively fast to the substrate plate, whereas in case of the multiple layer, the heat is only slowly conducted to the substrate plate. This is partly due to the reduced cross-sectional area and partly due to the dissipated heat from the previous layers. Consequently, the heat is constantly accumulated in the part until an equilibrium between heat input and dissipation is achieved. Since this accumulation of heat influences the welding result, variation of the process parameters is necessary depending on the height. An effective method to obtain a constant result would be adapting the travelling speed according to the actual height of building part.

In **Fig. 3**, thin walls made of 8 layers are shown without and with machining. In case of the part without machining between depositing layers, the instability of arc welding process caused a defect in the middle of the beads. Initially small in size, the defect in the second layer influenced the height of the next deposited bead and, thereby, amplified itself until a further deposition was no longer possible. Therefore, machining the bead perpendicular to z direction is not only necessary to increase the part accuracy, but also to make the process more stable for the further deposition. When milling the deposited beads perpendicular to z direction, a change of the height was observed. The first four layers had a height of around 2.8mm, while the succeeding layers showed a decreased height of around 1mm. This result is to explain with the changing cooling rate in the part, as mentioned in the previous paragraph.

The analysis of the cross-section in the wall reveals a different microstructure depending on the height. The microstructure taken from the upper area of the wall shows enlarged grains with a spherical shape (see a in Fig. 3). In each grains, a second phase can be observed which is only viable when the cooling rate is relatively low. Compared to that, the microstructure of the lower area contains relatively small grains as well as some dendrites (see b in Fig. 3). Such a microstructure results from rapid cooling due to the large amount of heat conduction to the substrate plate. In conclusion, the formation of microstructure also proves the changing cooling rate with increasing height. Therefore, an adjustment of the process parameters according to the height is necessary to maintain a homogeneous microstructure in the part. Otherwise, the part has to be heat-treated.

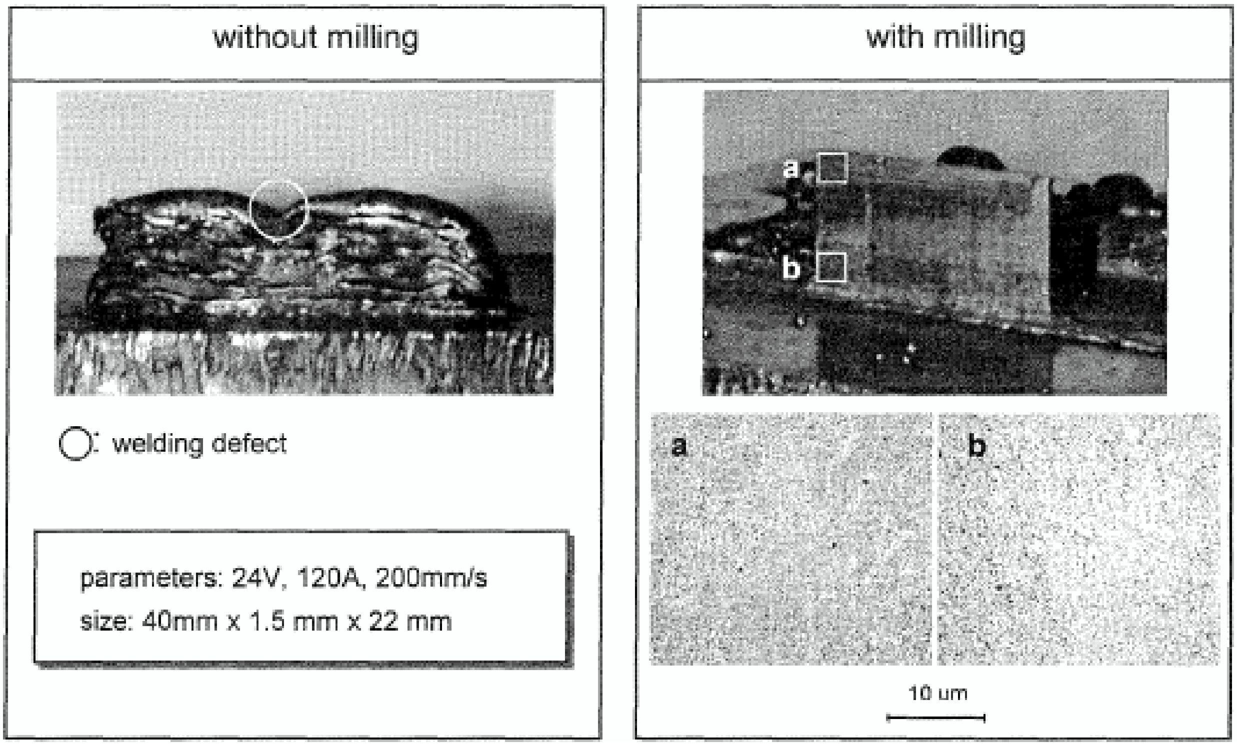


Fig. 3: Thin-walled parts without milling and with milling

In **Fig. 4**, two inclined walls built with an offset value of 0.5 mm and 1 mm, respectively, are shown. After depositing 15 layers, the walls were machined with a tilted milling tool in one operation.

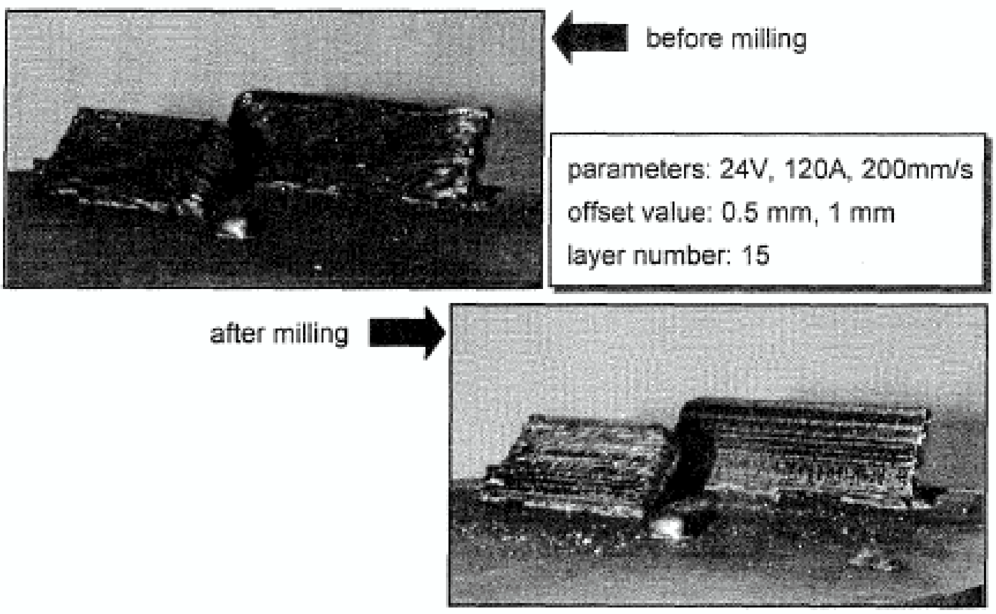
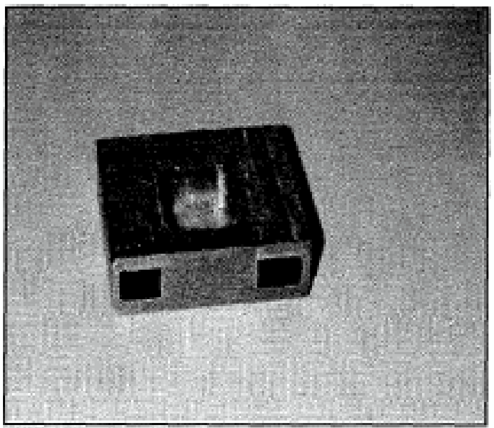


Fig. 4: Inclined walls with angles of 24° and 44°

Besides thin walled parts, 3D welding and milling also enables manufacturing solid parts with good surface and dimensional accuracy. In **Fig. 5**, a solid part fabricated with 3D welding and milling is shown. The shifting distance between each beads was 3.7mm. The test part contains an internal channel around the rectangular cavity. Theoretically, it would also have been possible to machine the internal channel of the part from a block and close the channel with welding afterwards. The cavity in the middle of the part could also have been completely machined after finishing deposition. However, it would have taken much more time because of the large volume to be removed. If the volume to remove were less than the deposited one (e.g., the walls of the internal channel were thicker than the channel itself), then machining would have been preferable to welding.

This example implies how flexible the combination of welding as additive and milling as substractive technique can be applied for prototyping. To use the process effectively, however, an intelligent process planning is necessary taking the complexity and the size of features into consideration as well as the required mechanical properties. Based on this consideration, it has to be decided which features of the part to build with additive or substractive method.



parameters: 24V, 120A, 200mm/s
size: 70mm x 65 mm x 20 mm

Fig. 5: Solid test part

4. Conclusions

According to the current state of the art, dimensional accuracy as well as surface quality of rapid prototyped metallic tools are still far behind that of conventionally machined tools. To increase the quality of rapid prototyped tools, a hybrid approach comprised of an additive and a substractive technique called 3D welding and milling is being developed.

The combination with milling operation not only increases both the surface quality and the dimensional accuracy, but it also gives a great manufacturing flexibility. To use the process combination effectively, however, an intelligent process planning depending on the part geometry and its size is a prerequisite. In addition, a process control is required as the heat dissipation changes with increasing part height.

5. References

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