3D Welding and Milling
- A Direct Approach for Fabrication of Injection Molds -

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Abstract:

Solid Freeform Fabrication (SFF) gives designers a new freedom to build parts which have been not able to be manufactured by conventional techniques. However, the surface finish and the accuracy of SFF parts are still lower compared to that of conventionally machined parts. To overcome this problem, a process combination of additive and subtractive techniques is being developed. This hybrid approach called "3D Welding and Milling" makes use of welding as additive and conventional milling as subtractive technique, thereby exploiting the advantages of the both processes. In this paper, it is shown whether this process combination can be applied for the fabrication of injection molds.

1. Introduction

With an increasing demand for metallic prototypes and tools, several direct SFF techniques have been developed. The common feature of these approaches consists in direct melting of metals which are normally supplied either in form of powder or wire. Due to the complete melting, however, the accuracy as well as the surface quality are generally lower than that of machined parts.

To overcome this process inherent problem, a combination of additive and subtractive technique offers as a possible solution. This kind of process combination has been already implemented in SDM (Shape Deposition Manufacturing) of Stanford University [1,2] and CMB (Controlled Material Buildup) developed by IPT Aachen [3]. In these processes, each layer is deposited as a near-net shape using thermal deposition including spraying, welding or laser cladding. The layer is then shaped with CNC milling to net shape before proceeding with the next layer.

The combination of welding as additive and milling as subtractive operation offers distinctive advantages over conventional machining. First, in case of parts with a large amount of volume to remove, the fabrication of near net-shape with the additive method and the consecutive surface finishing can be a competitive approach. In addition, if the material is difficult to machine, the additive fabrication of a near net-shape with welding and subsequent surface finishing with milling can be an alternative method. Second, features either impossible or difficult to be produced by conventional milling can be easily manufactured by this process combination. Such features include arbitrary internal channels such as conformal cooling channel. Third, the process combination enables the fabrication of parts with different materials.

Although the process combination demonstrates a great potential so far, process inherent problems such as warpage due to thermal stress [4] put a severe obstacle to its wide application. Therefore, a continuous process development regarding effective thermal management and increased speed are necessary. In this paper, it is investigated how far this process combination of welding and milling can be used as direct approach for the fabrication of mold inserts.

2. Process Principle and Equipment

The principle of 3D Welding and Milling is shown in **Fig. 1**. First, arc welding is used to build a layer by depositing single beads side by side. After the deposition, the top surface of the layer is machined to obtain a smooth surface for the further deposition with an exact thickness in z direction. The side faces of the layer, however, remain unmachined. The successive operation of deposition and face milling repeats until the part is completed. As a result of this procedure, a near net-shaped metal part is built. To remove remaining stair steps on the surface and to increase the accuracy, a surface finishing by milling is applied in the final stage. All the necessary steps take place with only one set-up in the machine, therefore errors caused by set-up changes are avoided.

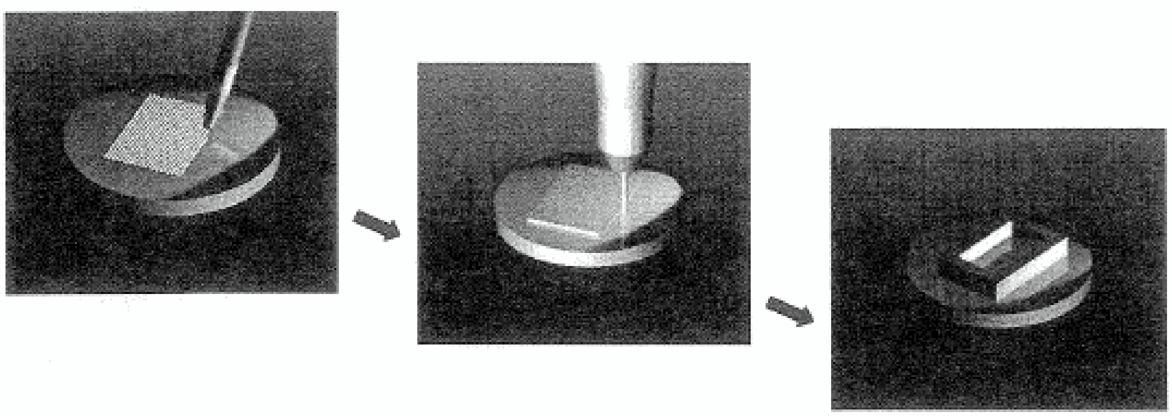

Fig. 1: Process principle of 3D Welding and Milling

In contrast to SDM, there is no support structure used in the 3D Welding and Milling process. Due to this process characteristic, the process is currently only able to produce metallic parts with 2 1/2 features such as injection molds.

The 3D Welding and Milling facility consists of a conventional 3-axis vertical milling machine and an arc welding equipment. To use different materials, the machine can be equipped with two arc welding guns. As wire material, mild steel or stainless steel is used. The substrate plate is mounted on the linear x-y table of the machine. This kind of configuration has an distinct advantage over other additive processes in that only a simple retrofitting of an existing 3-axis machine is required to realize the process instead of acquiring a special equipment.

3. Mechanical Strength and Microstructure of Welded Structure

In order to find out the mechanical value of multiple-welded structures, three tensile specimens according to the specification of ASTM were made and tested, **Fig. 2**. The values measured parallel to the building direction are 60 kgf/mm^2, whereas the used mild steel material has a tensile strength of 55 kgf/mm^2. This result shows that the strength of the multiple-welded structure is comparable to conventional mild steel, therefore an application in injection molding seems to be possible regarding the mechanical strength.

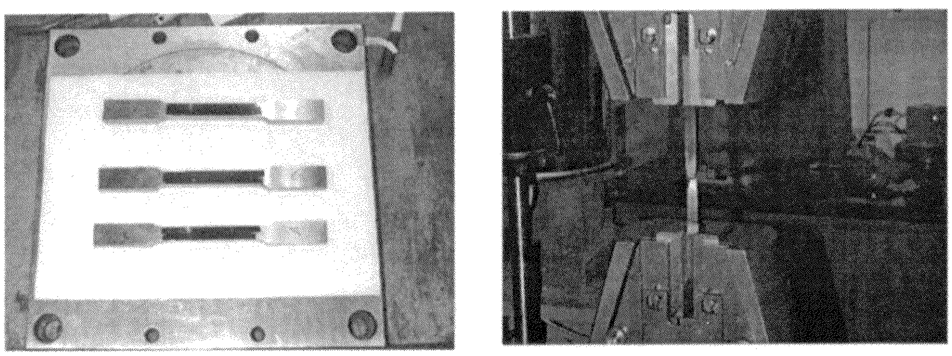

Fig. 2: Tension test specimens fabricated by 3D Welding and Milling

The analysis of microstructure shows a nearly full dense structure, as shown in **Fig. 3**. Only a few number of process inherent pores are recognizable in the microstructure. Most of the pores which are normally detected in the overlapping areas between the beads are removed during the face milling operation, therefore the number of pores is kept relatively small in the microstructure. The investigation also shows a change of the microstructure along the height of the part. This result is due to the changing heat condition during the deposition. Adjacent to the substrate plate, the microstructure is coarse because of the rapid heat dissipation into the cold substrate plate when the first beads are deposited on the substrate plate. With the increasing height, however, the cooling rate is reduced due to the decreased heat dissipating area which corresponds to the cross section area of the part and moreover, the accumulated heat from the previously deposited layers. Therefore, the grains take a globular structure.

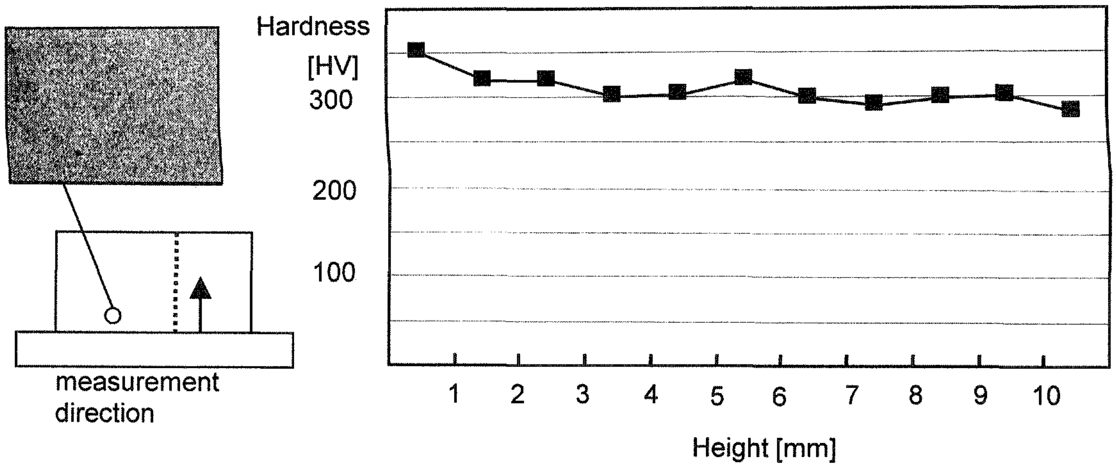

Fig. 3: Microstructure and hardness in the test specimen

The measurement of hardness proves the different microstructures along the height of the tensile specimen. As shown in Fig. 3, the hardness is decreasing from near the substrate plate to the top of the specimen. Starting from a hardness value of 331.8 HV at the bottom where mostly coarse grains are located, the hardness decreases to 280.5 HV at the top of the specimen. To avoid such a difference in microstructure, a preheating of the substrate plate can be used.

4. Experimental Results of Fabricating Injection Molds

To see whether this process combination is applicable for the fabrication of mold inserts, different sets of cavity and core inserts are selected as test parts and fabricated by the 3D Welding and Milling process. In **Fig. 4**, the fabricated parts of the core and the cavity inserts for cellular phone cover are shown with its CAD model. In **Fig. 5**, the lamp cover as test part and its injection molds are also shown.

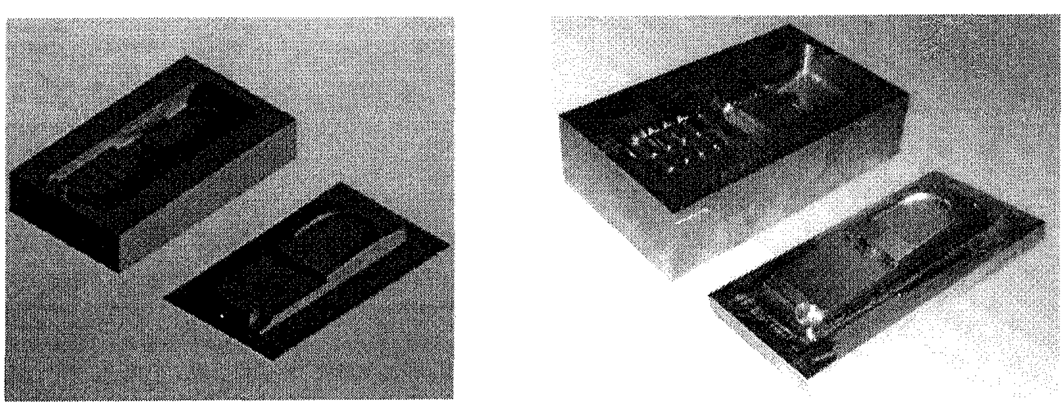

Fig. 4: CAD model and fabricated core and cavity inserts

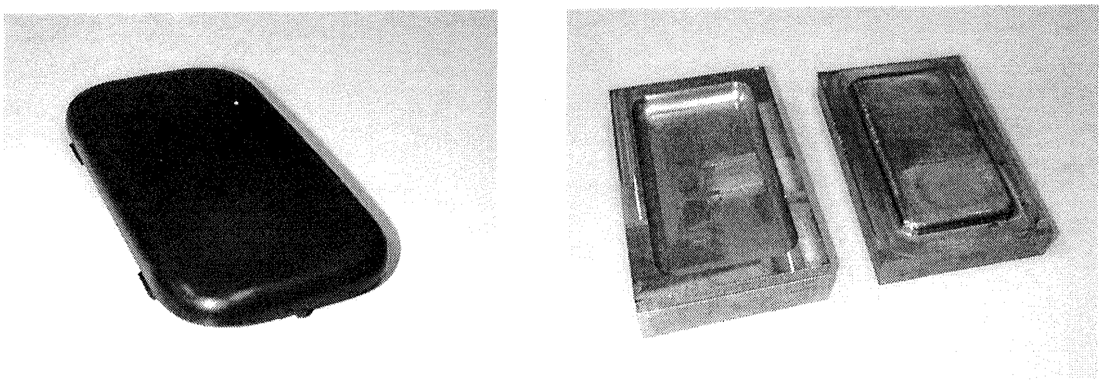

Fig. 5: Lamp cover as test part and its injection molds

The successful fabrication of injection mold inserts demonstrates the viability of the 3D Welding and Milling process. However, a further detailed experimental analysis regarding the accuracy and manufacturing time is required to verify its applicability for industrial usage.

The main advantage of SFF processes becomes evident when building parts with internal features. Among internal features, conformal cooling channel for injection molds is gaining an increasing importance for rapid tooling. The results so far indicate the positive effect of such conformal cooling channels on the lifetime of injection molds as well as on the quality of injected parts [5, 6]. Like 3D Printing and SLS processes, 3D Welding and Milling also enables building conformal cooling channels without using support structure when an appropriate value of offset for welding beads is selected. For the test purpose, a W–shaped conformal cooling channel is integrated in the mold insert, **Fig. 6**. The result shows the capability of 3D Welding and Milling to build the channels inside of the part. Due to the bead thickness, however, the limit of channel diameter is set around 20 mm.

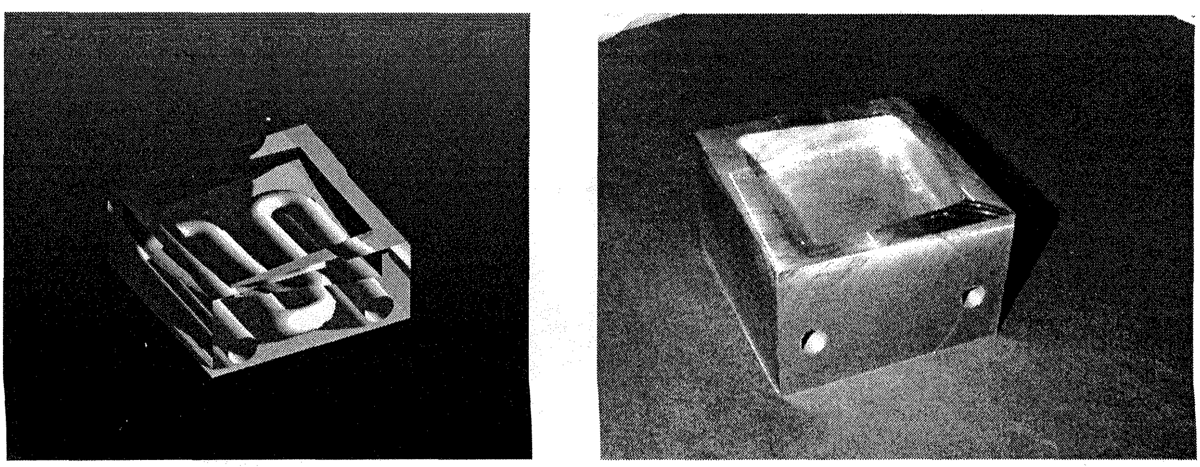

Fig. 6: Mold insert with conformal cooling channel

5. Thermal Management

The involvement of heat causes a thermal warpage of parts which is a common problem of additive processes [7]. To reduce the warpage, several possibilities can be taken into consideration. Besides the increase of thickness of the substrate plate, its preheating before the deposition is an effective method to reduce the warpage [8]. Moreover, preheating can be of benefit for a homogeneous microstructure. For these reasons, a heating plate is placed directly beneath the substrate plate to preheat it up to 200 °C.

The cooling rate after completing the deposition process exerts also an influence on the warpage. To reduce it, the part should be cooled down as slowly as possible. Therefore, the part is cooled down in the machine with the natural heat convection. When reaching the room temperature, the surface machining of the cooled part starts. In this machining operation, the total distorsion of the part then completely corrected.

Besides the experimental investigation, a theoretical analysis of the deposition process is performed to minimize the thermal distorsion. The analysis regarding the influence of different building directions on the warpage was performed in case of a single layer with a commercial FEM package ANSYS. The simulation indicates that the deposition with long beads causes more warpage than with short beads, as shown in **Fig. 7**. Consequently, when selecting building direction, the bead length should be taken into consideration.

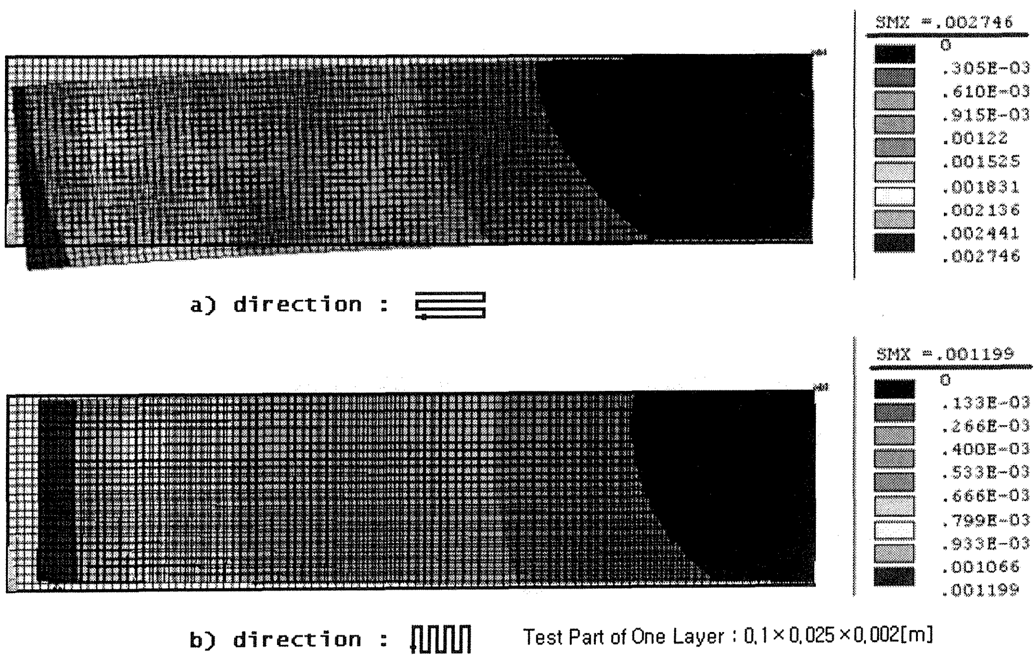

Fig. 7: Simulation result

6. Conclusions

According to the current state of the art, dimensional accuracy as well as surface quality of metallic parts and tools produced by SFF techniques are still far behind that of conventionally machined. To increase accuracy and surface roughness, a hybrid approach consisting of additive and subtractive technique called 3D Welding and Milling has been developed.

The multiple-welded tensile specimen fabricated by 3D Welding and Milling has a tensile strength of 60 kgf/mm^2 in the building direction which is comparable to the value of conventional mild steel. This value implies that the multiple-welded structure can be used as mold regarding the mechanical strength. The microstructure is nearly dense with a hardness value of 300 HV.

The successful fabrication of metallic parts, especially molds demonstrates that 3D Welding and Milling is an appropriate process to produce prototype molds. The combination of welding with milling operation not only increases both surface quality and accuracy, but it also gives a more manufacturing flexibility. Features like conformal cooling channels and multiple materials can be built.

A further process development should be focused on the increase of mechanical properties as well as effective thermal management to increase the quality of parts.

7. References

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