Stepwise Consolidation of Metal Powder by Localized Microwaves for Additive Manufacturing of 3D Structures

E. Jerby[a]*, Y. Meir[a], A. Salzberg[a], A. Levy[a], R. Rubio[b], X. Planta[b], B. Cavallini[b], and J. Ardanuy[b]

[a] Tel Aviv University, Ramat Aviv 69978, Israel
[b] ASCAMM Prívate Foundation, Av. Universitat Autònoma, 23 08290 Cerdanyola del Vallès, Spain
* E-mail address: jerby@eng.tau.ac.il

This paper presents local solidification of metal powder, irradiated by localized microwaves, as potential means for stepwise additive formation of 3D structures. Experimental results of metal powder solidified locally by microwaves are presented in forms of spheres and rods in a 1-10 mm range. The feasibility of extending solid structures by adding powder batches and solidifying them locally, as building blocks, is demonstrated as the basic action for a stepwise additive construction. The experimental observations and numerical results suggest that the enhanced electric field between the metallic particles excite electric discharges (micro-plasmas) which initiate the magnetic heating process. The experimental results lead to the development of localized microwave technique for stepwise formation of metal structures, as a low-cost substitute for laser-based technologies for rapid prototyping (RP) and additive manufacturing (AM) systems in >1-mm^3 resolution.

Keywords: Additive manufacturing, rapid prototyping, localized microwaves, metal powder

INTRODUCTION

Beside mass production in manufacturing industries, there is also a growing need for custom made products tailored for specific needs and produced therefore in small quantities or even in single units. Rapid prototyping (RP) and additive manufacturing (AM) techniques have been widely studied in the last decade [1] as techniques to fabricate physical models layer-by-layer. Rapid manufacturing (RM) is the application of layer manufacturing techniques for the creation of long-term usage models or end-use products. It is a one-step process in which tooling is eliminated thereby reducing production time and cost, by using laser for the manufacturing of metal parts [2]. This process is suitable for low volume production of materials difficult to process, and for the fabrication of complex parts of high aggregate values for the automotive and aerospace industries [3]. It also offers great potential for mass-customization, for example the fabrication of implants for the biomedical industry.

In the selective laser sintering (SLS) the object is created layer-by-layer from powder heated locally by a scanning laser-beam process [4, 5]. Lasers are applicable directly for metal powders in techniques also referred to as direct metal laser sintering (DMLS). While most of the known microwave-processing techniques are volumetric in nature, the microwave drill [6] is an example for an intentionally localized applicator. The underlying physical effect that enables the sub-wavelength focusing of the microwave energy by this applicator is the induced thermal-runaway instability [7], which enables for instance the localization of 2.45-GHz microwave heated zone within the material into a ~1-mm$^{\varnothing}$ spot in rapid heating rates (>300°C/s). However, unlike the remote laser operation, the localized microwave heating (LMH) [8] is a near-field effect which requires a close proximity (or even a physical contact) of the microwave applicator and the processed object.

In this study we apply the LMH concept to the local solidification of metal powders, as proposed by [9]. This technique enables also to solidify powders added to previously solidified substrates hence to extend them, as in the laser-based SLS technique. The microwave device could be simpler, cheaper, and smaller than the laser-based system, and hence the practical motivation to combine it with rapid prototyping and manufacturing systems.

MATERIALS AND METHODS

The localized microwave applicator is illustrated in Fig. 1a as a modified microwave-drill device, with a small batch of powder in front of it. The powder is heated and melted by the localized microwave energy hence it is attached as a *building block* to the underlying structure, as illustrated in Fig. 1b. The rest of the process could be similar to the existing laser-based rapid prototyping and manufacturing technologies, except that the laser used for the powder sintering is replaced by the *localized microwave* applicator. The powder feeding of the localized-microwave applicator could be performed either in the layer-by-layer method, as in the existing laser-based systems, or locally by a powder feeder incorporated within the microwave applicator. The latter represents a more efficient and faster method for selective powder deposition, and it could be implemented also in a coaxial structure integrated within the coaxial applicator shown in Fig. 1a.

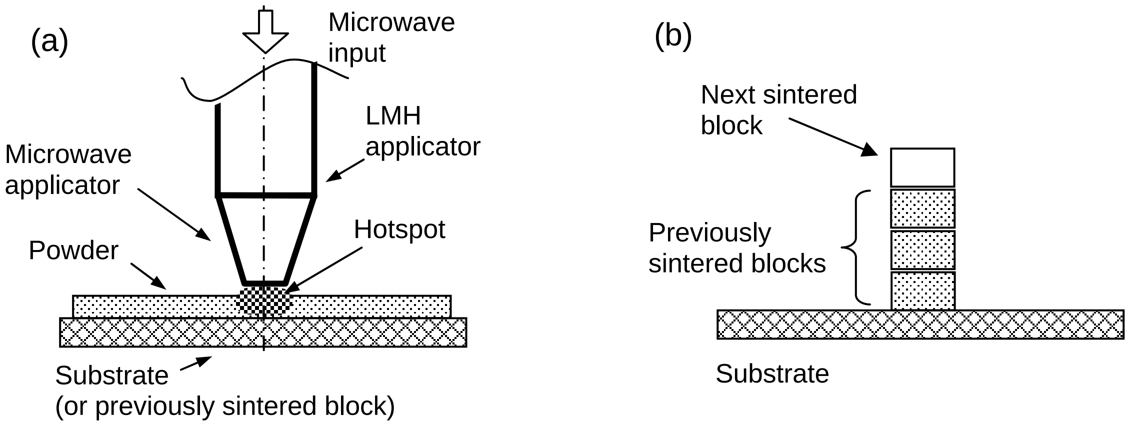

Figure 1. Conceptual illustrations of the stepwise powder consolidation: (a) A simplified scheme of the localized microwave heating (LMH) device, which concentrates the microwave energy into a small volume of the powder. (b) A stepwise construction of a 3D structure by additive blocks solidified and integrated with the previous ones.

The microwave system feeding the localized-microwave applicator may employ a standard magnetron-based industrial generator (2.45 GHz, 1-kW) or a lower-power solid-state system [10]. Additional components may include an isolator to protect the microwave source, a coupler to measure the incident and reflected waves, a tuner for adaptive impedance matching in the various operating conditions, and a controller. In general, the processed raw material could be metal, ceramic or plastic, in either a powder or solid form. Fine-grain bronze-based metal powder (DirectMetal-20) was tested in the experiments presented below. This powder type is used for laser sintering, in layer thickness of 20-60 μm for the skin and 60-80 μm for the core, and is characterized by sintered products that feature good corrosion resistance.

RESULTS AND DISCUSSION

Various experiments were performed in order to examine the feasibility of the localized microwave solidification concept. The first experiments were intended to verify our ability to solidify small quantities of powder in free space, and to form the basic building block such as spheres of ~2-mm diameter. The second stage was aimed at the solidification of larger elements (e.g. 10-mm diameter rods). The third-stage experiments tested our ability to extend existing solid bodies by additional amounts of powder sintered by localized microwaves, hence demonstrating the feasibility of the stepwise construction concept. These tests examined the basic steps needed for the construction of more complicated metal structures, and they demonstrated the feasibility of the proposed AM concept.

Most effective, in terms of duration, power, and hardness, was found to be the experimental setup in which the applicator was projected towards the powder as in Fig. 1a with an air gap of $0.5-1.0$ mm between the tip and the powder. In this setup, an instant plasma discharge was associated with the powder solidification. Figures 2a, b show rods produced in this technique in top and bottom views, respectively. The corresponding microwave power absorbed was ~300 W for ~1 s, indicating a ~40 J/mm^3 energy density absorbed within the solidified object. The spectral composition of the plasma emitted during the process (Fig. 2c) was examined using the material-identification by microwave-induced breakdown-spectroscopy (MIBS) technique [11]. Spectral lines of copper, nickel and tin are clearly identified in accord with the powder's composition. Figures 3a and b show a solidified rod of ~2-mm$^{\varnothing}$, extended from a ~3 to ~5 mm length, respectively, in a mould, by repeating the process twice. Figure 3c shows an extension in 7 steps in free space without a mould. Both examples demonstrate the feasibility of the fundamental additive step in a ~1-mm scale.

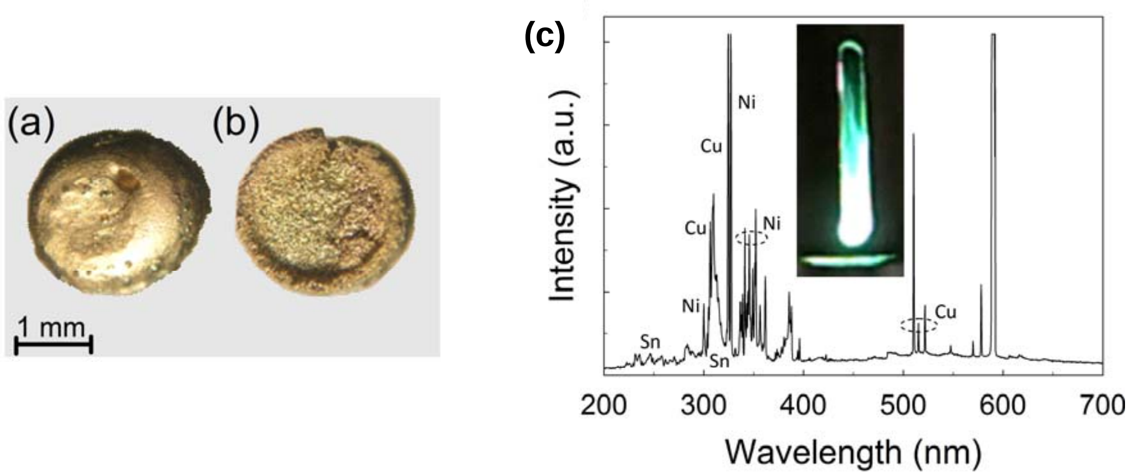

Figure 2. Metal rods solidified additively by localized microwaves from metal powder: (a) The upper and (b) bottom sides of the rod. (c) The optical spectrum of the discharge observed during solidification.

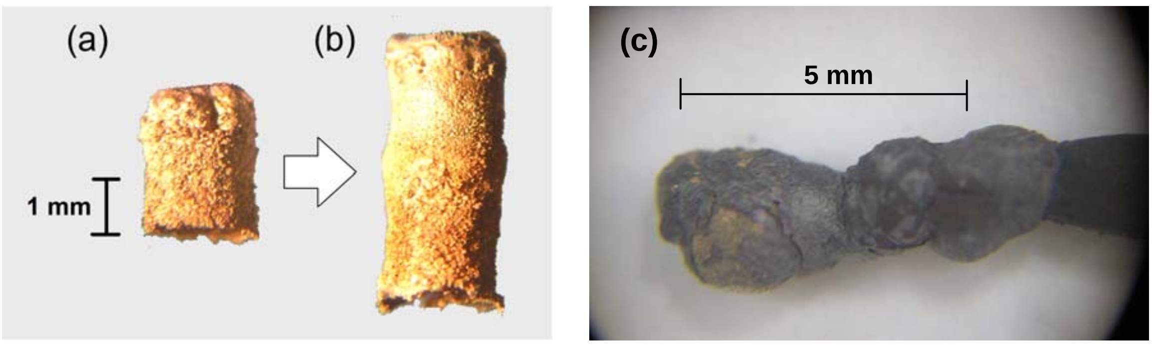

Figure 3. Additive solidification by localized microwaves: (a) A rod created from a powder batch (b) elongated by a second batch irradiated on top of it in a mould. (c) Extension in 7 steps in free space.

Figure 4 presents an accumulation of experimental results as shown for example in Figs. 2 and 3a, b in a chart of the process duration and number of tests vs. the transmitted microwave power. The histogram presents the number of success and fail operations in each power range, and the dots show the actual duration vs. power. On average, the successful cases in which the solidification occurred are characterized by a power level of 500-700 W in durations of ~1 second and shorter, which corresponds to an energy density of ~50 J/mm^3. These experiments demonstrate the feasibility of the localized microwave sintering as a potential means for RP and AM techniques.

Various analyses were performed in order to find the composition and properties of the metal powder after consolidation by localized microwaves. The first analysis was intended to characterize the chemical properties of the samples. This was done by both inductively coupled plasma (ICP) and energy-dispersive X-ray spectroscopy (EDX). The second test was aimed to find the hardness of the samples. The third test examined the product's density and hence its porosity. The hardness measurements of a typical sample obtained by the additive extension procedure resulted in ~160 HV with standard deviations smaller than 20. The hardness obtained by localized-microwave technique is comparable to the hardness obtained by laser sintering [4], and is actually slightly higher than the hardness obtained when the powder is processed by DMLS. The hardness depends on the remaining porosity and on the cooling rate after sintering; both are controllable to some extent in the localized-microwave technique.

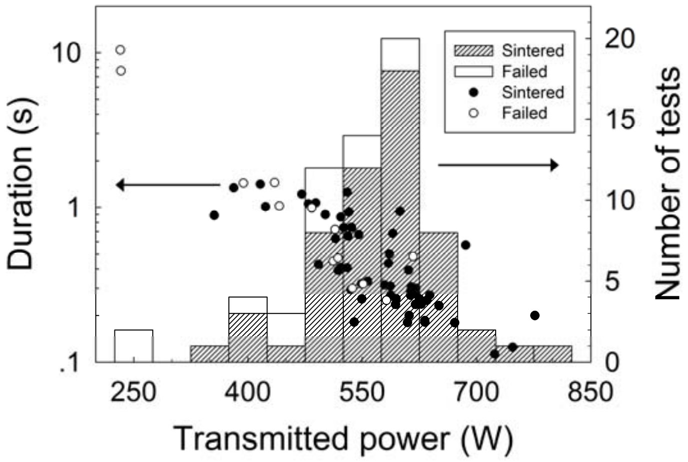

Figure 4. An accumulation of experimental results showing the process duration as a function of the microwave power, and the success and failure statistics in the various power ranges.

CONCLUSIONS

The results presented in this paper demonstrate the fundamental ability of a stepwise construction of solid structures by localized microwaves, hence providing a basis for a variety of potential additive techniques for 3D rapid prototyping and manufacturing. Future studies shall include the development of localized-microwave applicators, also with magnetic coupling capabilities, and experimental and theoretical studies with a variety of powders in different microwave frequencies. In particular, higher frequencies and shorter wavelengths (e.g. millimeter waves) may improve the localized consolidation accuracy towards the sub-millimeter range. The operation in shorter pulses at higher power may also improve the spatial resolution. In the stepwise construction level, further developments are needed to examine ways to build complex 3D structures by localized-microwave consolidation. Though the technology presented here is premature yet, one may expect, as proposed in [9], that its implementation in practical RP and AM systems will reduce significantly the cost and size, and expedite the throughput of these systems.

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