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BUILDABILITY OF MORTAR FEEDSTOCK IN MATERIAL EXTRUSION ADDITIVE MANUFACTURING

Mortar feedstock is extruded to form bead and it is selectively placed line by line in the material extrusion additive manufacturing. With respects to part building process healthiness, load-supporting ability of overlaid beads is emphasized as buildability. Buildability is primarily dependent on thixotropic properties of feedstock and vertical overlapping schedule. In the present study, water-to-binder (w/b) ratio was chosen as material aspect to assess buildability. Uneven bead shape evolution and premature failure were highlighted owing to low yield stress of high w/b ratio feedstock. Feedstock with optimum w/b ratio showed good buildability even at the interval time of 19 sec.

Keywords: additive manufacturing, mortar feedstock, shape retention ability, buildability, overlaying mode

1. Introduction

Construction-scale additive manufacturing [1] is emerging to enlarge design selectivity and improve productivity. Material extrusion AM technology [2] for mortar backbone building is overwhelming up to date. Mortar is a typical non-Newtonian fluid and particularly it is regarded as a Bingham fluid. In mortar flow, applied stress should be higher than yield stress which causes transition from elastic deformation to viscous flow. In addition, the viscoelastic behavior is dependent on time-dependent structural changes, which is called as thixotropy [3]. In the material extrusion additive manufacturing, processing ability and part healthiness are primarily dependent on thixotropic properties of mortar feedstock. Pumpability, extrudability, bondability and buildability are key-performance attributes [4]. Among them, buildability was assessed by changing water binder ratio in fresh mortar feedstock in the present study. Buildability is defined to the capability to sustain overlaid-bead shape under the incremental gravitational force which is encountered in layer-wise stacking of beads. In real situations, gravitational force incremental cycles are varied according to part designs and building strategies. Smaller parts and faster travel speeds decrease interval times for vertical overlapping. During the interval time, overlaid bead is at the state of rest and water drying and hydration reaction change internal structures. In this context, competition between thixotropic yield stress development kinetics [5] and applied force incremental cycle determines the buildability and corresponding building part healthiness.

2. Experimental procedure

Direct concrete building machine (KITECH, Republic of Korea) is composed of gantry subsystem and screw-type extruder subsystem. building volume is 2.5×1.5×1.0 m^3. Torque sensor and load cell are equipped to monitor extrusion process in the extruder. Mortar feedstock was composed of binders (ordinary Portland cement – OPC, fly ash – FA, silica fume – SF), fine aggregate (silica sand with a size range of 0.16-0.2 mm), water and other additives. Two types of mix proportions with different flowability were designed to evaluate buildability as summarized in Table 1. Raw materials were mixed for 6 minutes by a pan type mixer. After mixing, the flowability of mortar feedstock was evaluated via table flow test [6] before charged into the extruder. For both feedstock materials, weight extrusion rates were same though higher torque was measured for high yield stress one. Weight extrusion rate of feedstock was set to be 8.4 kg/min, which is equivalent to volume extrusion rate of 66,700 mm^3/sec.

Artifact test part design is shown in Fig. 1(a). Nozzle travel speeds were 50 mm/sec (a-1)(a-2), 75 mm/sec (a-3), 100 mm/sec

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TABLE 1

Summary of mortar feedstock characteristics

Feedstock	Mix proportions (kg/m³)					Flowability test result	Note
	OPC	FA	SF	Silica sand	Water	Table flow (mm)	
Mix 1	533	135	34	1054	215	163	High flowability (yield stress: 277.2 Pa)
Mix 2	585	156	39	1084	202	145	Low flowability (yield stress: 338.4 Pa)

(a-4), and 125 mm/sec (a-5)(a-6) and layer thickness was 15 mm. Removal of residual feedstock and preparation fresh mortar were carried out during 25-minute intermission period every 3-layer building. Uppermost bead width and accumulated part height were instantly measured just after each overlaying process. An accelerated buildability test was conducted for high yield stress feedstock as shown in Fig. 4(a). Interval time was 19 seconds.

3. Results and discussion

As overlapping number increases, morphological features of building part are shown in Fig. 1 Bead width is inversely proportional to travel speed by balancing volume extrusion rate and bead volume generation rate. For 125 mm/sec beads, they were fallen before overlaying 5th layer. As a matter of fact, severe deformation was already observed after overlaying 3rd layer. In the case of 100 mm/sec bead, collapse occurred after 5th layer. For both 75 mm/sec and 50 mm/sec beads, severe deformation was already observed after 7th layer Fig. 1(d-1) and it was further deformed above 2 hours as shown in Fig. 1(d-2).

Fig. 2 shows instant bead width and accumulated part height just after overlaying uppermost bead on part surface. From the viewpoint of volume conservation, calculated bead widths are 88.9, 59.3, 44.4 and 35.6 mm for 50, 75, 100 and 125 mm/sec respectively. For the first layer, bead widths are much wider than calculated ones. However, bead thicknesses are shorter than layer thickness. Cross sectional areas of flattened beads should be same to those of calculated beads because of volume conservation. As a matter of fact, volume extrusion rates from the measured widths and heights are 68924, 69008, 72909, and 68894 mm³/sec for 50, 75, 100 and 125 mm/sec respectively. It means that beads are further flattened after overlaying owing to low yield stress of high w/b ratio feedstock. From the 2nd layer, uncertainty arises from simultaneous flattening of uppermost layer and underlying layer. Nevertheless, inverse proportionality between layer thickness and bead width of uppermost bead is rational with respects to volume conservation under constant. In addition, repeatability of bead width and height variation is superior by comparing two walls (125 mm/sec (1) and 125 mm/sec (2)).

Premature failures for both 125 mm/sec and 100 mm/sec walls were due to the overlaying mode change from compression mode to free-falling mode. The transition is accelerated by increasing travel speed. Superficial bead width effects on bead overlaying are compared in Fig. 3(a) and (b). Significant bead width reduction is also observed for 50 mm/sec bead though it still undergoes compressive overlaying mode. To the contrary, free-falling mode transition is prominently observed during overlaying 4th layer for 125 mm/sec bead. Deflection of underlying bead results in significant deviation from tool path and deforma-

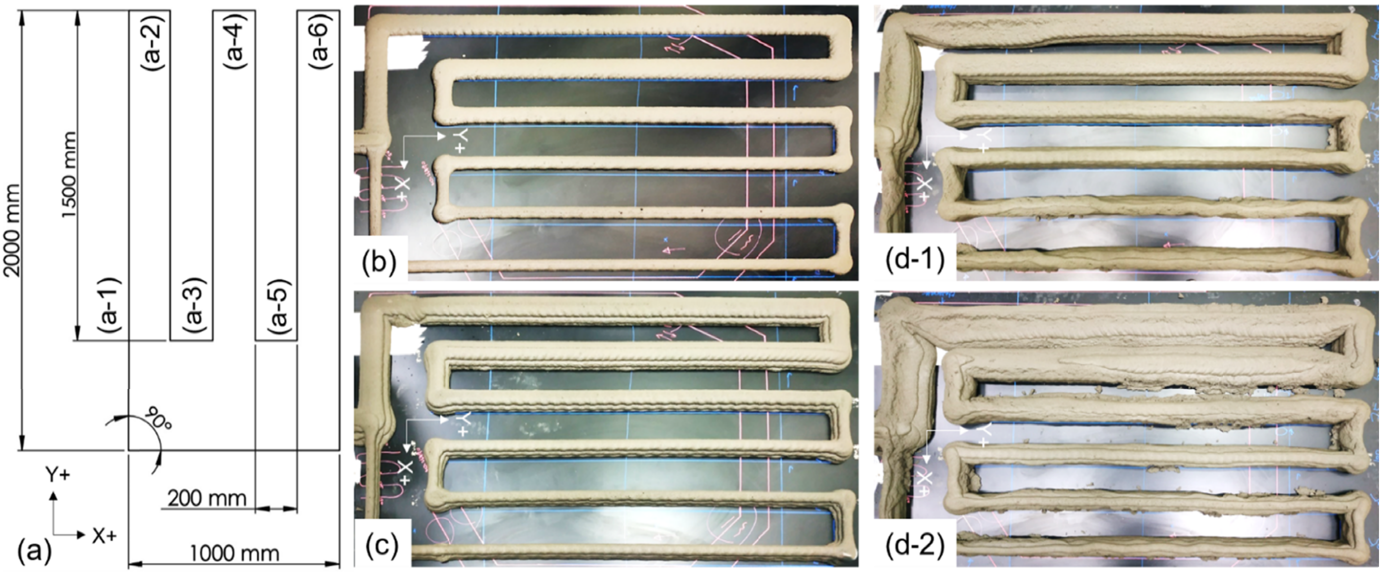

Fig. 1. Characteristic features of building part shape: (a) part design, (b) part after 3rd layer building, (b) part after 4th layer building and (d) part after 7th layer building

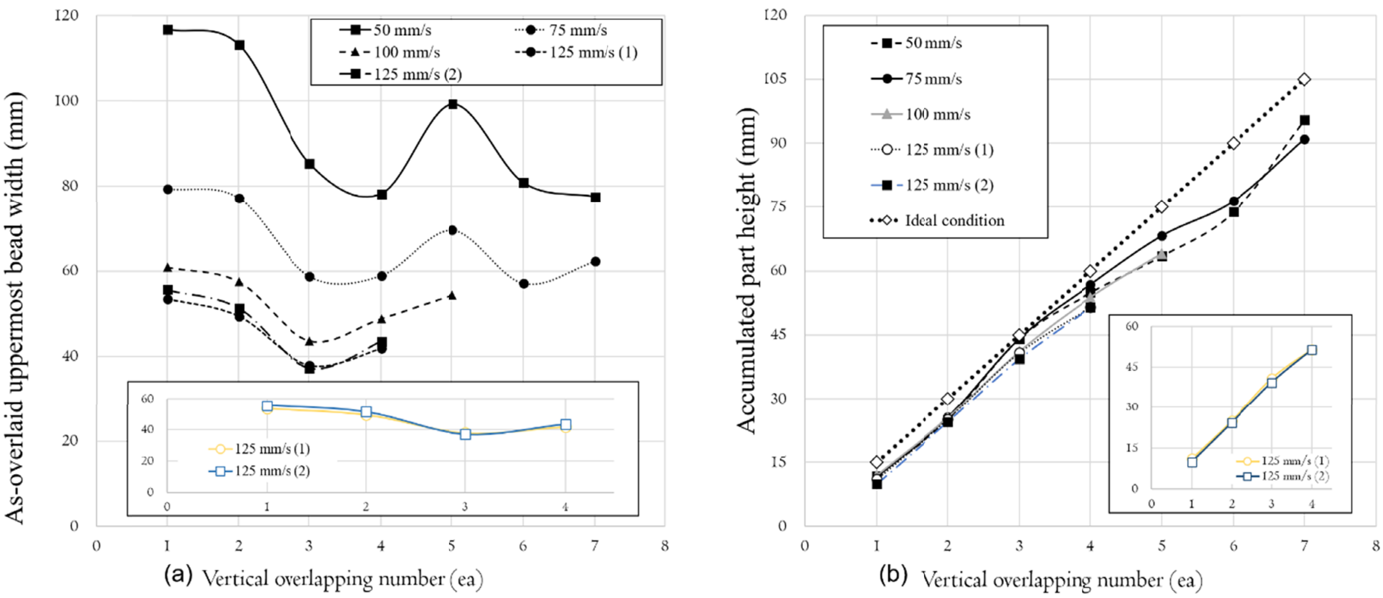

Fig. 2. Bead shape variations: (a) as-overlaid uppermost bead widths and (b) accumulated part height

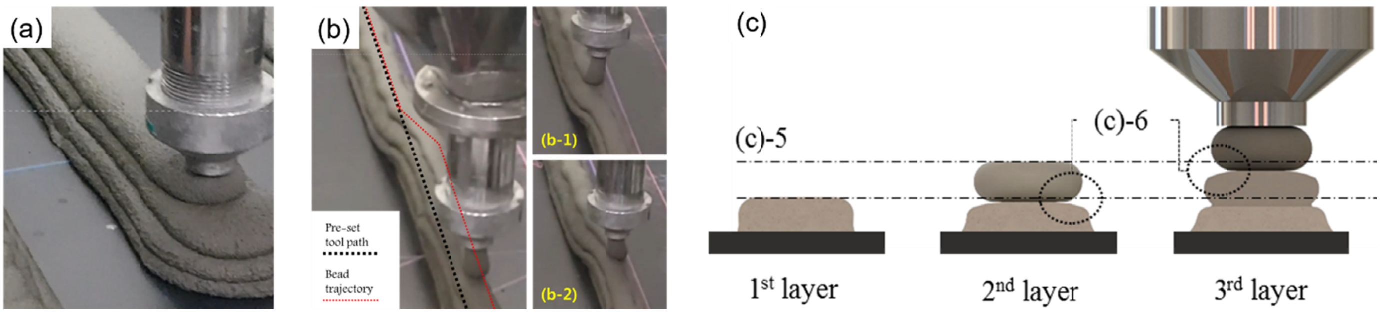

Fig. 3. Transition of overlapping mode via flattening of underlying beads: (a) travel speed of 50 mm/s, (b) travel speed of 125 mm/s and (c) schematic description of working distance change

tion. As a result, flowability as well as center of gravity change of overlaid bead result in instability of wall part.

To improve buildability, feedstock was modified (Mix 2) by lowering water-to-binder ratio within the constant weight extrusion rate of 8.4 kg/min. As an acceleration test, part model was designed as shown in Fig. 4(a). Interval time was much reduced to 19 sec at the same layer thickness of 15 mm. Part was stably built above 500 mm with continuous building.

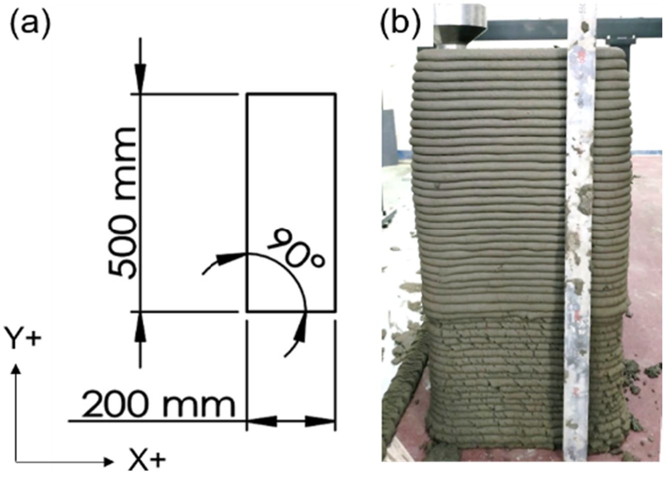

Fig. 4. Accelerated buildability test: (a) test model and (b) part from modified mortar feedstock

4. Conclusion

In the present study, effects of mortar feedstock formula on stability of bead morphology and buildability were investigated. Buildability is generally focused on part quality. However, effects of shape retention ability of underlying beads on processing ability is emphasized in the present study. To carry out layer-wise building, 3D model is sliced into 2D patterns with constant layer thickness. In the polymer material extrusion such as FDM and ceramic material extrusion such as robocasting, overlaid bead has equilibrium shape and sufficient strength within short time scales. Therefore, deformation of underlying beads is typically negligible and bead overlaying situation is sustainable during whole 2D pattern translation processes. However, flattening of underlying beads enlarge working distance of newly overlaying bead, which causes uncertainties of bead shape and stability of building part. It was verified that water-to-binder ratio is a critical attribute for buildability by accelerated buildability test. Improved buildability enlarges process window of material extrusion AM.

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