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DISTORTION CONTROL FOR P/M-BASED RAPID PROTOTYPING OF ADVANCED MATERIAL COMPONENTS

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ABSTRACT

Components of most powder-based Rapid Prototyping processes undergo shrinkage during powder consolidation. Distortion control approaches traditionally employed in Powder Metallurgy are not universally applicable to Rapid Prototyping because of the unique constraints and applications of this emerging technology. Additionally, the manufacture of advanced material components, with multiple constituent materials arranged in geometrically complex configurations and with varying compositions, poses a particularly strong challenge to known methods for dealing with non-uniform shrinkage. Manufacturing these advanced material components is the goal of an emerging powder-based Rapid Prototyping process known as Freeform Powder Molding (FPM)[1]. Distortion control is critical to the success of this process, as components undergo appreciable shrinkage during processing.

This paper provides an overview of powder-based Rapid Prototyping processes with particular emphasis on the Freeform Powder Molding process. Causes of distortion are examined and traditional distortion control approaches are reviewed. An experimental technique for characterizing process-induced distortion arising from non-uniform component shrinkage is developed, and experimental results are presented which highlight the often overlooked role of component geometry on distortion. The research presented here will ultimately lead to a computational system capable of automatically compensating for process-induced distortions.

1. INTRODUCTION

Non-uniform shrinkage during Powder Metallurgy (P/M) processing generally results in components which are geometrically distorted and fail to meet required tolerance specifications. Complex component geometry is a major cause of this shrinkage non-uniformity. Unfortunately, components of a number of emerging powder-based Rapid Prototyping (RP) processes undergo shrinkage during powder consolidation, and these processes are particularly well-suited for producing geometrically complex components. Process-induced distortions are especially troublesome to these RP processes because many conventional techniques for controlling distortion are not applicable. RP processes seek to efficiently transition computer-sensible representations of solid objects into the actual components themselves, and this is generally accomplished without any hard tooling such as the punch and die sets employed in conventional press-and-sinter P/M. This precludes the use of subsequent part-specific tooling to remedy distortion problems.

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[1] Patent pending. Freeform Powder Molding and FPM are trademarks of Manufacturing Solutions, Inc.

The nature of RP, with tight time constraints, small lot sizes (often one), and complex component geometries, makes dimensional control a formidable challenge. However, this challenge is further complicated when considering distortion arising in advanced material components. These may vary in composition throughout a component and may be fabricated from powders which are themselves prototypical and thus poorly characterized. Different powders will have different diffusion characteristics, thus inducing differential shrinkage within a sinter-body. In this situation, both component geometry and compositional variation will have a strong influence on distortion.

Rapid manufacturing capability of advanced material components is the ultimate goal of ongoing research into a process known as Freeform Powder Molding (FPM) [1]. FPM is an RP process being developed at Rensselaer Polytechnic Institute to directly produce structural components from powdered metals and ceramics. This process subjects green bodies to rather significant distortion during consolidation, and controlling this distortion is particularly complex given the ultimate goal of fabricating components with spatially tailored material composition. Dimensional control strategies well-suited for powder-based RP processes — and RP in general — have not been found in the literature.

Surprisingly little attention has been given to the issue of distortion control for powder-based processes by the RP community. Some have identified specific material systems which exhibit little dimensional shrinkage during sintering [2, 3]. However, most research appears to be focused on understanding distortion in the popular Stereolithography (photopolymer-based) process [4, 5]. Abating shrinkage seems to be the logical first choice for distortion control; however, this may not always be practical. It may place unacceptable constraints on the otherwise wide variety of materials which can be processed, and properties which can be obtained, via powder processing. An alternative is to adjust the shape of the "green state" component so that after consolidation is complete (accompanied by process-induced distortions) a component with the desired shape is produced. One group generically advocated the use of force-based techniques to discover inverse models for dealing with distortion in a non-powder-based RP process [6]. However, few results were presented and this work was apparently discontinued [7].

Preliminary results presented in this paper will show that even in the presence of a locally uniform shrinkage in a homogenous sinter-body, appreciable distortion can arise for components of complex shape. Before exploring some origins of distortion and discussing preliminary results, it is beneficial to review some characteristics which make RP — and the FPM process in particular — rather unique.

2. RAPID PROTOTYPING & SOLID FREEFORM FABRICATION

Rapid Prototyping (RP) originally described the "fast production of prototype models" [8]. It was applied early in the product development cycle to make concept prototypes from non-structural model materials; however, this technology is now finding application in nearly all phases of the product development cycle — including manufacturing.

The key point that differentiates RP from traditional manufacturing processes is that RP makes intensive use of information to drive a process [9]. Consequently, it remains highly flexible and thus able to fabricate a wide variety of complex parts in relatively short times. Product specifications are typically provided in the form of a three-dimensional computer-aided design (CAD) solid model, and some process or set of processes which are numerically controlled are then used to quickly generate the required component.

A particular sub-class of RP processes, known synonymously as Solid Freeform Fabrication (SFF) [10] or Solid Freeform Manufacturing (SFM) [11], have received substantial attention in the last decade. These additive processes require no part specific tooling or human intervention, and are driven directly from CAD model information [10]. Most build up material in discrete layers to form a final three-dimensional component, and subsequent operations may be employed to improve the properties of the resulting parts.

Several case studies have highlighted the benefits of Solid Free-form Fabrication (SFF) for engineering and medical applications [12, 13]. Form and fit prototype parts, fabricated by commercial SFF systems, have been used in iterative design evaluation, human factors analysis, marketing efforts, early tooling design and assembly sequence planning — significantly reducing development time and cost [14]. Most reports cite very favorable cost and time savings in the range of 30-95% when comparing SFF techniques to conventional prototyping methods [12, 14-16]. Creating molds and tooling using these SFF parts as patterns has resulted in similar savings for the indirect manufacture of structural parts which more closely match properties desired in end-use components [17, 18].

RP technologies are being developed with the goal of directly manufacturing structural components which have properties meeting or exceeding those of conventionally produced components [1, 19-23]. Many of these processes have their origins in powder processing.

2.1 Powder-based Rapid Prototyping

Powder-based RP processes are extremely versatile and can operate on an exceptionally wide variety of materials. Some processes aim to directly manufacture functional end-use components, while others are best-suited for creating tooling which can subsequently be used to manufacture desired parts [1, 24, 25].

Selective Laser Sintering (SLS) uses laser energy to selectively fuse successive layers of powder which, although initially included only polymers or waxes, now can use special binder coated metal powders [21]. Additionally, other researchers have directly processed metal powder using the SLS principle [26]. Three-Dimensional Printing selectively inkjets a liquid binder onto a powder substrate, and after the binder solidifies the resulting green-body can be de-bound and sintered [24]. The Freeform Powder Molding process, as is overviewed below, also deposits various powders which can subsequently be consolidated to form a desired component [1].

Many other RP processes either consume powder or are being adapted to support the creation of powder-based components. Mask Deposit Recursive (MD*) [22] and Directed Light Fabrication (DLF) [23], for example, both consume powder although material does not remain in the solid state throughout processing. Laminated Object Manufacturing is being adapted for processing ceramic green sheets [27] and other similar processes are also being developed [28]. Fused Deposition Modeling is being adapted to use powder-loaded thermoplastic filament [29, 30]. Others are pursuing similar processes which either use heat [31] or photo-initiated reaction [32] to solidify a selectively deposited powder slurry. More direct adaptations of the photopolymer-based Stereolithography process are also being investigated [33].

There is apparently substantial interest by the RP community in realizing the many potential benefits associated with powder processing. The manufacture of advanced material components is of particular interest since the FPM process has some unique capabilities which makes it well-suited for manufacturing such components. However, to one degree or another, all these processes share the common problem of process-induced distortion given geometrically complex components.

2.2 Freeform Powder Molding

One powder-based RP process of particular interest is Freeform Powder Molding [1]. A brief overview of the layer-wise additive FPM process is provided to clarify subsequent process-induced distortion experiments which draw on concepts of this process.

The layer-wise FPM process combines precise material handling with established powder consolidation techniques to directly realize structural components without any hard-tooling as typically required for P/M. The fundamental principle underpinning FPM is that different powders have different diffusion kinetics and will therefore respond differently to identical thermal, chemical, and mechanical conditions. By selectively arranging two different kinds of powder within a confining volume, it is possible to create a part whose geometry is defined by the interface between the powder which consolidates at prescribed conditions and the powder which does not. Powder which consolidates is termed *part powder*, and powder which does not consolidate at these same conditions is termed *tool powder*. Figure 1 illustrates how an FPM component could be fabricated by successive layer-wise additive deposition of selectively located powders.

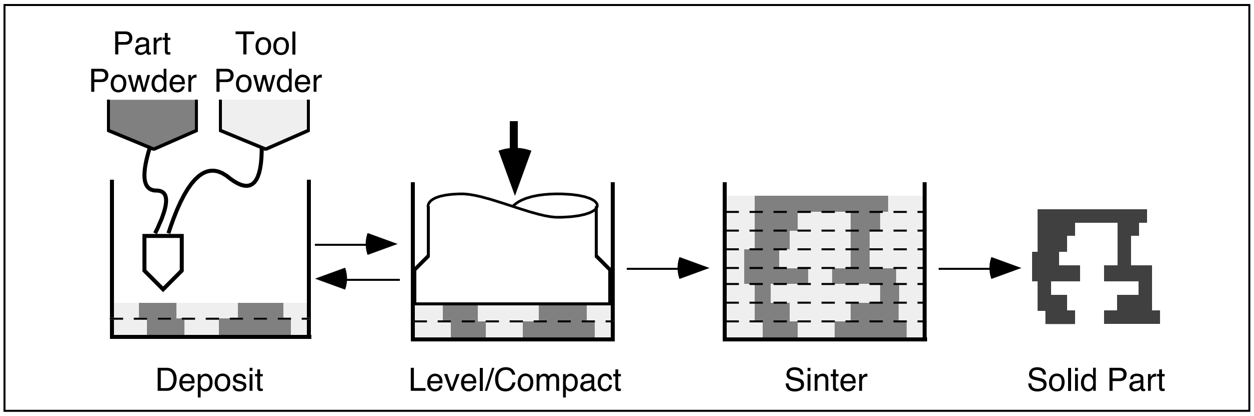

Figure 1. Layer-wise FPM Illustration [1]

Proof-of-concept has been demonstrated for a variety of metal powders, including: copper, iron, nickel, 304 stainless steel, and titanium. Consolidation has been performed both by loose powder sintering and hot isostatic pressing. Additional process details can be found in [1] and analysis of the interface between part and tool powders is presented in [34].

Since FPM relies on the part powder/tool powder interface to define component shape, it is not possible to remove the part mass prior to consolidation. This causes some rather interesting process-induced distortion behavior which differs from that found in traditional press-and-sinter P/M components. As FPM is developed and components with spatially tailored material composition are fabricated, process-induced distortion will undoubtedly become more challenging to control. Consideration of some origins of distortion, followed by an examination of known distortion control techniques, will prove helpful when evaluating a means for coping with non-uniform shrinkage experienced by the FPM process.

3. ORIGINS OF DISTORTION

Geometric distortion in P/M components arises from non-uniform shrinkage. Shrinkage gradients which are too severe can also lead to crack formation during sintering. Many factors can cause non-uniform shrinkage during consolidation and one has to appreciate the complexity of the material and its influences. These factors include powder characteristics, density gradients, thermal effects, and component geometry. However, non-uniformity introduced by the geometric structure of the sinter-body is of particular interest in this and related research, yet it appears rather poorly documented in the literature.

3.1 Powder Characteristics

Powder characteristics can play a significant role in P/M distortion development. Both powder size distribution and morphology affect local shrinkage behavior. Powders generally range in size across a rather wide distribution unless special measures are taken to obtain a narrow size distribution, and they may assume a variety of shapes based on the atomization processes employed and properties of the material.

Since powder surface energy per unit volume is inversely related to powder particle diameter, smaller powders sinter faster than large powders [35]. Consequently, any segregation in powder sizes throughout a component can result in non-uniform shrinkage behavior as one region of the component densifies more rapidly than another region. Careful attention must be given to this issue in FPM when using powders with a wide size distribution. The deposition techniques used to construct the powder mass must not cause a spatial separation of dissimilarly sized powders. Percolation, which can stimulate particle size segregation, must also be avoided through careful handling of the as-deposited (pre-consolidated) powder mass.

Sintering behavior is also related to particle morphology, and similar consideration must be given to any process operations which cause different regions of a component to be comprised of morphologically dissimilar powders. Fortunately, powder morphology does not typically vary as widely as powder size for a given powder, since powders atomized by one process with specific atomization parameters tends to result in powders of similar shape. Yet, even if particles are uniformly distributed based on size and their shape does not substantially vary, non-uniform shrinkage may occur due to powder orientation.

Non-symmetric particles may assume a preferred (non-random) orientation within a powder mass, and this may cause anisotropic sintering shrinkage. Any anisotropy within the powder particles themselves may also lead to non-uniform shrinkage if these particles assume an ordered texture type, rather than one which is uniformly random. FPM operations must seek to minimize the development of any preferential orientation of powder particles within a sinter-body.

Related difficulties may be avoided by selecting narrowly-sized powders with a rather uniform, symmetric morphology. To date, most FPM research has involved powders which are of spherical shape but a rather wide size distribution. Experimental evidence suggests that FPM components have not experienced substantial anisotropic behavior due to a non-uniform distribution of powder characteristics throughout a component.

3.2 Density Gradients

The fact that powder density gradients within a compact can lead to non-uniform shrinkage has been well documented [36]. Compact density is related to the particle coordination number, packing arrangement, and contact area shared with adjacent particles. These factors, in turn, affect the rate at which solid state mass transport proceeds at these particle contacts during sintering. When bulk transport sintering mechanisms are active, this mass transport is responsible for an effective shortening of particle centers which leads to overall compact shrinkage [35]. It is not necessary that contacts be uniform in number, spatial relationship, or area throughout a component in order to obtain uniform shrinkage.

Collections of powder particles take on an aggregate behavior which results from the many individual interparticle shrinkage interactions. It is important that density be uniform throughout a component because sintering rate varies inversely with green density [35]. Such differences in sintering rates can result in component distortion.

This distortion is particularly common for die compacted parts due to die wall friction effects. These interfacial friction effects lead to non-uniform pressure distribution throughout a compact which cause density gradients in the final component. Some methods, such as layer-wise compacting, have been demonstrated to significantly reduce density gradients within components [37, 38]. Additionally, lubricants can be used to reduce some of the interparticle and particle/die-wall friction effects which serve to inhibit uniform compaction [39].

3.3 Thermal Effects

The physical processes underlying sintering, such as diffusion, grain growth, and pore growth, are thermally activated processes; consequently, non-uniform temperature distribution in the sintering material can result in non-uniform final powder consolidation [35]. This will cause distortion in the final sintered product. This is an important consideration because during initial stage sintering, temperature has an exponential relationship to neck growth, while time has a relatively small effect [35]; therefore, sintering can be sensitive to small variations in temperature, particularly early in the sintering cycle.

Non-uniform heat transfer into the sinter-body powder could result from non-uniform energy introduction into the sintering furnace hot-zone. However, it could also be caused by variations in the insulating efficiency of material surrounding a part, or the effects of thermal conduction differences within a part of varying geometry. Conduction within powders is directly proportional to density, so non-uniform shrinkage due to component density gradients will be further enhanced by the thermal gradients they cause. It is important to consider the sintering rate sensitivity, with respect to temperature, of the part powder so that a suitable sintering schedule can be selected.

A potential problem with FPM is that the tool powder has a different thermal conductivity than the part powder. Even in the presence of a uniform hot zone, part powder surrounded by appreciable volumes of tool powder may not reach the sintering temperature as quickly as part powder near the periphery of the powder mass. The recourse in this situation is to reduce the heating rate, so that the powder mass has more time to transfer heat and equalize any thermal gradient which may exist within the sinter-body.

In addition to sintering, two other thermal effects are worthy of consideration. Residual stresses may be introduced during cool-down which can impart strain on components and serve to distort them. This can most likely be avoided by reducing the cooling rate during sintering cycle cool-down. In P/M processes employing binders, the binder removal process may contribute to overall component dimensional change [40].

3.4 Component Geometry

Distortion can result from constraints on the sinter-body during consolidation [41]. Forces external to a region of sintering powder can either retard or enhance the consolidation process. This may create regions of varied density within a component due to differential consolidation, which may cause further non-uniformities in sintering rate throughout a part. The complexity of the material interaction during consolidation must be appreciated; however, little research has been found which addresses sintering behavior on the macro-scale [42].

It is sometimes possible to ignore the effects of sinter-body interaction with its external environs for some part classes due to their high degree of symmetry. Shrinkage can be accounted for by simply scaling component geometry. If components are highly symmetric but constrained, these constraints may simply factor into the apparent shrinkage without causing a perceptible non-uniform shape change. In this case, it may still be possible to compensate for shrinkage by scaling alone. On more complex components, particularly those with concave geometries and wide variation in part surface to volume ratio, external forces can introduce non-uniform shrinkage within a component. Some research on in-situ monitoring of sintering shrinkage highlights this using parts of relatively simple geometry of two concentric rings attached by three spokes [43]. The outer ring apparently distorts from its original circular shape due to draw-in forces near the spokes.

Amaya finds that “part movement is a primary mechanism for part deformation (distortion)” and suggests the use of low friction supporting fixtures during the sintering process to reduce distortion resulting from part movement [41]. While this research focused on metal injection molding (MIM), it is generally applicable to the sintering of any self-supporting green body. The key point of this approach is to employ the sintering fixtures to allow the part to conform, rather than deform, to a particular shape. It is unclear if frictional effects due to sinter-body supports are the only cause for shape-related non-linearities during consolidation.

FPM is quite well-suited for producing geometrically complex components, and the resulting parts may be subject to distortion. Correcting these distortions by using sintering fixtures is unacceptable given the definition of RP and the mission of FPM. A method for controlling distortion which does not require part-specific tooling is desirable.

4. CONTROLLING DISTORTION

There are two basic philosophies for controlling distortion so that components which meet required dimensional specifications can be obtained from P/M processes: *eliminate* or *compensate* the distortion. Eliminating process-induced distortion is certainly the most widely used approach, and when it is practical, offers an ideal solution. This can be done by modifying processing conditions or the material itself. It may also be accomplished using secondary shape altering operations to remove distortion from a component which has emerged from the sintering process without the required dimensions. Compensating for distortion involves altering the initial powder configuration such that after distortion is imparted, a component of required dimensions results. Consolidation process repeatability is critical for application of this approach.

4.1 Distortion Elimination

Eliminating distortion by process alteration is often not without cost and may sometimes be impractical. In some instances, sintering temperature can be reduced to lessen the amount of densification which takes place [44] . This reduces the severity of component distortion at the expense of component final density. To completely eliminate distortion may require that very little sintering is allowed to occur. Control of other process variables, such as compaction pressure, sintering atmosphere, or sintering schedule may be useful in attempting to eliminate distortion. Low friction supporting fixtures have been used to reduce distortion resulting from part movement [41]. Component density variations which cause distortion have also been reduced by employing layer-wise compaction in press-and-sinter P/M [37, 38].

Alternatively, the material may be altered when attempting to eliminate distortion. Powder size may be increased to reduce the rate of sintering and to reduce non-uniformity in shrinkage. It may also be possible to tailor the powder composition so that shrinkage is reduced. It is reportedly quite common to alter the powder loading in Metal Injection Molding feedstock to “tweak shrinkage” behavior [45]. It seems that whether altering process or material, properties are frequently compromised in order to manage distortion.

An alternative is to eliminate distortion after the sintering cycle is complete. When using press and sinter P/M, a secondary pressing operation known as sizing may be performed to correct for distortions introduced during sintering [36]. Specialized dimensional correction procedures, such as coining or burnishing, may also be used for certain component geometries [46]. These all require specialized tooling and are not well-suited for eliminating distortion introduced by RP.

Post-machining operations may be used to meet critical component dimensions in cases where the material is machinable [46]. This approach may prove useful in realizing required tolerances from RP processes, and it is certainly more applicable than processes requiring specialized metal forming equipment. However, one of the main benefits of RP is the avoidance of delays associated with conventional manufacturing operations which require substantial human intervention. Part fixturing and tool set-up, particularly for part quantities of one, represents a significant additional cost to the RP endeavor. An alternative which does not require this human intervention or degrade component properties would be beneficial.

4.2 Distortion Compensation

When process-induced distortions are systematically repeatable, compensating for the distortions offers an alternative to attempting to eliminate them. This approach has been taken by P/M practitioners using rule-of-thumb shrinkage compensation measures, and it is illustrated in Figure 2.

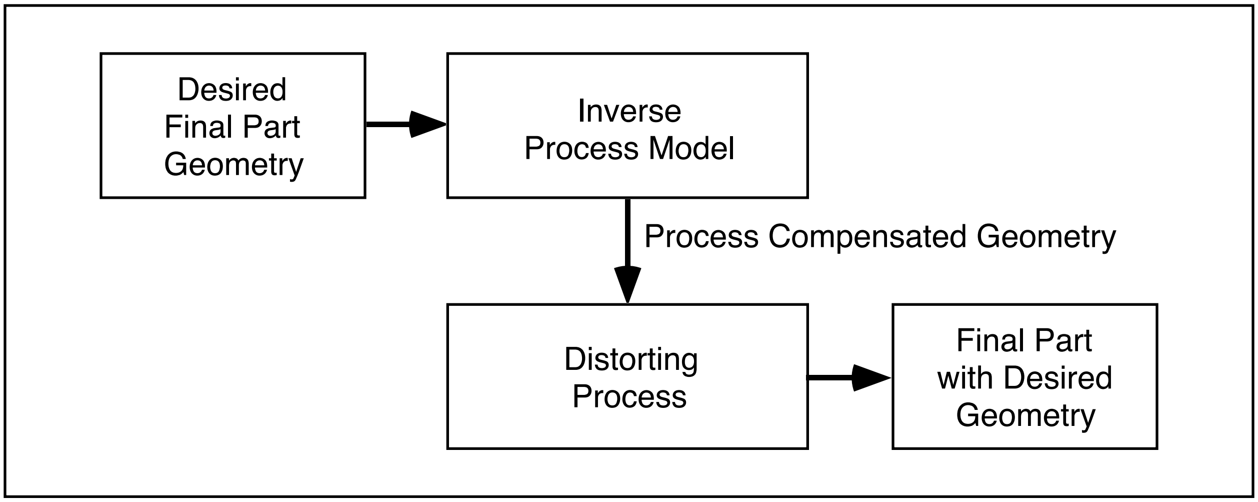

Figure 2. Distortion Compensation

Processes with appreciable shrinkages in the range of 20 to 25%, such as Metal Injection Molding (MIM), have been successfully compensated and used to produce components with tolerances of +/- 0.003” to 0.005” (0.08mm to 0.12mm) for many years [36]. Recent reports cite tolerances of

0.3% nominal as typical for commercial MIM components despite the presence of considerable shrinkage [47]. Similar compensation approaches have been used in the metal casting industry, employing tools such as the pattern maker's shrink rule [48]; however, the percent shrinkage is generally much smaller than for powder-based processes.

Components that possess a high degree of symmetry may be effectively compensated by dimensional scaling alone. In fact, most of the literature appears to characterize part dimensional change with a single "shrinkage" parameter irrespective of geometric complexity. For example, green state Metal Injection Molded components in one report are stated as being at least 15% oversize relative to final desired dimensions [41]. However, components of more complex geometry may experience non-uniform shrinkage and therefore require more complicated corrective measures. This is often achieved using manual, iterative trial-and-error tooling modifications which are both costly and time consuming to apply [49]. It relies on skilled artisans to correctly adjust each tool-set, and this may not be repeatable from part to part or artisan to artisan. While potentially acceptable in applications where this cost, and high level of human interaction, can be amortized across tens of thousands of components, this approach is too costly for small lot-size applications common for RP.

An automated distortion compensation approach is sought which will provide repeatable performance for complex component geometries producible by emerging powder-based RP processes. This may be achieved by closing the loop and iteratively using error information to converge on an initial green-state shape which yields the desired final component shape after processing. Similar closed loop process control techniques have been applied to the complex sheet metal forming task [50]. Alternatively, model-based techniques may be useful for predicting how a process will alter preform shape. This will require definition of a model and its parameters, either based on fundamental powder properties and process parameters, or based on observation of component behavior at a higher-level. While much research has been conducted on sintering behavior at the particulate level using highly idealized material systems, there appears to be little research available to connect this to overall sinter-body shape change during processing. Consequently, extracting model parameters from behavioral observations on "real sinter-bodies" appears attractive.

Regardless of the compensation method ultimately chosen, it is necessary to develop a means for observing and evaluating the distortion which takes place during consolidation of shapes with complexity typical of those which will be fabricated by powder-based RP techniques.

5. PROCESS-INDUCED DISTORTION CHARACTERIZATION

Whether the goal is to eliminate or compensate process-induced distortion, it is necessary to develop analytical techniques for characterizing sinter-body behavior in a manner consistent with the objectives of RP. A relatively low-cost, easy-to-apply technique has been developed for extracting distortion information from components subjected to FPM processing. Two-dimensional distortion information is extracted from samples using a uniform grid fabricated on the sample's planar surface. Images of this grid are captured before and after consolidation, and image processing techniques can be used to extract the distortion field for a particular component. This information can be used to assess the severity of distortion, serve to provide feedback to an automated but iterative distortion compensation function, or be used to characterize material distortion behavior for use by a model-based compensation technique.

5.1 Experimental Technique

Since layer-wise FPM process hardware is still being developed, a variant of the freeze-molding technique [49] was developed to fabricate two-dimensional shapes of interest with a fine grid placed on their top surface. The technique is relatively simple to apply and easily practicable without costly equipment. However, it is generally best suited to fabricating single material components. The same characterization concept will apply to advanced material components which are fabricated by a different means, such as layer-wise FPM.

Molds can be constructed from easy-to-machine plastic, which can be cut using an inexpensive bench-top numerically controlled milling machine. Molds for the experiments reported here were fabricated from two half-inch plastic sheets which were later bolted together. The desired component shape is machined into one sheet using a 2° draft angle to facilitate component release, and the other sheet is used to contain the powder and has a fine grid machined into its surface. Variation in mold fill height, either from mold-to-mold or throughout a single mold, will not be reflected in subsequent measurements because the grid is molded on the part face with the greatest cross-section.

Powder is mixed with a liquid carrier at room temperature. The mold is filled with the powder/carrier mixture and subsequently cooled to cause the mixture to solidify. The mold is then allowed to warm so it expands slightly and the frozen powder mass is ejected from the mold. The still-frozen, but warming, powder mass is re-frozen so it can withstand subsequent handling while it is encased in a second supporting "tool powder" as consistent with the FPM process concept described previously.

The top surface of the part is left exposed temporarily so it can be photographed. The resulting powder mass is then covered with tool powder and processed to drive off the carrier so that two, spatially discrete, loose powders are confined within a vessel suitable for sintering. After the sintering cycle, tool powder which remains loose atop the part is carefully brushed away to expose the resulting part with its grid. The resulting grid, which is often distorted, can be photographed and a comparison made between corresponding grid intersections (and grid/part edge intersections) of this and the original frozen green body. Other powder shaping methods, such as Metal Injection Molding or Slip Casting, may be suitable for creating similar evaluation grids on more complex component shapes. A similar technique has been successfully applied to metal flow studies in deformation processing [51].

At present, conventional photographic techniques are used to capture part shape information. A copy stand arrangement is used to ensure consistency between photographs so that any distortion introduced by camera optics is equivalent in images of both pre- and post-sintered components and is therefore canceled. Additionally, scale bars are used to ensure enlargement consistency between both photographs. Part shapes are captured from the resulting photographic prints using a flatbed image scanner. Grid crossings and grid/part boundary intersections can then be manually digitized or extracted using automated image processing techniques such that the distortion experienced by the component can be characterized.

5.2 Results & Discussion

Many components have been fabricated using the experimental freeze molding technique described above. Simple, convexly shaped parts and complicated parts with concavities have been produced. Although this process relies to a large extent on manual operations, results appear consistently repeatable.

Observation of distortion experienced by a part shaped like an elongated U provides an example of how component geometry affects non-uniform shrinkage. Figure 3(a) shows an as-molded part and Figure 3(b) shows this same part after sintering.

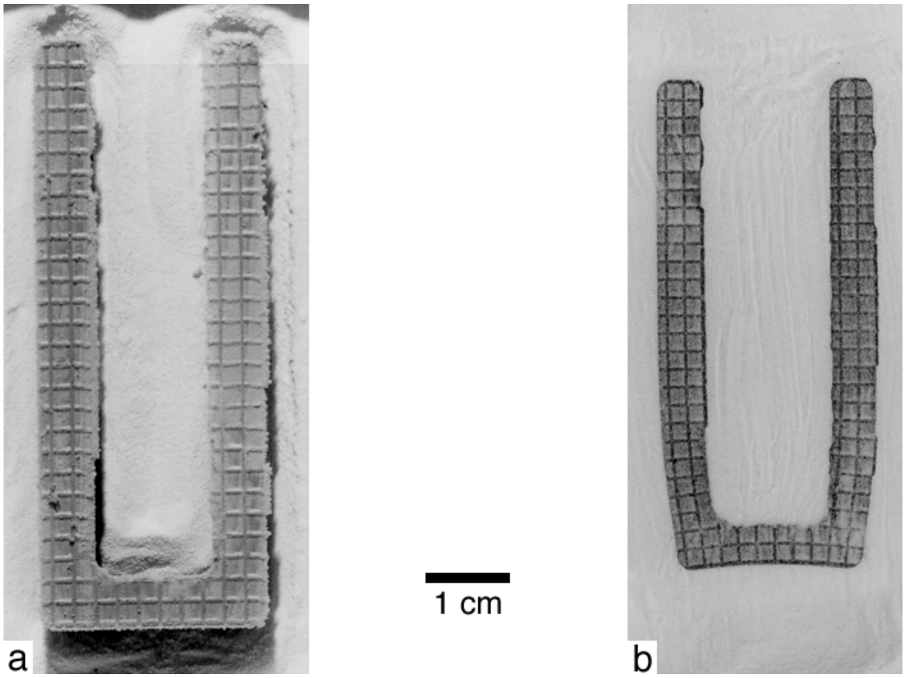

Figure 3. Distortion of U-Shaped Component

This part is made of spherical nickel with a mean particle size of approximately 15μm. This powder was mixed with a liquid carrier which was frozen to form the shape in (a). After freezing and ejection from the mold, the part was placed in a ceramic furnace boat and surrounded by spherical Alumina which served as the tool powder in accordance with the FPM principle. The top of the frozen part was brushed free of excess tool powder and photographed. The part was then covered with tool powder, placed in a sintering furnace, the carrier was driven off and the part was sintered. After sintering, powder on top of the part was again brushed off to reveal a distorted part and the result was photographed.

Sintering shrinkage of 16% (linear) resulted in significant distortion near the base of the U-shaped part. Neither segregation of differently sized powders nor the presence of density gradients within the molded component are suspect. Varying the procedures used to mix the powder and carrier, and fill the molds, did not appear to affect the distortion. Similarly, varying sample orientation within the furnace boat and boat positioning within the furnace hot zone did not result in observable deviation in distortion. The resulting distortion is primarily attributed to component geometry.

Examination of this component in its pre- and post-sintered condition reveals useful information about process-induced distortion caused by complex component geometry. It illustrates how shrinkage of the base segment of the U drew both uprights toward one another near their attachment to the base, causing them to bend. Resistance was apparently offered by the tool powder which limited the extent to which this base contraction affected each upright. The upward bowing of the base segment at first appears counter intuitive, as it is reasonable to predict the contraction of the uprights will draw the connected ends of the base segment toward their centers, thus causing a downward bow in the base segment. However, the observed bending suggests that moment forces near the intersections of the uprights and base segment resulting from draw-in of the bottom portions of each upright are dominant.

While these qualitative observations may be useful for better understanding the role of component geometry on distortion, it is anticipated that measures taken for such samples will provide valuable quantitative data which can be used to characterize process distortion behavior. Such measures can be taken by using a computer to digitize grid crossings and grid/part boundary intersections on scanned images of pre- and post-sintered photographs. This will enable the relative motion of corresponding intersection points to be measured and easily visualized. Figure 4 shows the relative motion, termed a distortion field, of such points for the component of Figure 3.

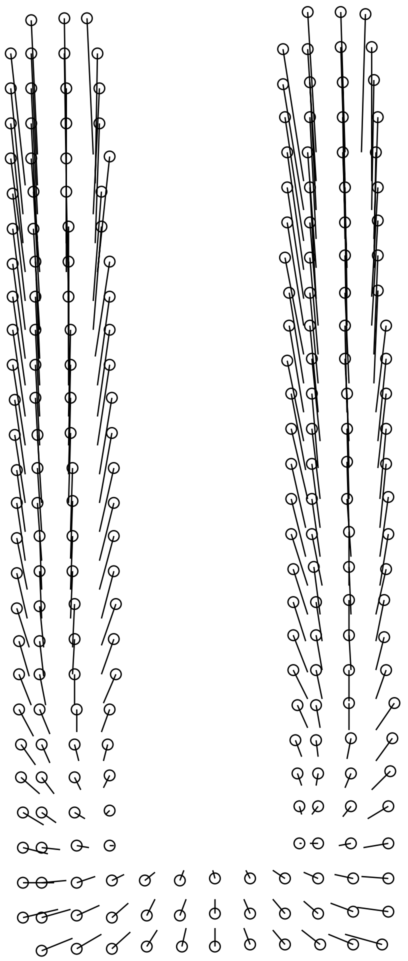

Figure 4. Distortion Field of U-shaped Sample

Each line in the figure represents a sinter-body displacement from the end which is circled to that which is not. This information may be used to drive automated distortion compensation algorithms, as discussed previously. Alternatively, relative density information may be determined by evaluating the areas defined by sets of intersection points. Measures, such as local density across the part, which are not expected to change substantially must be carefully scrutinized. A thorough evaluation of error introduced during the experimental procedures described has not yet been performed. It is particularly important to recognize that scanning an image into a computer will limit resolution due to spatial quantization. Additionally, techniques used to digitize grid intersections, whether automated or manual, may introduce some imprecision.

Experiments which place a measurement grid on various shapes, although simple relative to many end-use components, can provide substantial insight into geometry dependent consolidation distortion behavior. The example of Figure 3 illustrates the importance of component geometry on process-induced distortion. It clearly refutes the notion that, at least for powder-based RP processes capable of manufacturing complexly shaped objects, simple scaling is sufficient to compensate for process-induced distortions.

6. CONCLUSION

In traditional press-and-sinter P/M, and for any process with high tooling costs, adjusting the initial component geometry is both costly and time consuming. Manual tool-set modifications are error prone and rely heavily on die maker skill. When attempting to control process-induced distortion, it is often preferable to alter other process variables which are more easily controlled. In the case of Rapid Prototyping, component geometry can be altered with relative ease. These information-driven processes do not rely on part-specific tooling and impose few limitations on component shape complexity. Consequently, modifying the initial powder configuration to account for shape changes which are induced by processing offers a viable alternative for distortion control in the domain of RP.

This approach becomes particularly attractive when processing advanced material components, where multiple materials are arranged in geometrically complex configurations with varying compositions. Attempting to control shrinkage through process modifications is even more challenging in this situation given the diversity of possible material responses within a single component to changing processing conditions. Process modifications introduced to alter shrinkage characteristics, and reduce shrinkage non-uniformity, must be carefully scrutinized to ensure that they do not undermine intended final properties of a component.

Research presented in this paper provides a method by which process-induced distortions can be investigated and characterized. Particular attention is given to the constraints imposed by RP, which preclude the routine use of advanced analysis techniques such as real-time in-situ distortion monitoring. The application of a grid to sintering test specimens provides a powerful tool for evaluating distortion within a component, as well as on its periphery. The photographic measurement technique used in this work enables resolution to be easily improved simply by print enlargement. Distortion experienced by several experimental shapes can be characterized by contrasting pre- and post-sintered grids, and this information will ultimately be used to drive distortion compensation algorithms. As samples of more complex shape are analyzed, and its impact on distortion is recognized, more attention will undoubtedly be focused on developing efficient methods for controlling distortion by compensating for process-induced distortions — regardless of their cause.

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