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ORIGINAL PAPER

Interactive design for additive manufacturing: a creative case of synchronous belt drive

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Abstract

As a digital and direct manufacturing technology, additive manufacturing (AM) presents a powerful and unrestrained revolution for creative design. However the breakthrough in manufacturing technology is yet to be followed by a breakthrough in design. Firstly, the state-of-the-art overview of the existing design methods for AM is presented. Furthermore, as part of a fully 3D printed robot we envisioned, this work mainly put forward a novel synchronous belt drive as an illuminating case with the potential and constraints of AM. After capturing the flexibility based on shape innovation, a new type of continuous trapezoidal tooth belt transmission without matrix was designed. Next, using the nonlinear finite elements method, the effect laws of belt's parameters such as tooth height, tooth width, wedge angle and belt thickness were studied on the carrying capacity of belt transmission with pre-tensioning. Moreover, a new type of synchronous belt and timing pulleys were made via the 3D printing process of fused deposition modeling with the flexible polylactic acid (PLA) material. Lastly, a driving test was carried out and the experimental results showed that the presented 3D printed trapezoidal tooth belt transmission was stable, and could meet the requirements of low speed, small power transmission, especially apt to digital design and customization. This work completely demonstrates the intrinsic nature of digital design, interactive design and custom design from/with/for AM, as well as the ever-expanding room for innovation.

Keywords Additive manufacturing · Design methodology · Synchronous belt drive · Finite element method · Interactive design

1 Introduction

Additive manufacturing (AM), or 3D printing-as it is referred to in the mass communication, is a group of manufacturing processes which produces three dimensional objects by adding material, usually in a layer by layer manner [1]. As a digital and direct manufacturing technology, it has been considered to be a great achievement in the recent 30 years in manufacturing field [2,3]. Compared with the conventional removing machining and distortion processing methods, AM technology of layer by layer processing has many prominent advantages, such as direct manufacturing process without molds and tooling, unrestricted to the degree of structural complexity, providing more freedom for the innovative design, high utilization of materials, and environment friendly [2,3].

Nowadays, in some of the leading application areas such as aerospace, biomedical, and automotive, AM has demonstrated unprecedented flexibility for part consolidation, function integration, and lightweight designs of structure and component [4,5]. It can be said that inventions and creations from/with/for AM are becoming more and more prevalent. A landmark case is that GE successfully 3D printed the fuel nozzle of an aircraft engine and further put it into mass production. The 3D printed jet nozzle not only combined all 20 parts into a single unit, but it also weighed 25% less than an ordinary nozzle and was more than five times as durable. After being installed inside the LEAP, one of the bestselling jet engines in CFM's history, the first LEAP-powered Airbus A320neo started ferrying paying passengers in September 2015.

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In addition to cutting-edge applications, now 3D printing is gradually becoming a technology that can be learned and mastered by more and more general people due to the advantages of ease of use and low cost [2]. People can easily learn the use of 3D printing machines and then self-design and fabricate simple objects such as simple tools, teaching aids, interesting models, children's toys, and so on. Everyday thousands of 3D printable models from worldwide designers are shared onto the world's largest 3D printing community-Thingverse [6].

Obviously, additive manufacturing has marked the arrival of a new industrial revolution and also brought huge impacts on the traditional manufacturing industry [2,3]. Historically, a process innovation would lead to a product innovation, i.e., the development of a product with improved performance to provide the consumer new or enhanced services [7]. However, the overall transforming procedure from process innovation to product innovation is not linear and unconstrained. Although there are many potential opportunities of AM, the breakthrough in manufacturing technology is yet to be followed by a breakthrough in design [8].

According the theory of interactive design, the creation of a product is considered to be constrained by 3 factors: the experts' knowledge, the end users' satisfaction and the realization of functions. The challenge of interactive design is really to supply efficient solutions for leading product engineering: it is proposed from the analysis of cognitive, sensorial or physical interactions [9]. In terms of cognitive interactions, unlocking the design potential of AM process in adding flexibility and reducing shape dedicated tools requirements is a big challenge [1]. Technically speaking, although AM is also called Solid Free-form Fabrication, its freedom is relative and is not absolute, because that the new production process created new possibilities but also new restrictions to the design. The current body-of-knowledge is lacking the design considerations necessary for a designer to guide the design of the part to meet the fabrication process requirements [10]. Even for experienced engineering designers, the tradition and fixed mind-sets cannot make up for the lack of knowledge on the new technology.

Furthermore, for an end-user who wants to create a product or a part in AM, design choices (requirement or constraint) also should be considered coming from the interactions occurring between the device and the user (sensorial interactions) or from interactions happening between the device and the environment (physical interactions) [11]. However, some intrinsic limitations of AM processes inevitably affect the design requirements or constraints. For example, the mechanical properties of parts printed through Fused Deposition Modeling (FDM) exhibit a distinct anisotropy due to the layered process [10]. The anisotropy may reduce the durability of load bearing features. Another example, it is inevitable to have the stair-stepping effect on the surface of slopes, which affects the surface roughness [12]. Roughness is internal and external, which could influence the flow behavior of internal channels, in addition, the reduction of internal roughness requires (sometimes) very complicated methods [13]. Besides, there are some other disadvantages of AM such as slow build rates, limited component size (restricted by the size of the build chamber), considerable effort required for application design and for setting process parameters, dimensional accuracy, required post-treatment methods like surface finishing and the stability and quality of the used powder.

Therefore, to exploit properly the potential of AM in product innovation and product manufacturing, or to bridge the gap between the process innovation of AM and the creation of end-user applications, in recent years, several interactive design methodologies and tools for additive manufacturing have been developed from different focuses. In this paper, we first present a state-of-the-art overview of the existing design for additive manufacturing (DFAM) methods. Hereafter, we would mainly present a novel synchronous belt drive as an illuminating case with the potential of 3D printing perspective.

2 Interactive design methodologies and tools for additive manufacturing

2.1 DFAM method based on the process-structure-property-behavior model

Rosen [14] summarized the unique capabilities of AM technologies from three aspects: shape complexity, material complexity and hierarchical complexity. Then he gave the definition of DFAM: the synthesis of shapes, sizes, geometric mesostructures, material compositions and microstructures to best utilize manufacturing process capabilities to achieve desired performance and other life-cycle objectives.

Furthermore, focusing on the application of cellular materials to replace bulk materials, Rosen [14] presented a DFAM method that encompasses conceptual design, process selection, later design stages, and design for manufacturing. This method is expanded from the process-structure-property-behavior model that is common in the materials design context. As illustrated in Fig. 1, the overall DFAM method consists of a traversal of the frameworks from function to process, then back again to behavior.

The mapping from function to process is called design, where functional requirements are mapped to properties and geometry that satisfy those requirements to structures and through process planning to arrive at a potential manufacturing process. Reverse direction, one can simulate the designed device and its manufacturing process to determine how well it satisfies the original requirements. As a starting

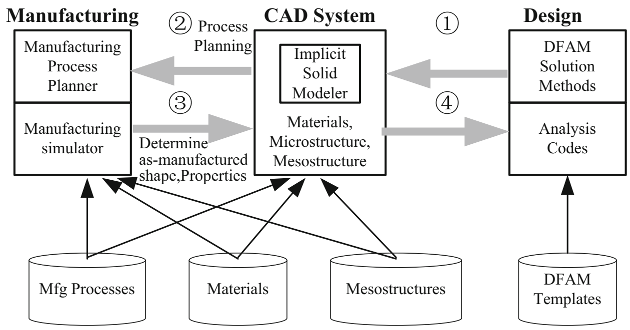

Fig. 1 DFAM method from Ref. [14]

point for design, the designer can define the DFAM synthesis problem, using an existing problem template if desired. According to the author, for different problem types, different solution methods and algorithms will be available. Analysis codes, including FEA, boundary element, and specialty codes, will be integrated to determine design behavior. After planning a manufacturing process, the process will be simulated on the current design to determine the as-manufactured shapes, sizes, mesostructures, and microstructures. The as-manufactured model will then by analyzed to determine whether or not it actually meets design objectives. As a typical of DFM methods, the basic concept of this method is focusing on the exploration of expanded design spaces, rather than the focus on constraints imposed by the manufacturing processes.

2.2 An early DFAM method

Conducting a review of existing DFAM methods, Laverne et al. [15] asserts that there are three types of DFAM methods: opportunistic DFAM, restrictive DFAM, and dual DFAM. Opportunistic DFAM methods are useful to help designers explore the geometric and/or material complexity offered by AM. Its goal is to seek new shapes or new concepts with a creative approach based on the following premise that there is no limit on feasible shapes and on materials distribution in AM. Restrictive DFAM methods aim to take into account the limits of AM, such as available materials and their properties, the performance and characteristics of AM machines, or product manufacturability. They pursue a convergence between the nominal geometric model corresponding to an ideal representation of intermediate representations (IRs), i.e., one without defects; and the actual model including the expected or predicted geometric variations due to the manufacturing process and thus corresponding to a realistic representation of the IRs. Finally, dual DFAM refers to methods that combine the two approaches described above. Laverne et al. [15] assert that dual DFAM methods are more suitable for product innovation since it guides designers to exploit AM potential in a realistic way. However, the authors also fund that despite their significance for innovation, dual DFAM methods only account for 30% of existing DFAM methods. According the research of Laverne et al. [15], the most likely reason for this problem is AM techno-push innovation is partially used. Furthermore, current DFAM methods only study the static aspects of a product and have little consideration about kinematics or dynamics of the components. To overcome these limitations, they developed a methodology called eA-DFAM (early assembly based DFAM), focused on the preliminary stages, and intended to foster designers' creativity on AM optimized working structures. The results of their case study indicate a first prospect, highlighting the significance of AM knowledge during the idea generation process. Their case study also helps them to refine the eA-DFAM because the contribution of AM knowledge without distinction between restrictions and opportunities is not relevant during a creativity session. To provide designers with the right AM knowledge at the right time, they splited the creative stage of the eA-DFAM into several stages: concepts, working principles, and working structures, and proposed an optimized eA-DFAM method as shown Fig. 2.

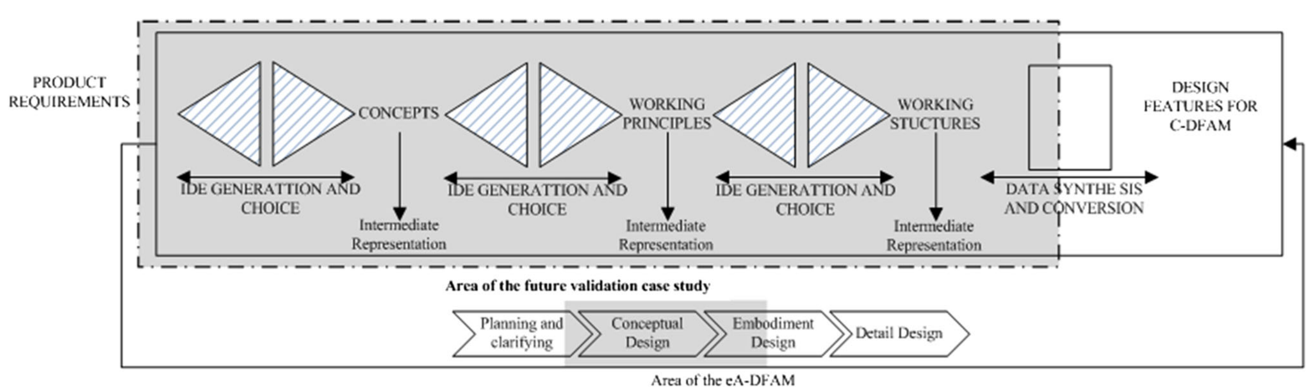

Fig. 2 eA-DFAM method from Ref. [15]

2.3 Creative-DFAM method based on intermediate representation

From the input data to the generated concepts during the dual DFAM process, Rias et al. [16,17] deem there are three levels analysis approaches: Level 1-formal newness, Level 2-functional reconfiguration, and Level 3-AM form and function implementation. Furthermore, they retain that a suitable IR sequence for creative AM concepts generation would provide to designers preexisting 3D virtual models and would allow designers to experiment dynamic concepts and behaviors. Hence, their research focused on input data, design strategies and intermediate representations in order to foster the generation of creative AM concepts. This focus resulted in the proposal of a five stages framework of a creative approach to be integrated in the early stages of DFAM: 1/Features discovery, 2/Exploration, 3/Ideas evaluation, 4/Concept generation, and 5/Concept evaluation. Their cases studies showed that AM questions the conventional interactive design approach based on feature-based modelling. Considering interactive design theory, they then introduced a definition of a new kind of intermediate representation, specifically oriented to creative design for additive manufacturing: Additive Manufacturing of Intermediate Objects (AMIO). AMIO are meant to be at the crossing point between closed and open-ended objects. Certainly, their hypothesis that AMIO foster the generation of AM creative concepts still need a lot of validation.

2.4 DFAM method based on the axiomatic design

The axiomatic design is based on mapping the customer needs (defined as functional requirements (CNs)) on functions that the object is expected to perform (defined as functional requirements (FRs)) then derive design parameters (DPs), indicating how the object can satisfy such FRs and finally describe the process variables (PVs) for the manufacturing of the object [18]. This procedure is usually implemented through zigzag decomposition, having in mind two fundamental design axioms, the independence axiom (each functional requirement should be independent) and the information axiom (select the design alternative with the minimum information content).

Using the axiomatic design approach, Salonitis [18] proposed an approach for taking into consideration the manufacturing capabilities and limitations as depicted in Fig. 3. The core of the proposed framework is the axiomatic design decomposition of the design space into domains (shown as ellipses in Fig. 3); however, in order for the manufacturability of the design to be improved from the early design phases, in addition to the theorems and corollaries, information such as manufacturing guidelines need to be imported into the functional and physical domains during the decomposition of these domains. Therefore, for the sake of the manufacturing capabilities to be taken into consideration, the zigzag decomposition should not occur only between two adjoining domains. manufacturing guidelines and constraints were extracted from additive manufacturing practitioners. The method was validated for the case of additive manufacturing of a component. In the work of Salonitis [18], the axiomatic design was firstly combined with surface topology optimization for the high-level decomposition. Based on such a combined approach, designers can take advantage of the process capabilities in order to design complex objects by using unexplored regions of the design space and assess their creativity using the two axiomatic design theorems.

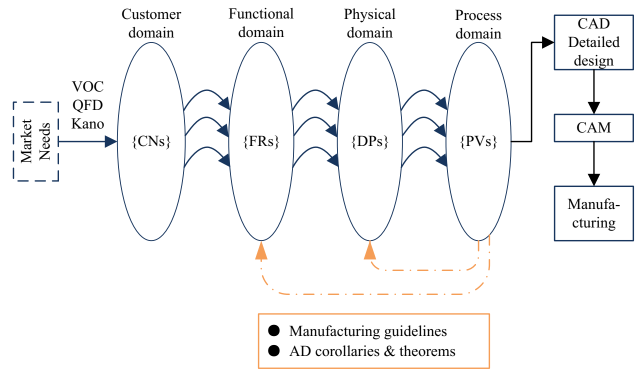

Fig. 3 DFAM based on axiomatic design from Ref. [18]

2.5 DFAM method based on skin-skeleton model

Asadollahi-Yazdi et al. [19] assert that there is no integrate and complete approach in AM that consider all requirements and constraints coming from it in order to provide an interoperable process through product development. Therefore they consider that it is really necessary to integrate all utilization, design and manufacturing attributes inside the product description to take into account the requirements in a complex system by introducing Systems Engineering. For this purpose, they proposed an integrated methodology of DFAM approach based on the skin-skeleton model as shown in Fig. 4. This skin-skeleton model consists of usage and manufacturing model which are used to characterize the customer requirement, product specification and design trend by usage model as well as manufacturing procedure and its constraints by manufacturing model. In their work, usage skin and skeleton is created by topological optimization and power crust algorithm. Also, manufacturing model is presented due to AM characteristics. Finally, an interface model as a database is created though analysis of design and manufacturing skin-skeleton that supports both design and manufacturing attributes simultaneously to define a product. The authors claim this model can help to identify usage and

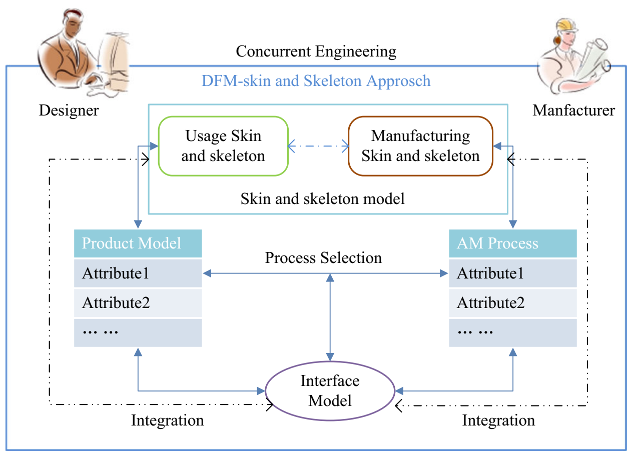

Fig. 4 DFAM based on skin-skeleton model from Ref. [19]

manufacturing attributes to provide an interface model to define the product model by analysis of different parameter related to design and manufacturing and their interconnections comprehensively. Therefore, this model permits to consider manufacturing constraints and attributes as soon as possible in the design stage to provide a better solution as a final product model for design and manufacturing concurrently as a compositive approach.

2.6 Interactive aided design tools for AM

From design to manufacturing, the overall process of AM is digital. Innovative design not only relies on innovative approaches but also requires innovative tools to turn design concepts into digital, analytic, and manufacturing models. Hence, to fully exploit the capabilities of AM, apart from the interactive design methods, interactive aided design tools are essential configurations for designers, such as new CAD modelling system, new CAM simulation and inspection system, new CAE simulation system and new database management system. However, in fact, many researchers said that they foresaw the lack of capable CAD tools as a serious impediment for their research and for the utilization of AM technologies for production manufacturing applications [14].

Nowadays, most CAD software packages are developed with the assumption of homogenous part's interior from both geometrical and materials point of views. Nevertheless, an appropriate CAD tool for AM should grant the freedom to tailor the material's distribution and composition inside the part. Due to the nature of AM that builds the parts layer by layer, the mechanical properties of the part are a function of the material used and the processing parameters [14]. Therefore, the strength of the part and its stiffness depend on the strength of the fusion and bonding between the extruded infill and the air gaps separating them. This makes simulating AM parts in FEA a challenging task. Until now, there are no available packages for simulating AM parts and research is still in progress [14]. In addition, AM technology lacks the effective design software for printing and prototyping of tissues and scaffolds [3].

Of course, there is still some progress in the development of innovative tools. Currently, there are some commercial CAD tools that support AM such as Creo 4.0, which allows the fabrication of the parts and its interior parametrically and slice it for printing directly. Solid Thinking is an example of CAD software that allows topology optimization as per the loading and the user defined requirements [14]. To inspire greater creativity in design, Maidin et al. [20] proposed the use of a "design feature" database to serve as a rich source of inspirational information for design practitioners and students when designing parts to be produced by AM. Topological shape optimization can explore new concepts and solutions in areas of "no comfort" for engineers, and its free-form nature and its ability to discover novel, high performance solutions, makes it a natural design tool for integration with AM processes [21]. Hence, their combination has attracted quite a lot of research. Usually, most operators lack formal training in structural mechanics, which can hinder the process with many iterations and costly failed attempts. Therefore, for automatically generating designs which satisfy some user-defined structural requirements, Christiansen et al. [22] present a fully automated design tool for designing structurally sound structures which can be manufactured, constructed or printed. The modeler only has to specify boundary conditions, the optimization objective, constraints and an initial structure. This design process is significantly different from today where a designer manually models a structure and requirements are taken into account during this design process. As a common AM pre-processor, Materialise Magics can create high accuracy tessellations for smooth outer interface volume surfaces [8]. From environmental impact and eco-design, Freitas et al. [23] introduced sustainability awareness for additive manufacturing technologies. In the case of fused deposition modelling process, they proposed D4E computational tool allows obtaining data about a product's environmental impact, for each life cycle stage, which can contribute to optimize the design product and minimize its environmental impacts along the life cycle.

Undoubtedly, the DFAM method above will have a good guide and inspiration for the designer. Yet as an emerging field in engineering design, DFAM still has untapped research issues for better design performance [12]. Overall, a key limitation of all research is that there is no all-powerful approach in AM that consider all criteria and constraints coming from it in order to provide an interoperable process with product development [19]. Next, this paper is not to outline a so-called new methodology, but to show how to break through the boundaries of innovation step by step to design

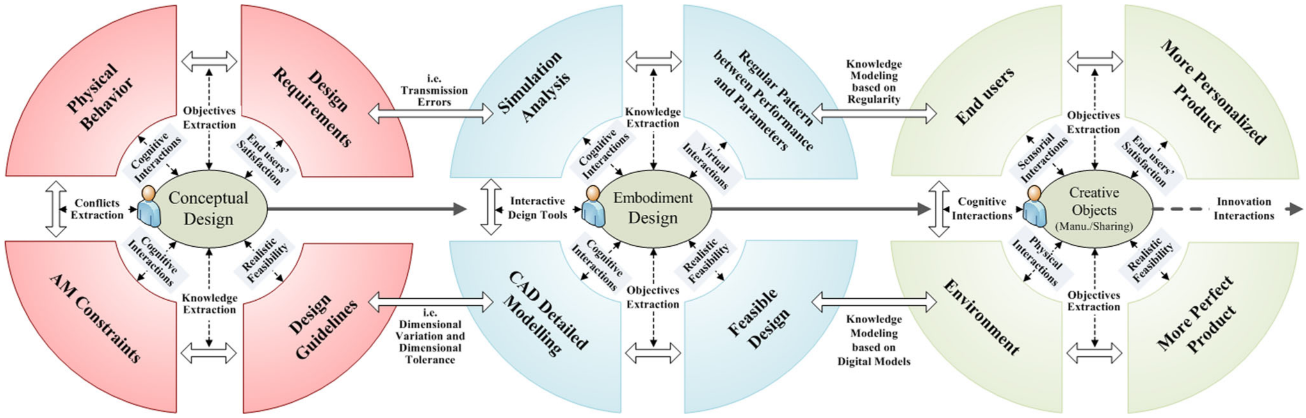

Fig. 5 Interactive design for/with/from AM

an innovative case for/with/from AM. In our case of a flexible and dynamic component, we will see the intrinsic nature of digital design, interactive design and custom design for/with/from AM, as well as the ever-expanding room for innovation.

3 Interactive design for/with/from AM

3.1 Design iteration procedure

According to the research results mentioned above, in our opinion, interactive design for/with/from AM contains three basic aspects. First of all, "For AM" represents the direction from design to manufacturing, designers should intend their plans to be full printability, manufacturability, manufacturing costs, manufacturing cycles and so on. Secondly, "From AM" represents the direction from manufacturing to design. Designers should fully exploit the technical potential of AM, continuously break through the boundaries of technical constraints and maximize the transformation of its technological advantages into innovative advantages. Finally, "With AM" refers to the process of repeated as well as complex interactions among innovative thinking, professional knowledge, process knowledge, demand cognition and supporting software. In some partial stages, seemingly there may be a certain sequence of three aspects, but in the whole process, they are inseparably intertwined as shown in Fig. 5. The destination of interactive design is to meet the needs of end users, such as customization, lightweight and multi-functional integration. In addition, product supply chain optimization, open sharing, higher added-values, and greater benefits are also considered.

In the conceptual design section of the product, cognitive iteration is first generated among the designer, the customer's needs as well as the physical behavior of the product, and design requirements are derived. In addition, cognitive iterations require designers to fully understand the technical advantages and constraints of AM and to abstract design guidelines. Facing the conflicts between functional requirements and design guidelines, designers must use innovative thinking to come up with innovative solutions. Designers can also get inspirations and solve problems with innovative aided design tools [20].

When establishing the concept of innovation solution, the designer is entering the embodiment design stage. In this process, digital design tools are essential. First, the designer is going to transform a conceptual model into a three-dimensional digital model. In the modelling of digital models, we must give full considerations to the process boundaries, such as size deviation, minimum wall thickness, small features, etc. Second, the designer also need to simulate the physical behavior of the product and the working conditions in the CAE virtual environment based on statics, kinematics, dynamics and other simulation analysis. Through the simulation analysis, the influence laws of shape configurations and size parameters on the physical behavior of component should be explored. This would surely lay the cognitive foundation for the design optimization, validation, series reuse, continual improvement and open sharing.

After obtaining the final design, the designer transforms the model into a format file that the printer can read, adjusts to a suitable posture, and then slices to produce a numerical control program that drives 3D printer movements. After printing, the 3D printed objects still need corresponding post-processing, such as removal of supports, surface treatment and so on. The product is then forwarded to the end user for evaluation or for a prototype test. At this point the product is entering into the actual sensorial interaction or physical interaction stage. Of course, we can further share the achievement to the online community, and accept more popular evaluation and improvement. These sensorial, physical or popular interactions are also a new starting point for further customization or next innovation.

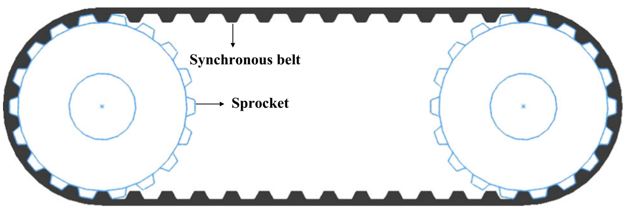

Fig. 6 Synchronous belt drive meshing mechanism

Next we take synchronous belt drive as a 3D printing innovation design example, to show how to break through the boundaries of innovation step by step according to the design iteration procedure for/with/from AM.

3.2 Synchronous belt drive

Initially, this work of this article belongs to the fully 3D printed robot that we envisioned. Therefore, this work does not focus on the timing belt drive mechanism and its optimized research, but rather focuses on a new design scheme of synchronous belt drive with the advantages of 3D printing.

First, we briefly introduce the basics of timing belts. Synchronous belt (also known as toothed belt, or timing belt) drives have higher transmission precision and carrying ability than flat rubber belt drives and produce less noise and better damping characteristics than chain drives. Besides synchronous belt drives can offer high accuracy, lower maintenance and accommodate many different product conveying requirements. Therefore, synchronous belt drives are broadly used as ideal solutions for power transmission and linear drive applications in automotive applications, robotics, production lines, industrial machines, combustion engines and other industrial applications. For example, Akbari and co-workers [24] designed a timing belt gear boxes to solve the backlash problem of gearbox gears which would lead to inaccurate and volatile motion when the Ballbot robot was moving. By using this method to transfer power and precise control of motors, the robot has a good balance and quick reaction to the tensions.

As shown in Fig. 6, a synchronous belt commonly consists of tensile cords, a rubber compound that forms the teeth bulk and the backing of the belt, and facing fabric covering the belt face and teeth face. The tensile cords bear the external loads, and the facing fabric reinforces the wear resistance of the belt and teeth. Industrially, the production of synchronous belt contains a dozen processes: mixing, rolling, molding, curing, cooling, grinding, stripping, cutting, etc.

Certainly there are many issues with the timing belt drive need to be studied especially in the high-speed dynamic conditions, such as slippage, geometrical mismatch, contact compliance and transmission error. Multi-body dynamics as well as finite element method (FEM) are state of the art simulation techniques applied to belt drives. Butnariu [25] developed a multi-body model in ADAMS software to predict the load distribution between the belt tooth and pulley. Jia and Song [26] developed a rigid-flexible coupling dynamic simulation with the dynamic software RecurDyn to study the precise influence of inertial and damping forces on the dynamic performance of synchronous belts under high acceleration or high speed. Kilic et al. [27] presented a viable position estimation scheme for timing-belt drives using artificial neural networks.

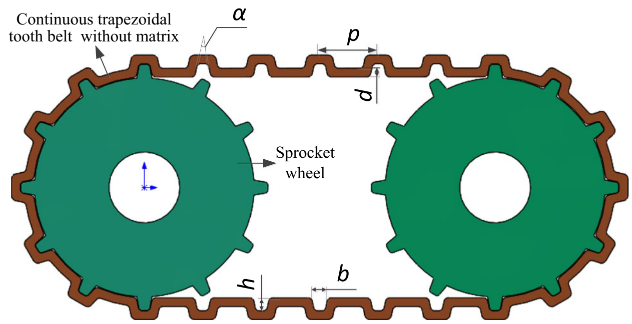

Fig. 7 Basic configuration of trapezoidal tooth timing belt without matrix

3.3 Redesign of synchronous belt drive

The basic goal of our redesign is a new timing belt that is 3D printable. According the basic framework of our design as shown in Fig. 5, the first step is innovative design considering transmission function as well as the manufacturing constraints and capabilities of 3D printing. Secondly, shape and parametric optimization is implemented using the finite element method. Lastly, we fabricated a prototype of the presented timing belt drive via the FDM process with the material of flexible polylactic acid (PLA).

As a output of Step1, we design a creative shape for the timing belt which has continuous trapezoidal teeth (Fig. 7). This formal newness is mainly to get greater flexibility and to ensure the strength as much as possible under 3D printing conditions. The tooth width of the synchronous belt is expressed as b. The tooth height of the synchronous belt is expressed as h. The wedge angle of the synchronous belt is expressed as α and the belt thickness is expressed as d. The tooth pitch of the synchronous belt is expressed as p.

Undoubtedly, the structure parameters above would affect the transmission capacity, transmission efficiency as well as durability. On the other hand, the structure parameters are also limited by the performance of AM machine. For the 3D printer we use [28], the minimum wall thickness allowed is 0.5 mm, and features with smaller dimension than 1.0 mm should be avoided as they might fail to be rendered. And the minimum layer thickness is 0.2 mm and minimal fillet radius is 0.5 mm. Under these constraints, for obtaining a sound parameters set to meet working conditions, we had better first find out the effect laws of belt's parameters on the carrying capacity. Moreover, according to the synchronous belt friction transmission principle, the timing belt must be tensioned to work properly. Belt also would relax for a period of time, in order to ensure the ability of the belt, we must re-tighten it in order to work properly. Additionally, the pretensioning force also significantly influences the stress state and transmission efficiency of timing belts, hence pretensioning analysis should be carried out before the parametric analysis. In order to solve these problems, we need to steps into the second step, i.e. simulation optimization.

4 Pretensioning simulation analysis

4.1 Modeling of finite element analysis

Analysis of the meshing between the belt and pulley can be simplified as a two-dimensional elastic mechanics problem. The material of the 3D printed synchronous belt is flexible PLA supplies. The elastic modulus of flexible PLA material is 170 MPa. The material of the 3D printed timing pulley is non-flexible PLA supplies. The elastic modulus of non-flexible PLA material is 4000 MPa. The model of the synchronous belt contains many irregular boundaries. Analytical simulation is based on mechanics of elasticity. When the ANSYS software was used to do finite element analysis, two-dimensional eight-node plane element PLANE 183 are adoped separately. The PLANE183 element can better adapt to the irregular boundary. In ANSYS, the CONTA172 element is used to describe the contact and slip states between the 2D target surface and the deformation surface defined by the element. The PLANE183 element can be used as the lower element of the CONTACT172 element. In the contact analysis, refining mesh algorithm is required and the mesh shape distortion should be avoided.

To simulate the meshing status between the belt and pulley in synchronous transmission, contact element is built using edge to edge. The synchronous pulley is defined as target surface. The synchronous belt is defined as contact surface. In order to take the synchronous pulley displacement, torque is applied, and a control node is set at the center of the pulley. The concentrated load is applied by changing the axis of rotation to MPC multipoint restriction. The synchronous pulley has only one rotational degree of freedom around the Z axis. Constraints and loads need to be imposed on a driving wheel, a driven wheel and a belt. Here the driving wheel is loaded with angular velocity. Improper engagement of the belt and pulley result in "Jumping over teeth" and skidding. Therefore, pretension is required before bearing. The load of displacement along the X direction from the wheel control

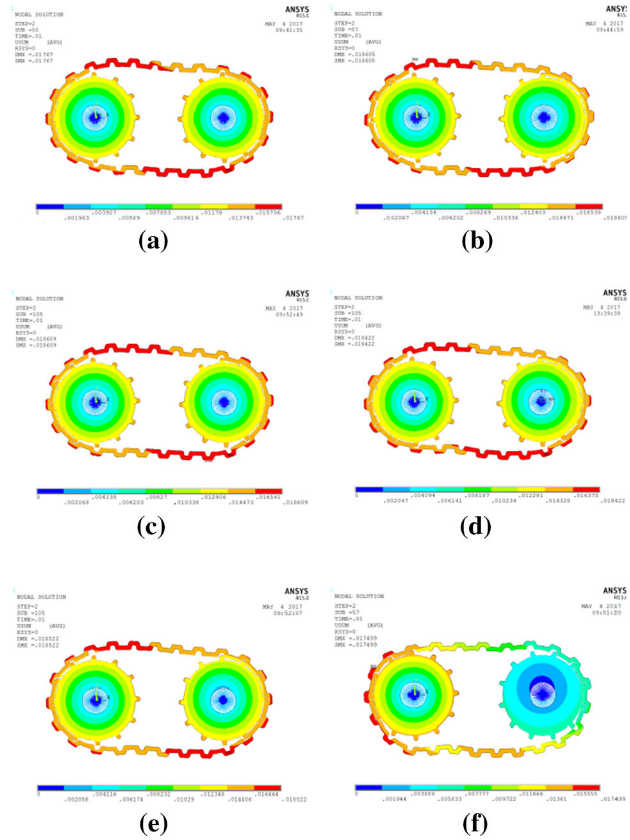

Fig. 8 Simulation results under different preloading magnitude **a** X = 0 mm **b** X = 0.2 mm **c** X = 0.4 mm **d** X = 0.6 mm **e** X = 0.8 mm **f** X = 1.0 mm

point is assumed to be equivalent to a pretensioning force applied to the belt.

4.2 Discussions of pretensioning analysis

The influence of pretension on the transmission performance of timing belt with different structural parameters is studied by finite element simulation. The relationship between the magnitude of pretension and the performance of timing belt transmission is obtained. As shown below, that is the result of the finite element simulation.

Following the establishment of the structure parameters of the synchronous belt model, where the tooth height is 3 mm, the pressure angle is 20°; the tooth width is 2.4 mm and the tooth thickness of 2.5 mm. X direction displacement load values were 0, 0.2, 0.4, 0.6, 0.8, 1.0 mm. The rotation angle of the driving wheel is 34.4°. The results obtained are shown in Fig. 8.

Important results can be obtained in the post-processing of ANSYS. When the driving wheel rotates at a certain size of angle, a different pretension force is applied to the synchronous belt. The rotation angles of driven wheels in each group are arranged as shown in Fig. 9. In summary, it can

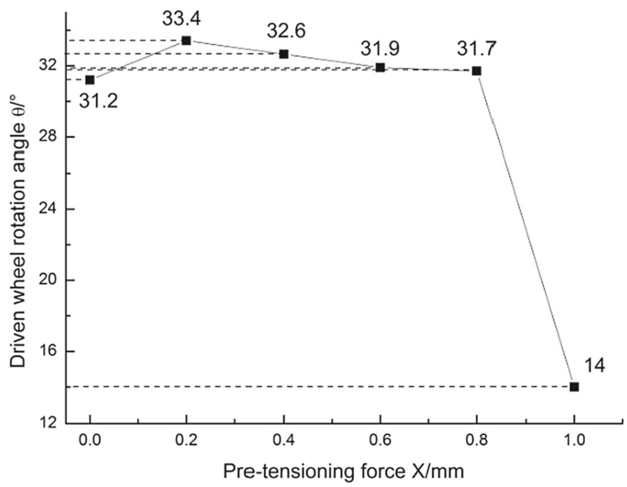

Fig. 9 Rotating angle of driven wheel under different pretension

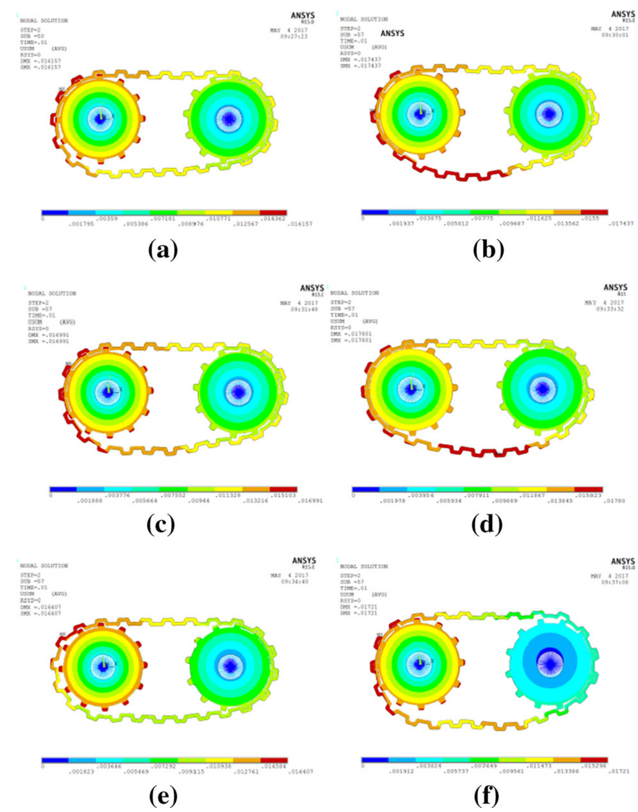

Fig. 10 Simulation results under different preloading magnitude **a** X = 0 mm **b** X = 0.1 mm **c** X = 0.2 mm **d** X = 0.3 mm **e** X = 0.4 mm **f** X = 0.5 mm

be seen that with the increase of pretension, the angle of the driven wheel increased first and then decreased. When the pretension force is unloaded, the transmission accuracy of the synchronous belt is affected. The rotation angle of the driving wheel is 34.4°, and the rotation angle of the driven wheel is only 31.2°. When the X direction displacement load values is 1.0 mm, the synchronous belt increase of the width of the teeth of belt and the contact force between the synchronous pulley and the synchronous belt is too large. The normal transmission of the synchronous belt is affected. When the X direction displacement load value is 0.2 mm, the driven wheel rotation angle reaches to the maximum of 33.4°. Therefore, if there is not a proper pretension of the size, the motion accuracy of the synchronous belt transmission declines.

Following the establishment of the structure parameters of the synchronous belt model, where the tooth height is 3 mm, the pressure angle is 20°, the tooth width is 3.4 mm, the tooth thickness of 2 mm. X direction displacement load values were 0, 0.1, 0.2, 0.3, 0.4, 0.5 mm. The rotation angle of the driving wheel is 34.4°. The results obtained are shown in Fig. 10.

Important results can be obtained in the post-processing of ANSYS. When the driving wheel rotates at a certain size of angle, a different pretension force is applied to the synchronous belt. The rotation angles of driven wheels in each group are arranged as shown in Fig. 11. In summary, it can be seen that with the increase of pretension, the angle of the driven wheel increased first and then decreased. As shown in Fig. 10a, when the pretension force is unloaded, the transmission accuracy of the synchronous belt is affected. The synchronization has a tendency to fall off the wheel. The rotation angle of the driving wheel is 34.4°, and the rotation angle of the driven wheel is only 22.2°. When the X direction displacement load values is 0.5 mm, the synchronous belt increase of the width of the teeth of belt and the contact force

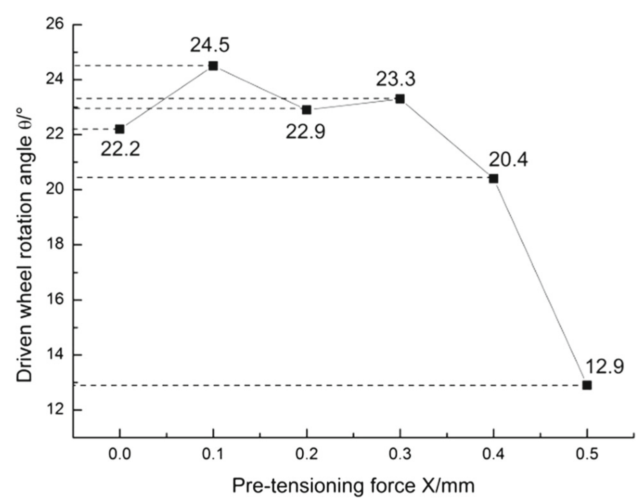

Fig. 11 Rotation angle of driven wheel under different preloading magnitude

between the synchronous pulley and the synchronous belt are both too large. The normal transmission of the synchronous belt is affected. In the process of synchronous belt transmission, the phenomenon of "Jumping over teeth" occurs. When the X direction displacement load value is 0.1 mm, the driven wheel rotation angle reaches to the maximum of

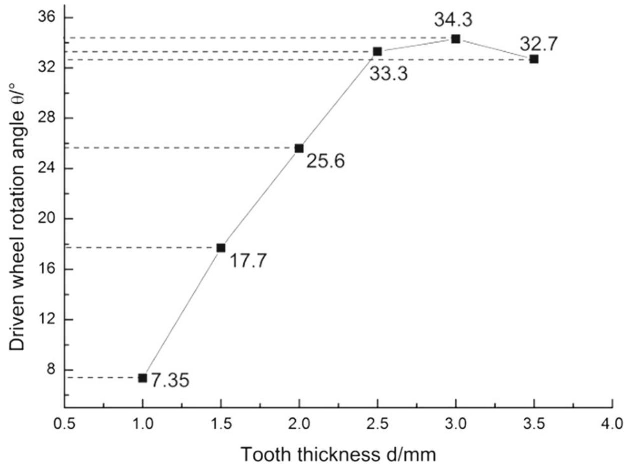

Fig. 12 Relationship between different tooth thickness and driven wheel rotation angle

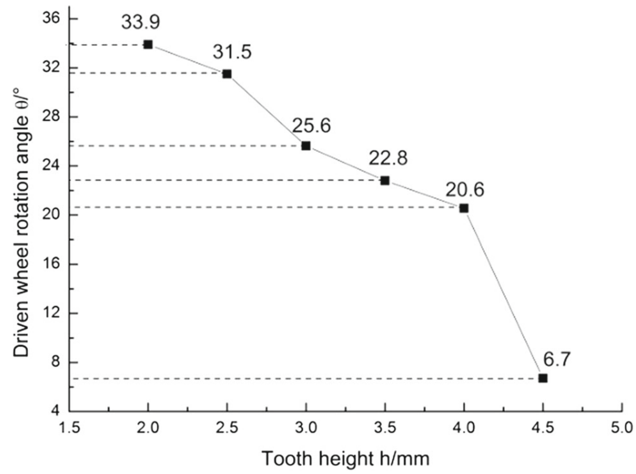

Fig. 13 Relationship between different tooth height and driven wheel rotation angle

25.1°. The angle of the driven wheel is far lower than the angle of rotation of the driving wheel by 34.4°. Therefore, if there is not a proper pretension of the size, the motion accuracy of the synchronous belt transmission declines and improper engagement of between the belt and pulley occurs.

5 Parametric simulation analysis

The engaging state between the belt and pulley is the direct embodiment of the transmission capacity of synchronous belt transmission. The motion accuracy of the synchronous belt transmission is the direct embodiment of the engaging state. When the driving wheel rotates the angle of a certain size, the greater the angle of rotation of the corresponding driven wheel, the higher the accuracy of the motion of the synchronous belt drive. In this paper, the angle of the driven wheel is taken as the main judgment basis to analyze the influence of the structural parameters of the synchronous belt trapezoidal tooth on the transmission capacity.

5.1 Discussions of the influence of tooth thickness

Assuming other parameters do not change, only change the thickness of the belt. The belt thickness are 1, 1.5, 2, 2.5, 3, 3.5 mm. The results are shown in Fig. 12. It can be seen from the Fig. 12 that the rotation angle of the driven wheel is increased and then decreased with the increase of the belt thickness. When the belt thickness is 3.0 mm, the drive wheel rotation angle reaches the maximum value of 34.3°. When the belt is thicker than 3.0 mm, the angle of the driven wheel will decrease. When belt thickness is 1 mm, the phenomenon of "Jumping over teeth" occurs in synchronous belt transmission. Large deformation of belt with too small thickness can affect synchronous belt transmission.

5.2 Discussions of the influence of tooth height

Assuming other parameters do not change, only change the height of the trapezoidal tooth. The tooth height of trapezoidal teeth are 2, 2.5, 3, 3.5, 4, 4.5 mm. It can be seen from the Fig. 13 that the rotation angle of the driven wheel is reduced and then decreased with the increase of the tooth height. When the tooth height is 2.0 mm, the drive wheel rotation angle reaches the maximum value of 33.9°. When the tooth height is 28.5 , 29, 29.5 mm, the driving wheels encounters "Jumping over teeth".

5.3 Discussions of the influence of pressure angle

Assuming other parameters do not change, only change the pressure angle of the trapezoidal tooth. The wedge angles of trapezoidal teeth are 10°, 20°, 30°, 40°, 50°, 60°. It can be seen from the Fig. 14 that the rotation angle of the driven wheel is reduced and then decreased with the increase of the pressure angle. When the pressure angle is 10°, the drive wheel rotation angle reaches the maximum value of 34.3°. When the pressure angle of the synchronous belt is more than 10°, the angle of the driven wheel will decrease very quickly. When the pressure angle is 60°, the driving wheel has the phenomenon of "Jumping over teeth" and slipped from the synchronous pulley.

5.4 Discussion of the influence of tooth with

Assuming other parameters do not change, only change the tooth width of the trapezoidal tooth. The tooth width of trapezoidal teeth are 1.4, 2.4, 3.4, 4.4 mm. The results are shown in Fig. 15. When the tooth width is 2.5 mm, the drive wheel rotation angle reaches the maximum value of 25.6°. When the

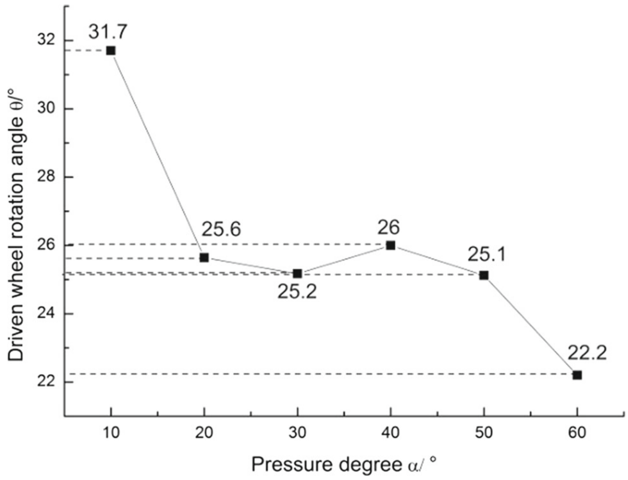

Fig. 14 Relationship between different pressure angle and driven wheel rotation angle

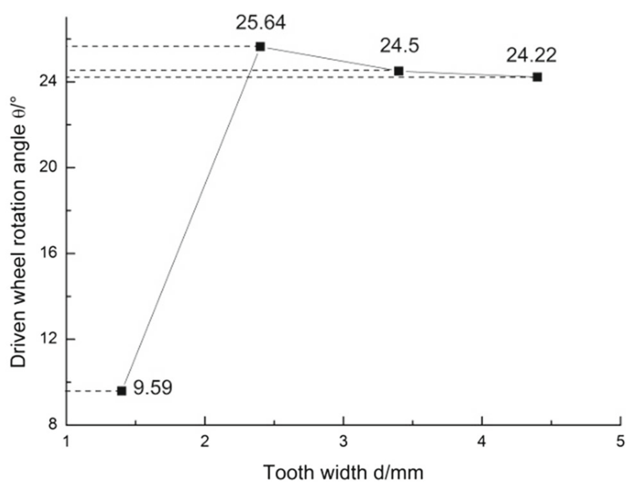

Fig. 15 Relationship between different tooth width and driven wheel rotation angle

pressure angle of the synchronous belt is less than 2.5 mm, the angle of the driven wheel will decrease very quickly.

6 Driving test of new timing belt drive

The conclusions obtained by the finite element analysis provide guidance for the design of the synchronous belt without matrix. Results of the finite element analysis showed that the sound structure parameters of the synchronous belt model, where the tooth height is 3 mm, the pressure angle is 20°, the tooth width is 2.4 mm, the tooth thickness of 2.5 mm are appropriate. The displacement load along the X direction is applied to the control point of the driven wheel 0.1 mm. The rotation angle of the driving wheel is 34.4°. The corresponding rotation angle of the driven wheel is 34.3°. The synchronous belt and synchronous pulley displacement cloud

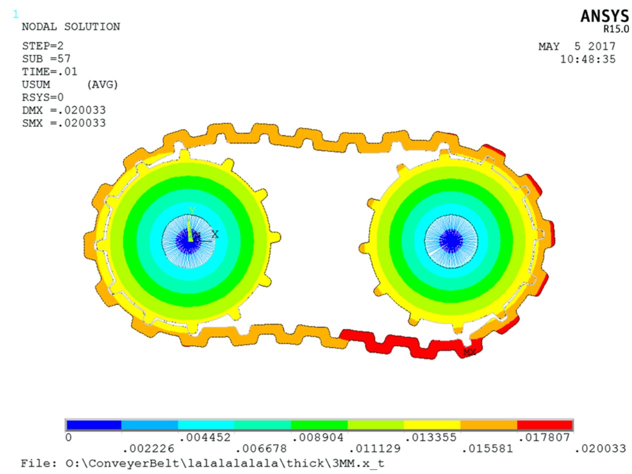

Fig. 16 Deformation of timing belt driving

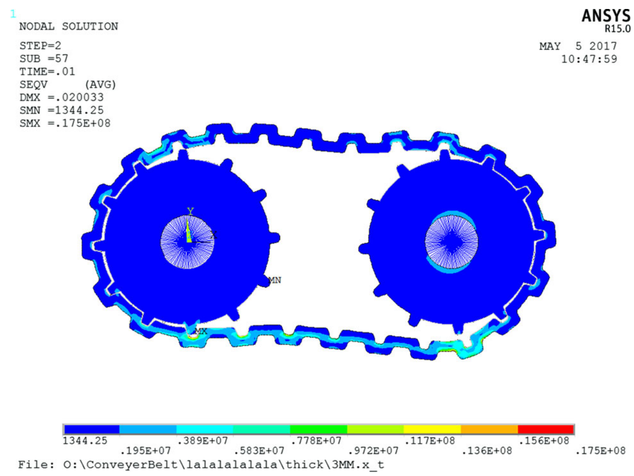

Fig. 17 Von Mises stress of timing belt driving

chart is shown in Fig. 16. The synchronous belt and synchronous pulley von Mises stress contour is shown in Fig. 17. It can be seen from the diagram that the belt of the structural parameters of the synchronous belt and the teeth meshing well, in line with the needs, so we can use the structure parameters as the digital design to manufacture the synchronous belt.

A prototype of the presented timing belt drive was fabricated using FDM process as shown in Fig. 18. The drive test is carried out by using the printed synchronous belt. Observations found that the belt worked well with the pulley and the timing belt run smoothly with low noise in the synchronous belt transmission.

These analysis results provide a theoretical reference for the design of synchronous trapezoidal belt without matrix. Using FDM 3D printer and flexible PLA supplies can realize the rapid iteration and shorten the development cycle of the design and manufacture of the synchronous belt. The synchronous belt is manufactured by 3D printing can meet

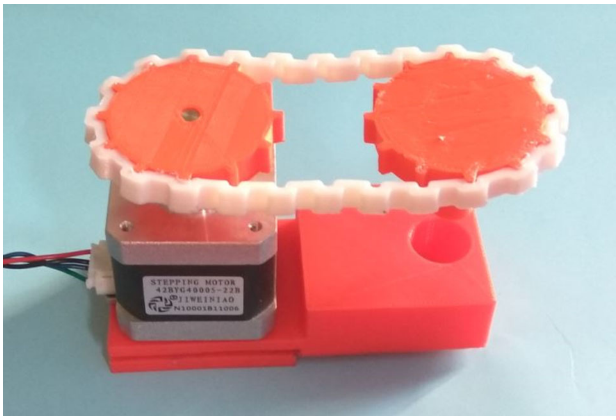

Fig. 18 Prototype of 3D printed timing belt drive

the requirements of low speed and low power in transmission. Therefore, it has important application value. Further research is required to completely study the fatigue life for the 3D printed timing belt. Additionally, the attempt to make timing belt using composites 3D printing technology should be made.

7 Conclusions

As part of a fully 3D printed robot we envisioned, this work mainly present a novel synchronous belt drive as an illuminating case with the benefit of 3D printing perspective. This flexible and dynamic part design based on shape innovation completely demonstrates the interactive design process among AM process, product functional behavior and physical environment. We should not ignore its important meaning because of a seemingly simple case as well as a complicated design process. Like the snap-fit joint that Klahn et al. [29] designed, and like the soft flexible gripper Fras et al. [30] designed, and like augmentation of everyday objects Chen et al. [31] presented, we need more inspirations than disdains to expand more design spaces. At least we can see that design or redesign for or with or from 3D printing are by no means easy things. Here we try to give some conclusions.

Firstly, creative or interactive design for 3D printing puts forward a higher level of requirements to the designers. Designers must first have a strong sense of innovation to fully exploit the freeform of AM. Besides, designers need to master the digital design tools, such as CAD/CAE software. Furthermore, it is necessary to identify specific, manufacturing capabilities as well as manufacturing constraints that must be respected. In the case of selective laser melting processes designers should consider the necessity to remove the powder from the part once it's been built. This constraint prevents the part from having any closed hollow volume otherwise which would be full of unmolten powder [32]. For another instance, If the chosen AM process requires support for overhanging structures those should be accessible to mechanically remove them after the build process.

Secondly, only innovative design could promote AM processes and push them onto the top of the value chain. Although the design cost for AM has increased, integrated design (less or free assembly design) [12,33], topology optimization design [22,34], augmentation or extension design of exiting objects [31], metamaterials design [35–38], individualization design [39], these design concepts and cases would promote AM to a valuable manufacturing trifecta, as well as would help to establish the body-of- knowledge for AM production innovation. More and more new design models are shared into the community, we only need to download and then improve the design into the wanted one.

The last but not the least, creative design or redesign for 3D printing requires innovative design software. As mentioned earlier, currently the vast majority of commercial CAD/CAE/CAM software are difficult to design and analyze complex models, nor does it have 3D printing process analysis tools. We need more powerful software like Grasshopper®, which is a graphical algorithm editor tightly integrated with Rhino's 3D modeling tools, and which allows designers to build form generators from the simple to the awe-inspiring [40].

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