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Flex-it: Exploring emotional expression and experiences through elasticity in digital manufacturing

Abstract

This research investigates the potential of structural flexibility as a functional and affective design element, and its potential applications. Our research bridges the areas of jewellery design, emotion design and structural development in the Additive Manufacture (AM) of metals. The paper begins with a theoretical review of the nature of flexible structures and of current deformable Additive Manufacturing (AM) geometries and their applications. This has been complemented through a series of practical experiments exploring the creation of emotional expression through AM flexible geometries.
Both existing examples and the outcomes of the experiments are evaluated against the framework of emotional expression developed by Niedderer with regard to the emotional responses they elicit. The outcome and contribution of the research will be a better understanding of the structural geometries and potential uses of flexibility in AM as well as of its expressive potential.

1. Introduction

Additive Manufacturing (AM), or 3D printing, is becoming increasingly widespread in both industrial production and studio practice. Research into AM in metals, in particular Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM), is largely driven by the exacting engineering applications of the aerospace, motorsport and medical sectors, which focus on materials and process performance issues such as available materials, material properties, build quality and efficiency, and increasingly complex build structures.

Our research is situated within the area of AM metals concerned with structural development with application in jewellery design. We investigate the potential of structural flexibility as a functional and affective design element, and its applications. In contrast, current research in this area mainly focuses on structural complexity, seeking to eliminate flexing to create stability and enhance strength and stiffness (Murr et al. 2012). Although some approaches to flexible structures exist such as live hinges and spring clips (Gibson et al. 2010), these are developed for technical purposes, and not with regard to any emotional affect. Similarly, current artistic explorations of AM generally focus on semiotic–narrative rather than soma-aesthetic expression of flexibility to create emotion (Niedderer 2012: 60–61).

Flexibility can, however, create both surprising emotional expressions and experiences as well as functional uses and affects, for example through tactile feedback based on the mechanical capacity to deform, which can have subtle but surprising and engaging emotional effects.

While previous work by Niedderer (2012) used conventional analogue metal fabrication techniques to assemble spring-like forms to create emotional expression, our current research explores diverse flexible structures through the use of digital manufacturing technologies. The aim is to exploit the geometric freeform potential of AM to create affective flexible elements. The ability to control and fine-tune movement is enhanced through the ability to add and remove material at will within the editable CAD environment (Dean and Pei 2012).

For this research, a theoretical review of the nature of flexible structures and of current deformable AM geometries and their applications has been conducted. This has been complemented through a series of practical experiments exploring the creation of emotional expression through AM flexible geometries. Both existing examples and the outcomes of the experiments are analysed using the framework of emotional expression developed by Niedderer (2012) with regard to the emotional responses they elicit and their potential applications.

2. A review of the use of flexible structures in AM

This section provides a review of flexible structures in general and where they occur, and then focuses on examples of flexible structures in the use of AM and more specifically in AM metals.

2.1 Elasticity and flexibility

Flexible structures occur in all areas of life and can take many forms for many different purposes: from spider silk to bungee jumping ropes, from DNA to the slinky toy (Figures 1 and 2), there is a large variety of natural and artificial elastic materials and structures in a ubiquitous range of applications. An important distinction to be made in this context is that flexible structures on the one hand rely on the elastic qualities of the material they are made of, such as spider silk, rubber and many other elastic materials. This is due to their elastic structure at micro level, that is at molecular level (Balakrisnan et al. 2012; Smela 2012; Hopkins 2013) that either deforms and reforms or that stretches and contracts under stress/when released. On the other hand, flexible structures may rely on specific structural characteristics at macro level (instead of elasticity at micro/material level) to facilitate flexible movement (e.g. Kleemann 2012).

In this paper, we therefore make the terminological distinction between 'elasticity', which we use to refer to the springiness of a material, i.e. its micro structure, while we will use the term 'flexibility' in relation to macro structures. In this regard we understand elasticity to refer to a *material substance* 'that spontaneously resumes … its normal bulk or shape after having been contracted, dilated, or distorted by external force' (elastic, n.d.). In the same way, for the purpose of this paper, we define flexibility to pertain to a *structure* that spontaneously resumes its normal bulk or shape after having been contracted, dilated, or distorted by external force.

In many cases, the two aspects of elasticity and flexibility are combined (e.g. parametric | art 2013; AWOL 2012). They can, either singly or in combination, enable flexible movement as exemplified by the well-loved slinky toy: a simple metal or plastic spiral which can be made to 'walk down' stairs due to the interplay of elasticity/flexibility, material weight and gravity (Poof-Slinky 2012; Figure 2). Elasticity/flexibility thus offers the potential to design movement into otherwise static structures.

Figure 1. Spider web, 2012. Photograph: Kristina Niedderer

Figure 2. 'Slinky Toy', 2012 by Poof-Slinky. Original design by Richard James, USA, 1943. Photograph: Kristina Niedderer

2.2 Flexible structures

Flexible structures seem relatively under researched, and often developed by trial and error (Pai 2013), and there is little systematic literature on the subject (e.g. Wright 2005; Pai 2007; Sclater 2011; Hall 2013; International Industrial Springs 2013; Wikipedia 2013). We therefore present here a somewhat eclectic overview of some of the most common flexible structures, which we analyse according to their geometric and functional characteristics.

Perhaps the most ubiquitous flexible structure is that of the spiral or helix, the helix having a constant diameter and a gradient, while the diameter of the spiral changes and the gradient can be (but does not have to be) zero. In nature, flexible spiral or helix shapes tend to occur, e.g. in DNA or flower tentacles (Figure 3) where they are either of structural importance (e.g. DNA) or have developed as a support mechanism, e.g. for plants to hold on to a supporting structure. As an artificial structure, helix and spirals have become important as springs in countless applications, from roller ball pens to bed-springs, from coil springs as part of a car's suspension to angle-poise lamps, from coiled electrical leads to spring balances. Thereby most applications work on compression, some on expansion such as the spring balance or the angle-poise lamp, and yet others on torsion such as torsion springs or spiral springs in watches (Pai 2007; Hall 2013; International Industrial Springs 2013; Wikipedia 2013) (Figures 4, 5, 6).

Figure 3: Spiral (cucumber plant), 2013.
Photograph: Kristina Niedderer

Figure 4: Spiral spring, 2013.
Photograph: Kristina Niedderer

Figure 5: Compression spring of a roller ball pen, 2013. Photograph: Kristina Niedderer

Figure 6: Tension spring of an angle-poise lamp, 2013.
Photograph: Kristina Niedderer

Other applications of springs include cantilever springs, which find application in springboards or in tweezers, and leaf springs, which can be found, e.g. in the bow (and arrow), in traditional suspension systems, and in light switches.

A second group of structures include loops (as in knitted structures, Figure 7) or the repetition of loosely connected geometrical structures through folding, bending, mechanical connections or layering, etc., where the lack of internal connections between threads, wires, etc., allows the material to flex, usually creating fabric-like structures or membranes. The intrinsic characteristics that all these flexible structures appear to be based on are that they are instable/flexible due to long stretches of unsupported thin thread/wire or sheet, which also applies to spirals and helix shapes.

Figure 7: Flexible knitted structure, 2012. Photograph: Kristina Niedderer

2.3 AM and SLM as a process for creating flexible structures

For this research, we focus specifically on one process and material to create flexible structures: this is the use of stainless steel with SLM. The reason for this is that until now AM metal processes have mainly been used to create structural complexity, seeking to eliminate flexing to create stability and enhance strength and stiffness (Murr et al. 2012). Although some approaches to flexible structures exist such as live hinges and spring clips (Gibson et al. 2010) as well as research into being better able to predict the behaviours of flexible structures (Pai 2007, 2013), these are developed for technical purposes, often with the aim of prototyping the functionality of injection-moulded plastic components, with regard to material and structural durability, and not with regard to any emotional affects. In order to advance this area, we are investigating the potential of structural flexibility as a functional and affective design element, and its applications.

One limitation and challenge of using SLM with stainless steel is that the SLM process creates a metal structure that is akin to cast metal, whose material structure is less elastic than metal that has been work-hardened and annealed to reinstate its cubic molecular structure. We therefore deal here with a material with limited intrinsic elasticity. While future research may investigate enhancing the elasticity of laser-sintered stainless steel, this present research focuses on the creation of flexible (macro) structures.

While AM metals processes, perhaps due to cost and technical challenges, have not yet been explored with regard to the production of flexible structures, a few interesting examples of flexible structures can be found in the broader area of AM. For example, technology provider EOS have created a demonstration piece that illustrates a conventional hinge, live hinges, snap-fits and compression fittings in a Selective Laser Sintered (SLS) polyamide part built in one piece (Figure 8). Another example is the use of certain elastic polymers combined with flexible structures to create extremely flexible objects: Kleemann (2012a, 2012b) has created an ultra flexible ball, using the repetition of a geometrical motive with an elastic laser-sintered polymer to test how flexible laser-sintered objects can be.

Figure 8: EOS SLS demonstration tool. Photograph: Lionel T Dean

On an industrial scale this phenomenon is already utilised by the textile industry to create novel super flexible textile structures. For example, i.materialise (2013) offers a thermoplastic polyurethane named TPU 92A-1 with rubber-like qualities, which was used to create Iris van Herpen's digitally-fabricated dress (Core 77, 2013). Research at Loughborough University has explored Impact Absorbent Rapid Manufactured Structures (IARMS) in polyamide (Brennan-Craddock et al. 2008). These designs are based on the cellular structure of foams with an intended application in sports personal protective equipment (PPE). The aim of the project was to create customised PPE optimised for both impact and fit to the curvature of the individual's body. The structures developed include cellular frameworks made up of struts which were helical in form rather than straight; the structure effectively becoming a matrix of extension/ compression springs (Figure 9).

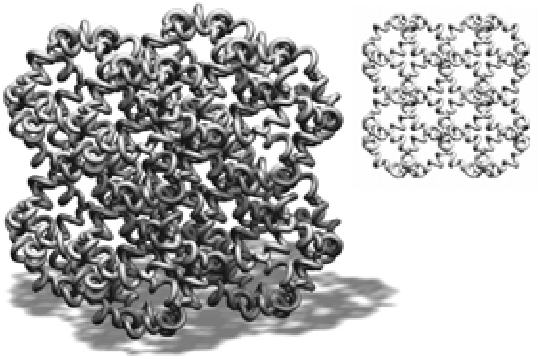

Figure 9: Helical strut matrix, Brennan-Craddock, 2008.

To conclude this broad review, it demonstrates that while new elastic materials are being developed and different kinds of flexible structures are being explored, little thought has been given as to their affective qualities. In the following, we therefore discuss the emotional characteristics of flexible structures in the context of the affective framework developed by Niedderer (2012).

3. Flexibility and emotions

Niedderer's work (2012) has explored how the movement inherent in flexible structures can be used as a medium for expressing complex emotions in design. Using Argentium silver and laser welding in the context of silver design, Niedderer has explored the notion of movement as an alternative to visual semiotic and appraisal approaches to create product expression. The study offers a soma-semiotic framework as an aid for creating and interpreting complex emotions in design, and which we utilise in the following.

The framework distinguishes expressive, functional and behavioural movement, which can have both concrete and symbolic meaning, and which is read through a combination of semiotic and somatic interpretation. Semiotic interpretation is based on the recognition of iconic, indexical or symbolic shapes and features, while the somatic reading is based on semiotic reading and empathic intuition (Niedderer 2012: 61–63). For example, in reciprocating (mimicking) someone else's smile we feel that someone else is happy. This intuition is capable of very fine discrimination, e.g. whether a smile is happy or sarcastic or sad (Shusterman 2011). Niedderer distinguishes three features as key elements of the framework. These include: semiotic and semantic object indicators, their individual emotional meaning, and the summative interpretation of all meanings as shown in Table 1 (2013: 65–66).

Table 1: Schema of soma-semiotic framework of emotion

Meaning Indicator	Description of movement/image	Soma-semiotic interpretation of individual movement/ image with regard to emotion	Soma-semiotic interpretation of combined movement/image with regard to emotion
Movement 1 (expressive/ functional/ behavioural)	…	…	…
Movement 2 (expressive/ functional/ behavioural)	…	…	
Visual image 1	…	…	

Niedderer further provides an example of how to use this framework to read artefacts which we offer here, and which we will follow in the subsequent discussion of examples.

> 'Fruit Bowl 1' [Figure 10] used 16 looped silver strips arranged in a 2-layered star shape to create a flattish ball shape, which transforms into a doughnut shape when laden with fruit, visualising the weight of the fruit. This construction is very springy and can be made to bounce as if in 'elated joy', displaying the corresponding movement qualities described by Walcott (1998: 893) for elated joy, i.e. high movement activity and dynamics. Thus far the design's expression was predicted, what was not predicted was that once the 'bowl' was laden with fruit, it sheared also sideways. With the fruit in the middle, the long silver

strips on the outside and the rolling movement (combined up-down as well as sideways movements), together, these components made the bowl not just ‘joyous’ but also comical, raising associations to a ‘drunken spider’ (body high up in the middle on long legs ‘wobbling about’). This is due to the combination of two contradictory emotions, that of joy (bounce) and fear (image of spider). The ‘wobbly’ sideways movement, signifying unsteadiness/drunkenness/incapacitation of a potential ‘danger’ (spider), can be seen to evoke relief as a third emotion. Below is a demonstration of the completed soma-semiotic framework grid [Table 2] to show that it can help with identifying the individual indicators and meanings for the analysis. (Niedderer 2012: 65–66)

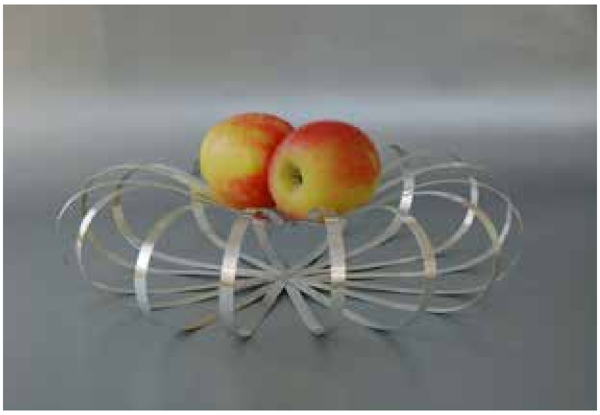

Figure 10: Fruit Bowl 1, Kristina Niedderer, 2009.

Table 2: Example of soma-semiotic framework completed for fruit bowl 1

<table>
<tr><td>Meaning

Indicator</td><td>Description of movement/ image</td><td>Soma-semiotic interpretation of individual movement/ image with regard to emotion</td><td>Soma-semiotic interpretation of combined movement/ image with regard to emotion</td></tr>
<tr><td>Movement 1 (expressive/ functional/ behavioural)</td><td>bounce +

high movement activity and dynamics</td><td>elated joy</td><td rowspan="3">Put together, joy (bounce) and fear/scariness (of spider) are a contradiction of emotions, which leads to a humorous reading. Especially when the third component, ‘unsteadiness/ helplessness’, is added, which can be read as incapacitating the potentially scary ‘spider’, the image becomes comical and elicits laughter and feelings of ‘fun’.</td></tr>
<tr><td>Movement 2 (expressive/ functional/ behavioural)</td><td>wobbly circular/sideways ‘rolling’ movement</td><td>unsteady, drunken, helpless</td></tr>
<tr><td>Visual image 1</td><td>visually heavy centre (fruit) +
long silver strips emanating from the centre</td><td>Heavy centre and centrally emanating strips are read as body and legs, inferring the image of a spider because of the similarity of their relationship/proportions. Spiders are widely perceived as ‘scary’ and associated with fear.</td></tr>
</table>

Before applying this framework to our own prototypes, it seemed useful to analyse one of the existing examples to understand the capabilities of the framework better. Due to its similarities (and subtle differences) with the previous example, we chose to analyse the flexible sphere by Kleemann, which is shown in Table 3. This analysis shows that the use of the framework is able to elicit quite subtle differences in emotions, based on the semiotic and somatic interpretation of the different indicators. One limitation of the analysis of this example is that we have not been able to hold the actual ball, but have worked from the images. Therefore we cannot say whether the object has subtle vibrations or bounce, etc., other than those reported by the maker (Kleemann 2012a, 2012b).

Table 3: Example of soma-semiotic framework completed for fruit bowl 1

Meaning Indicator	Description of movement/ image (as provided by the maker, Kleemann 2013)	Soma-semiotic interpretation of individual movement/ image with regard to emotion	Soma-semiotic interpretation of combined movement/ image with regard to emotion
Movement 1 (expressive/ functional/ behavioural)	Squeegee: it can be pressed between the fingers into a doughnut shape, resuming its shape following pressure release.	Fun (to squeeze) Holding tight (when squeezing) – tension, restraint Soft, squeegee – pliant, vulnerable Pushing back when squeezed – resistance	This object and the interaction with it invokes a complex set of emotions including those of the interactant as well as the perceived emotions of the object which takes on an animated character. These emotions include: the fun of squeezing the small object and of holding it tight as if restraining it, which together with its softness makes it feel 'vulnerable'. At the same time it 'pushes back' as if to regain its freedom and to make a bid for escape. Together, this can be seen to invoke a complex mixture of pleasure, power and care.
Movement 2 (expressive/ functional/ behavioural)	Bouncy, bounces off the wall	Energetic, active, quick	
Visual image 1	Visually intricate but abstract, possibly association with a small creature due to intricate surface which might remind one of fur or other organic material	Alive	

In the following, we describe first the design and technical development of the experimental pieces, followed by their affective analysis.

4. Creating flexible structures using AM metals

In this section, we describe the decisions made in selecting the design for the experimental work, and then how the design was developed technically in relation to formal considerations.

4.1 Design decisions

In spite of their free form potential, AM layer-build technologies each have their own practical limitations (Dean 2013: 170–173). SLM, the process used for prototypes in this research, in common with many other AM metal technologies, requires a sacrificial scaffold-like support structure to be built along with the part to counter the movement associated with cooling molten metal. Whilst this support structure is designed to be minimal and easy to remove, its addition pre-production in CAD and its manual removal post-production adds difficulty to an already costly process. Designs created for additive manufacture frequently exploit the technology's potential for geometric complexity and fine detail: support removal can be almost impossible in difficult-to-access forms and in finer sections where the strength of the break-away support comes closer to that of the part itself. In SLM support structure is needed to anchor the part securely to the build platform; beyond this it can be largely eliminated by designing within the limitations of the process. As a design builds up layer by layer from the machine platform substrate the added material is secured in place by the fused metal structure below. If the form develops within a certain angle to the vertical, usually around 40 degrees, the geometry can be self-supporting without the need for supplementary scaffolding support (see Figure 11) (Dean 2008).

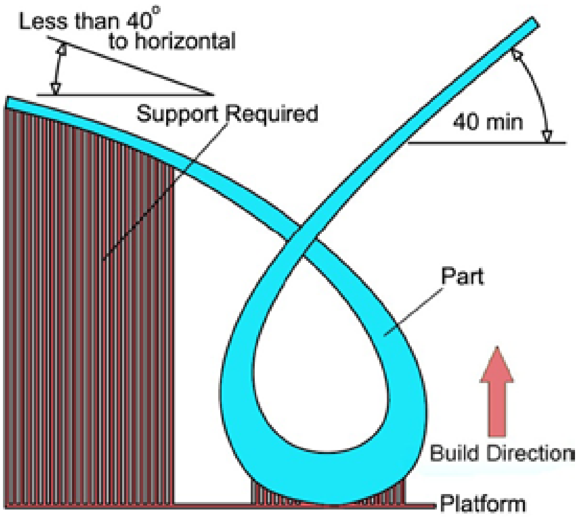

Figure 11: SLM support requirements.

An example of this is the Cuore pendent (Figure 12), the form of which is designed to maintain the growth of each of the fine tendrils within 40 degrees to the vertical.

While only a few designs have been considered to-date, it is clear that the outputs are likely to be geometrically complex as otherwise they could be equally well fabricated conventionally. In addition, the material sections must be fine enough to flex without undue force yet have their movement restricted to avoid plastic deformation. We are dealing therefore with relatively small, fine, jewellery pieces of complex geometry: support structure therefore presents a significant issue.

Figure 12: Cuore pendants on the build substrate. Photograph: John Vickers 3T RPD Ltd

4.2 Designing the prototypes

The first design considered developed from a set of 'conventionally' fabricated rings created by Niedderer in 1994 (Figure 13). The move to additive manufacture allowed for greater complexity in terms of the number of spring elements while the nature of the formed AM material restricted the design to finer movements than in the conventionally made pieces.

Figure 13: Three Rings, Kristina Niedderer, 1994.

The resulting form is effectively an array of springs arranged radially around the finger and joined by a rigid outer ring (Figure 14). As can be seen, the coiled leaf-shape of the spring element is designed to remain within 40 degrees to the vertical apart from the underside of the loop where the supports can be easily accessed and 'cleaned-off'.

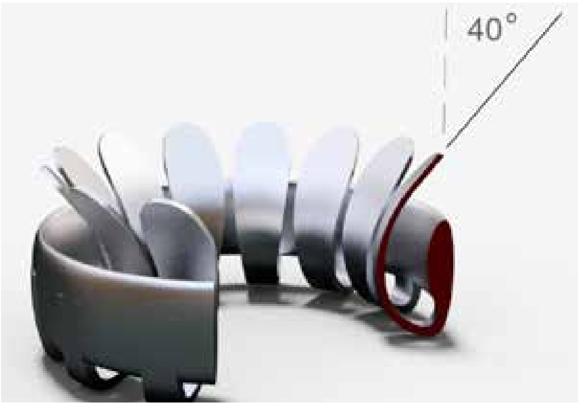

Figure 14: CAD model 'translation' of the original ring design, 2013.

The first problem encountered was that, because the material sections of the design were relatively fine and the elasticity of the material limited, the geometry could easily be damaged during its removal from the build platform substrate. As the SLM system was routinely used for more substantial geometries, common practice was to saw the pieces from the substrate. This proved inappropriate for our application and resulted in plastic deformation of the parts and a distortion of the radial arrays (Figure 15).

Figure 15: First test with deformed radial arrays after removal from the base plate.

Removal of the parts by wire erosion using an outside supplier solved this problem to an extent although the geometries remain prone to distortion during support removal. Where the fine supports can be gripped individually they can be removed with relative ease and without risk; where supports are grouped in confined spaces, however, their combined strength presents a problem. Support is typically added using pre-defined tools in either the technology provider's software or a proprietary AM file processing package such as Magics or Nettfab. The software flags up areas of risk to the build with a scale of colours. The amount and pattern of the support used to alleviate any problems is largely empirical, however, and based on the experience of the user. There are different types of support including square pillars and rectilinear sections. The pillars proved more effective in our application as they are more or less equally weak in all directions. Care had to be taken in placing these pillars because if placed too close to one another they would fuse together to become a single entity.

An example of the problems which support removal can present was provided by the initial test pieces. Following the failure of the first build and in spite of the restricted angles to the vertical fine supports were added internally to stabilise the geometry (Figure 16). These simple pillars were relatively fine and weak; on screen their removal appeared straight forward. In practice, however, access proved extremely difficult and the removal of each required threading a fine hacksaw blade through a tiny aperture. Until these internal supports were removed the affect of any movement could not be explored as the pillars effectively cross-braced and neutralised the spring.

Figure 16: Test pieces on base plate with additional internal supports, 2013.

The design was developed through a series of iterations exploring variations in the number of springs or radial petal forms, the cross-section of the spring along its length and the interface between spring and supporting band. The principal aim was to achieve an appropriate resistance. The problem proved to be in making the petal forms strong enough to avoid plastic deformation while at the same time maintaining some amount of flexibility. Reducing the number of springs allowed them to be wider, making them stronger laterally, to protect the radial array from plastic deformation whilst continuing to allow flexibility to resistive force to and from the centre

5. Putting emotions to the test: Interpreting the prototypes using the soma-semiotic framework

Once the first set of prototypes was developed sufficiently, we used the soma-semiotic framework to analyse the pieces with regard to their affective qualities and expression, as shown in Table 4.

Table 4: Example of soma-semiotic framework completed for ring prototype 1

<table>
<tr><th>Meaning Indicator</th><th>Description of movement/ image
(as provided by the maker, Kleemann 2013)</th><th>Soma-semiotic interpretation of individual movement/ image with regard to emotion</th><th>Soma-semiotic interpretation of combined movement/ image with regard to emotion</th></tr>
<tr><td>Movement 1
(expressive/ functional/ behavioural)</td><td>Squeezes, grips the finger</td><td>Grip, security, adjustment</td><td rowspan="3">The movement and force associated with Movement 1 dominates and, coupled with the technical/industrial aesthetic, the overall impression is of an adjustable device</td></tr>
<tr><td>Movement 2
(expressive/ functional/ behavioural)</td><td>Can be twisted or rolled radially against the finger

(more an aspiration as yet needs to be bigger)</td><td>Playful, distraction</td></tr>
<tr><td>Visual image 1</td><td>Visually intricate but with an overbearing technical, industrial aesthetic</td><td></td></tr>
</table>

The result of the analysis was that while the design had been intended to offer an aspect of playfulness, the current design actually emphasized perceptions of functionality. The design had been intended to be sized to fit the desired finger comfortably without any flexing of the geometry, the idea being that once in place the ring can rock against the finger. The unintended but predominant act, however, is to force the ring further down the finger or onto larger fingers working against the springs. The intended 'function' of the springs is perceived to be a 'one size fits all' adjustability which unfortunately masks and distracts from the playful aims. Now that the performance of the SLM material is better understood, the intention is to disassociate flexible movement from function and create less obvious movements that provoke a greater emotional response, for example the flexible ball ring illustrated in Figure 17.

Figure 17: Flexible ball ring design, Lionel Dean, 2013.

6. Conclusion

This research has embarked on a new area of research, which is the development of flexible structures through DMLS with the aim of creating emotional expression. The research was framed theoretically through an analysis of the nature of 'elasticity' and 'flexibility'; through a review of existing flexible structures and their uses; and through an overview over current uses and developments of flexible structures using SLM.

The theoretical part was complemented through the development of a series of experimental prototypes using DMLS. The experimental pieces were developed firstly to explore the creation of flexibility using DMLS from a technical point of view, and secondly to understand how this flexibility can be used to enable emotional expression. The latter was assessed through analysis of both examples and results using the soma-semiotic framework developed by Niedderer.

The outcome and contribution of the research are twofold:

Firstly, a better understanding of the structural geometries and potential uses of flexibility in AM as well as of its expressive potential.

Secondly, it has shown the benefit of the soma-semiotic framework in analysing given examples with regard to their affective expression. In our case, the analysis has enabled a better understanding of the deficits of the current prototypes with regard to emotional expression.

In response to the findings, in future research we will investigate movements that are both unrelated to function, to avoid misinterpretation, as well as less obvious movements that are likely to provoke a greater emotional response.

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