# Improved performance of mechanical springs - Mechanical springs of amorphous steel

Project within FFI – Vehicle development

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## Content

# 1. Executive summary

The aim of the project was to develop lighter spring geometries while maintaining or improving performance. Mechanical springs are an important part of many different components in modern high performance vehicles. They are used in for example shock absorbers and in different types of valves. The performance of the springs affects the comfort, reliability, economy and safety of the vehicle. It is important in many applications to minimize the weight of the spring. Not only to reduce the vehicle's total weight, but also because the spring response is dependent on the weight, ie. the unsprung weight. A light spring reacts faster than a heavy spring and the dynamic properties can hence be improved by reducing the weight of the spring.

In this project, weight-optimized mechanical springs have been produced using additive manufacturing (AM). The optimized spring geometries developed within the project are difficult to produce using conventional methods, thus making AM a prerequisite for their production. Apart from the geometric freedom, AM also allows for local control of the microstructure and thus the material properties in a way that is not possible with conventional manufacturing methods. This is possible since the component is built additively as new powder is added and melted together with the solidified parts. The manufacturing process also allows for high cooling rates, enough to make it possible to achieve an amorphous structure. Metals with amorphous structure have excellent mechanical properties, both high strength and high elasticity, which leads to a high ability to store elastic energy. In this project the possibilities to reduce weight and improve dynamic behaviour of mechanical springs, using both new geometries and new materials, have been investigated.

Within this project we have shown that it is possible to produce iron-based amorphous metals in bulk dimensions using AM. These findings have attracted a lot of attention by the media and have been reported in a press release from Exmet and Mid Sweden University as well as articles in Ny Teknik. Both electron beam based and laser beam based AM methods have been used, and by changing the process parameters the microstructure can be controlled locally, ie. amorphous or crystalline. The specimens that have been produced within the project have had a relatively large amount of voids or micro-cracks, and the limited resources in the project have restrained further efforts to optimize the process for this new material. To reach the goal of producing mechanical springs with reduced weight and improved dynamic behaviour, a crystalline Titanium alloy was used instead. Using numerical tools, a new, optimized spring design was conceived for mountain bike suspension systems and produced by AM. The weight of these springs is about 25% of the weight of a standard spring used today. The new springs were evaluated in several fatigue tests as well as subjected to track tests, mounted on a professional mountain bike. The results show very good results and this new spring design will be commercialised by project partners.

# 2. Background

The purpose of this project was to develop optimized mechanical springs with reduced weight by using additive manufacturing. Additive manufacturing enables the production of new geometries which will reduce the weight without decreasing the performance of the spring. These new geometries are difficult to achieve with conventional production techniques but can relatively easy be made by AM-methods. In a next step the purpose was to further increase the performance of the spring by making the spring in amorphous steel instead of conventional crystalline materials. This will lead to a dramatic reduction of the weight of the spring and a significant increase in the dynamic performance of the spring. In the following a short description is given of mechanical springs, amorphous metals and their properties and applications.

## 2.1 Mechanical springs

Mechanical springs are an important part of many different components in modern high performance vehicles and they are, for example, used in shock absorbers and in several different types of valves. The performance of the springs affects the comfort, reliability, economy and parts of the vehicle´s safety system. In many applications it is important to minimize the mass of the spring not only because the vehicle's total weight is reduced but also because the spring response is dependent on the weight. A light spring reacts faster than a heavy spring and the dynamic properties can be improved if the spring mass is reduced. Mechanical springs have been used for a long time and both geometry and materials have undergone gradual improvements that led to slowly improved spring performance.

## 2.2 Amorphous metals

When a metallic material is cooled from the melt to the solid phase a polycrystalline structure is usually obtained. In such a micro-structure, the atoms in each grain are arranged in a regular pattern. The number of grains and the size of the grains can be changed by, for example, using different cooling rates from the melt or by various types of mechanical processing and heat treatment of the solid material. If the entire material is composed of only one crystal, the specimen is a single crystal material in which all the atoms are placed in a regular manner. If the atoms instead are completely disordered without grains with ordered structure it is said to be an amorphous material. This can be achieved for example by cooling a melt very rapid so that no grains have time to grow, or by extensive mechanical deformation of the crystal grains. Amorphous metals have been known since the 60s, but they required very high cooling rates for forming an amorphous structure and thus only micrometer thick stripes could be manufactured. Not until the early 90s Professor Inoue in Japan [1] succeeded in developing several multi-component systems consisting of common metallic elements that gave rise to an amorphous bulk structure, i.e.

millimetre thick structures, upon cooling from the melt. In subsequent years, a variety of amorphous metal systems have been found see e.g. Miller and Liaw [1, also 1] or Greer [2] and Burgess and Ferry [3]. Amorphous bulk metals have a number of typical characteristics that makes them unique and distinguishes them from conventional crystalline metals. The absence of a regular structure for these materials gives a much higher yield strength and a significantly higher elastic elongation. Figure 1 shows the strength and E-module for some amorphous (marked red) and crystalline (marked in black) alloys. Amorphous metals have an elastic elongation of approximately 2% while the crystalline metal in the figure has an elastic elongation of approximately 0.65%. The ideal or theoretical strength is represented by the blue line and an elasticity of about 5%.

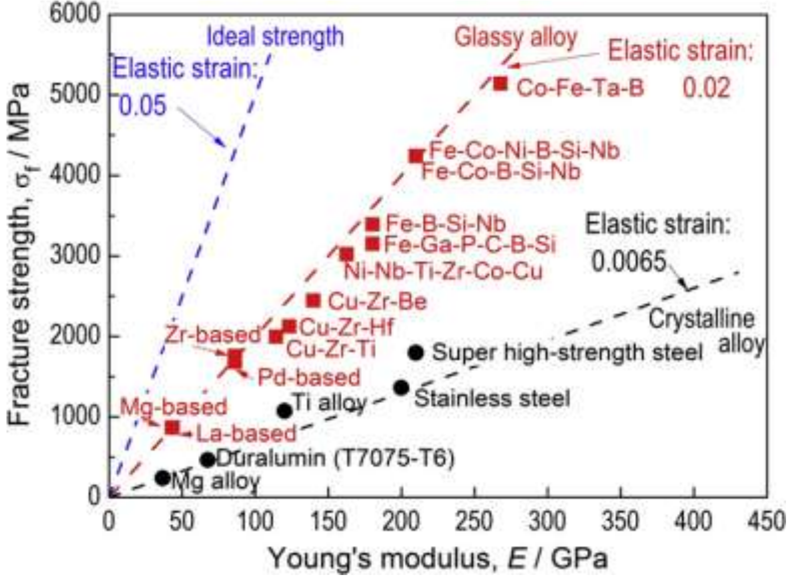

*Figure 1. Strength as a function of Young's modulus for selected amorphous and crystalline alloys. The straight lines in the figure represents the elastic strain for the materials, from Inoue et. al [4].*

The combination of high strength and relative low Young's modulus leads to a high elastic strain at the yield point, several times higher than for conventional metals. A consequence of this is that the elastic energy storage capacity is much higher than for crystalline metals. The structural characteristics are also discussed Ashby and Greer [5].

Amorphous bulk metals have been commercialized in various sports applications, such as golf clubs and baseball bats where the high strength combined with their good elastic properties are utilized for increased performance. Other applications where the high strength and hard surface are useful is in casings for electronics such as cell phones, computers and USB sticks. These applications have been commercialized by the US company Liquidmetal Technologies (www.liquidmetal.com) and are all based on Zirconium, which is a relatively expensive metal and has strength comparable to crystalline steel. Intensive research has been carried out to produce iron-based amorphous metals, partly because they have extremely high strength, but also because their high resistance to corrosion and the low price compared to the Zirconium-based alloys [6, 7]. In a large US research project (SAM, Structural Amorphous Metals), funded by DARPA (Defense Advanced Research Projects Agency) over 40 amorphous iron based alloys have been produced [6,7]. The applications for these alloys range from extremely corrosion-resistant and high-strength containers for nuclear waste to coatings for ship hulls. Other proposed applications for amorphous steel are in machining and tunnel boring [6,7]. Amorphous steel has also been commercialized in "Shot peening" applications [1, 4, 8] where small metal spheres impact the surface of a metallic part in order to induce compressive stresses on the surface and increases the parts fatigue strength. The examples above show that amorphous steel has excellent mechanical properties and that their endurance against repeated cyclic impact loading [1, 4, 7, 8] indicates that they can be applied in many engineering applications. Inoue and Takeuchi [4] shows that the fatigue strength of a commercial amorphous alloy steel called SENNTIX is 2.3 GPa at $10^7$ loading cycles, which is much higher than for crystalline steel alloys. An interesting application is mechanical springs where a thesis [9] performed at Saab Bofors Dynamics shows that weight reductions of 80-90% compared to an existing design is possible. The possibilities to exploit the high capacity to store mechanical energy in spring applications are also discussed by Ashby and Greer [5], Qiu and Ren [10] and Salimon et. al. [11]. The commercial success of amorphous metals have been limited by the difficulties to achieve sufficiently high cooling rates throughout the whole component. A new method, patented by Exmet AB, describes how additive manufacturing can be used to obtain an amorphous structure in the entire component. In additive manufacturing a component is built layer by layer by melting the metal powder in each layer with a computer controlled laser or electron beam. Since only a small amount of material is melted at any given time, high cooling rates can be achieved.

# 3. Objective

The aim of the project was to develop lighter spring geometries while maintaining or improving performance. These new geometries are difficult to produce using conventional manufacturing methods, thus necessitating the use of additive manufacturing. The use of additive manufacturing also makes it possible control the local material properties throughout the component in a way that is not possible with conventional manufacturing methods. The expected results were at the time of application defined as follows.

Goals:
- Manufacturing of prototype springs
- Manufacturing of test specimens of amorphous steel
- Manufacturing of springs in the amorphous steel

Impact:
- Components and vehicles that is lighter, resulting in lower fuel consumption
- Vehicles with reduced unsprung weight and also improved dynamic properties
- Introduction of free form fabrication, or AM, for product development in the automotive field
- Introduction of amorphous metals in the automotive industry

- Enhanced collaboration between academia and industry

# 4. Project realization

The project began with selecting and acquiring suitable powder materials. The alloys must not only have an ability to form an amorphous microstructure, they must also show appropriate mechanical properties, and otherwise fulfil the powder metallurgical demands of the AM-process such as flowability and particle size criteria. Next, process development started with building specimens of simple test geometries. The specimens were evaluated regarding processability and as-manufactured properties of the various alloys. Numerical simulations were also initiated with the aim of supporting the process development work by identifying critical process parameters related to cooling rates and residual stresses. Further numerical simulation work aimed at optimizing spring geometry regarding weight and performance. Several numerical tools were used, including LS-DYNA, Impetus Afea Solver, Octave, and in-house developed code. Combining the knowledge gained from process development and design-work based on numerical simulation, the optimized springs were finally manufactured and evaluated.

## 4.1 Manufacturing processes

In this project, two established AM-technologies where the metal powder is directly melted by a beam were used; EBM (Electron Beam Melting) and DMLS (Direct Metal Laser Sintering). The two methods differ in process conditions and powder requirements, but it is not yet known if one of the processes is more suitable for processing amorphous metal components than the other.

The EBM process is characterized by significant pre-heating of the metal powder before the parts are actually built. This is done to increase the electrical conductivity of the powder bed, thereby preventing charged particles from moving when they are bombarded with electrons. No such pre-heating is needed in the DMLS-process. Another difference in process conditions is atmosphere. The EBM method requires vacuum, while the DMLS process takes place in an atmosphere of nitrogen or argon. Layer thickness and metal powder particle size is much larger in EBM than in DMLS, which results in higher productivity but also inferior surface roughness and detail resolution. Regarding energy input, the EBM-system outputs an effect up to 4,5 kW while the DMLS-system used in this project is limited to 200 W. These process differences lead to different thermal gradients and cooling rates, and hence the resulting microstructures will also differ from the two types of technologies.

In this project, an EBM-system located at Mid Sweden University in Östersund was used. DMLS experiments were carried out by Exmet in close co-operation with EOS, a leading supplier of laser-based AM-machines, and with a partner in the USA.

Three iron-based amorphous alloys were examined in this project using both AM-technologies mentioned above. Furthermore, a standard titanium alloy of type Ti-6-4, was used in the EBM-process. The metal powders and the EBM process is described in more detail by Koptyug et al (14).

*Table 1. Metal powders*

| Powder 1 | Powder 2 | Powder 3 | Powder 4 |
|---|---|---|---|
| $Fe_{51}C_{15}Mo_{14}Mn_{10}B_6BCr_4$ | $Fe_{74}P_{10}C_{7.5}Mo_4B_{2.5}Si_2$ | Fe-based (confidential) | $Ti_{89.707}Al_6V_4O_{0.15}Fe_{0.1}C_{0.03}N_{0.01}H_{0.003}$ |

# 5. Results and deliverables

Here follows a summary of the results. First, the results of the process development for additive manufacturing of amorphous metal are reported, followed by the results of designing, manufacturing, and evaluating the weight-optimized spring.

## 5.1 EBM-manufactured iron-based alloy

Numerous experiments were performed using EBM with Powder 1 and Powder 2 listed in Table 1. Left part of Figure 2 shows an example of a 50x50 mm test sample of Powder 1. Original thickness was 5 mm, but the photo shows the sample ground to 4 mm to show the internal microstructure. The sample was evaluated using light optical microscopy (LOM), scanning electron microscopy (SEM), and x-ray diffraction analysis (XRD). The results show that the sample is amorphous with nanocrystalline areas. Hardness was measured to 63 HRC. The two right-hand photos in Figure 2 show several 20x20 mm test samples built to 3 mm thickness. These samples were made of Powder 2, and are surrounded by partially sintered powder.

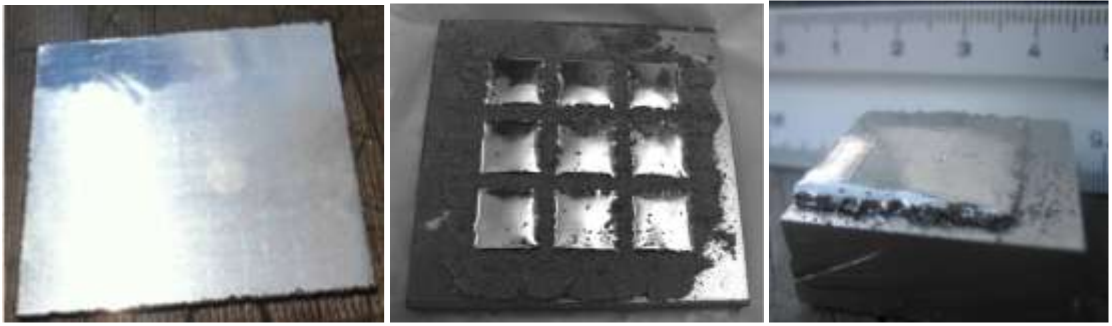

*Figure 2. Specimen 50x50x4 $mm^3$ manufactured from powder 1 (left). Specimens 20x20x3 $mm^3$ manufactured from powder 2 (centre and right).*

LOM studies of the microstructure of these samples of Powder 2 show that there are even more distinctly separate regions, “islands”, of crystalline structure in an amorphous matrix, compared to the samples of Powder 1. Figure 3 (right) shows the microstructure of a polished cross-section of one of the test samples (left), and areas with different microstructure can easily be distinguished.

*Figure 3. Specimens (left), and microstructure of specimen (right) manufactured from Powder 2. The upper and lower parts are amorphous, while the centre is partially crystallized due to manual changes in process parameters.*

## 5.2 DMLS-manufactured iron-based alloy

Numerous test samples were also produced using DMLS and different powders. A selection of typical samples is shown in Figure 4.

*Figure 4. Samples of Powder 3 made with DMLS.*

Both cylindrical and cubical sample geometries were produced, and sizes ranged 5-15 mm in diameter/side length and 7-10 mm in height. Several specimens had a high degree of amorphous microstructure while others contained a mixture of amorphous and nanocrystalline structure. Figure 5 shows results from XRD analyses performed to characterize the structure.

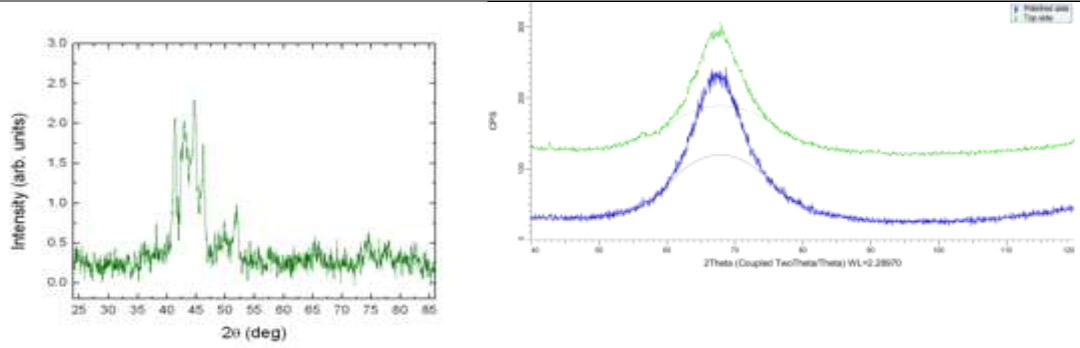

*Figure 5. XRD (X-ray diffraction) analysis results from material manufactured from Powder 3 (left) and Powder 2 (right). The left hand figure shows plenty of peaks, which*

*indicates that the material is partly crystallized, while the softer curve to the right is typical of an amorphous material.*

LOM analyses of the microstructure show that there are pores and microcracks in the material. This can be expected in the early stages of process development when the process parameters are not yet optimised. Fine-tuning of laser parameters will normally remove such porosity. The results also indicate that the chosen alloys are brittle and sensitive to cracking. It is known that the properties of amorphous metals generally are highly dependent on temperature, and it is to be expected that process conditions such as temperature, atmosphere, and laser parameters will need to be thoroughly investigated before amorphous iron based components can be produced.

## 5.3 Results Comment - amorphous metal

The project has proven that it is possible to produce amorphous iron based metals in bulk, i.e. samples with dimensions of tens of millimetres, using additive manufacturing. This was also publically announced in a press release [15] and in an article in the weekly technology magazine Ny Teknik [16]. This was achieved by using both electron beam- and laser-based AM methods, and by changing process parameters it was shown that the ratio of amorphous to crystalline structure could be affected. However, the test sample materials that were produced showed too high amounts of porosity and microcracks. Therefore it was not possible to produce prototype springs in amorphous metal in this project. Process optimisation was interrupted before reaching satisfactory results due to the limited project time frame and lack of resources. In order to achieve the target of producing mechanical springs with optimized design by additive manufacturing, it was decided that a conventional crystalline titanium alloy would be used instead for building the components.

## 5.4 Numerical simulation - optimization of spring geometry

The most common type of spring is the coil spring. It consists of a solid wire wound into the form of a helix. This type of spring is also the most common type for vehicle suspension systems, and the type of spring chosen as the most interesting for this project. In Figure 6 a section through such a spring together with the shear stress distribution over the solid wire cross-section is shown.

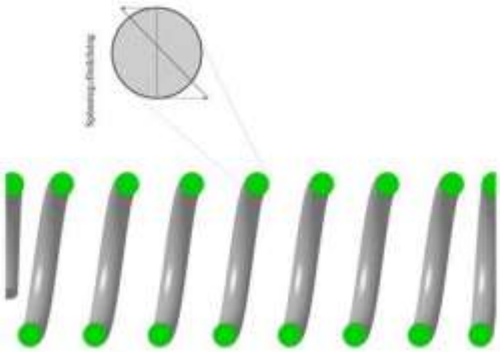

*Figure 6. Cross section through a coil spring and associated shear stress distribution.*

As can be seen from the figure, the stress is zero at the centre of the wire, and the stress at the wound wire's inner track is higher compared to the corresponding point at the outer track. This design does not allow for full exploitation of the materials strength, thus different alternative designs were conceived and evaluated using numerical models. The outcome of this work was a spring design based on the use of a wire with a channel, ie. a hollow wire, where the centre of the channel is eccentrically placed in relation to the wire's centre line. This geometry is difficult to manufacture with conventional manufacturing methods, but not with AM. With these changes to the spring design, a more homogenous stress distribution is achieved across the cross section, ie. the capacity of the material is exploited to a higher degree, see Figure 7.

*Figure 7. Example of optimized spring geometry, overview and detail. Note the eccentric channel in the wire.*

Several standard spring dimensions were optimized and evaluated at Öhlins Racing's request. For the optimized springs a dramatic weight reduction is achieved. Typically the weight can be reduced from about 600 g to 160 g for an Titanium alloy and to 50 g for amorphous steel. The reduced mass of the spring results in a lower total weight of the vehicle, as well as improved dynamic behaviour. The animation shows the dynamic behaviour of a standard spring (left) and an optimized amorphous spring (right) as they are compressed and then released. Note the faster response of the optimized spring when unloading.

## 5.5 Prototypes - Titanium

The project produced three types of spring prototypes. In Figure 8 two of them, manufactured with EBM, are shown.

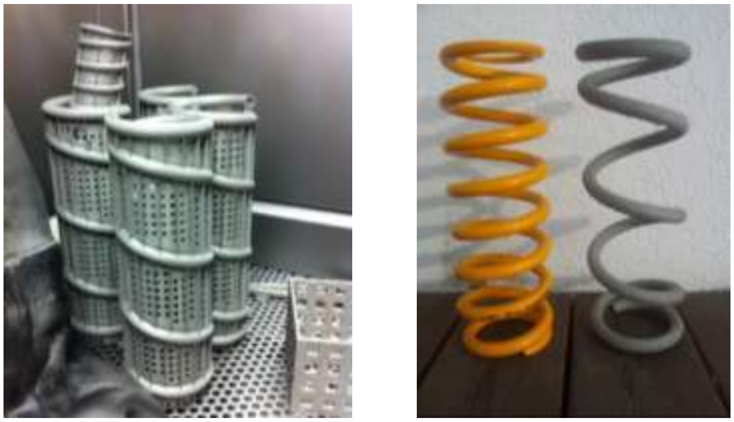

*Figure 8. Prototype springs with support structures in the blast box (left) and comparison of standard spring and prototype spring with support structure removed (right).*

Some of the prototypes were HIP:ed (Hot isostatic pressing) to reduce pores and then tested in the test rig and compared to the untreated springs. A number of design problems were identified that were considered in the development of the third spring prototypes. For the third prototype a smaller spring for mountain bikes was selected. In Figure 9 the yellow standard spring mounted on shock absorbers as well as the optimized spring is shown.

*Figure 9. Prototype Generation three along with standard spring mounted on shock absorbers for mountain biking.*

The optimized spring prototype was fatigue tested accord to a standard test program for suspension systems and the results were evaluated according to the applicable technical specifications. Overall, the results were good, and a number of necessary design changes before commercialization were identified. Work on this has begun outside the scope of the project. As a final activity, a test was conducted on a mountain bike track with the prototype mounted on a mountain bike. The driver was a professional mountain bike rider and the test was conducted in California in December 2014.

*Figure 10. Track test of the prototype spring by professional mountain bike rider.*

The prototype attracted much attention among the participants and spectators on the test track. Öhlins Racing has decided to proceed with the development and commercialize spring construction, outside the framework of the project.

### 5.6 Contribution to the FFI goals

The project has in many ways contributed to the objectives that are relevant to the FFI program. Efforts to develop the patented method to produce amorphous metals using additive manufacturing has led to industry-relevant technology and will continue beyond this project with leading high-tech companies, materials technology companies and manufacturers of AM equipment. Within the project, new methods for optimizing component geometries has been developed and applied and components then manufactured using additive manufacturing. AM is a manufacturing method that gives the designer extensive geometrical degrees of freedom together with short lead times, low energy consumption and almost no material waste. The project has thus helped improved the competitiveness of Swedish automotive industry and led to industry-relevant technology and skills development. The optimized springs will be introduced to the market by Öhlins and the project has thus provided a concrete and relevant contribution to Swedish industry. In the wider context, the project has led to increased collaboration between new industrial constellations and universities, which will survive the completion of this project.

## 6. Dissemination and publications

### 6.1 Knowledge and results dissemination

The knowledge generated is spread not only among the project participants but has also been presented at international conferences and through other open publications. Furthermore, a major part of the knowledge generated can be applied to product development in other industries than the automotive industry. For example, the optimization methods and techniques used here can be applied to other applications and components. The increased knowledge and awareness of AM technology in general has also increased as part of the project and the mechanical springs designed are likely to be one of the first AM components that are commercialized in the automotive industry. This will lead to increased awareness of the methods used in the project.

### 6.2 Publications

- Koptyug, A .; Rännar, L.-E .; Backstrom, M. & Langlet, A. Bulk Metallic Glass Manufacturing using Electron beam melting. International Conference on Additive Manufacturing & 3D Printing, 2013.
- Mid Sweden University and Exmet AB. Unique breakthrough for manufacture of amorphous metal [Press release]. 2012.
- 3d-skrivare bygger glasartat superstål. Article in Ny Teknik. 2012.
- Invited presentations at Volvo cars, Autoliv, Scania, the Swedish PM (Powder Metallurgy) day and the Vinnova/FFI day.

## 7. Conclusions and future research

In this project it has been shown that it is possible to produced iron-based amorphous metal using additive manufacturing methods. Extensive work remains to optimize the process to achieve an industrial acceptable material quality. This work is continued in co-operation with a number of industrial and academic partners outside the current project. The project also has shown that it is possible to produce spring components with optimized geometries that are not possible to produce using conventional manufacturing methods. The Titanium spring developed within the project will be improved and commercialized by project partners.

In conclusion:

- In the project it has been shown that it is possible to produce iron-based amorphous metals with AM technology.
- Extensive work remains to achieve an industrial acceptable material quality
- AM technologies allows for manufacturing of components with optimized properties
- A new type of mechanical spring with 75% weight reduction has been developed and will be commercialized

## 8. Participating parties and contact person

The project has been carried out by the organizations listed below. Contact details of representatives are also given.

| | | |
|---|---|---|
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