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第 35 回本田賞授与式 記念講演（2014 年 11 月 17 日）

「技術革新の成長と限界における材料の役割」

レオーベン鉱山業大学 金属物理・材料試験学部長

ヘルムート・クレメンス博士

The role of materials in progress and limit of technological evolution

Commemorative lecture at the 35th Honda Prize
Award Ceremony on the 17th November 2014

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■生まれ

1957年7月26日	クラーゲンフルト ケルンテン州 オーストリア生(オーストリア国籍)

■学　歴

1983年	レオーベン鉱山業大学材料科学科 修士課程修了
1987年	レオーベン鉱山業大学材料科学科 博士課程修了（工学博士）
1997年	レオーベン鉱山業大学金属間材料の大学教員資格（博士課程後の講義資格）取得

■職　歴

1987年～90年	レオーベン鉱山業大学 物理学部にて 研究助手
1990年2月 ～97年2月	プランゼー株式会社 「金属間材料」研究開発グループ長
1997年3月 ～2000年6月	シュトゥットガルト大学 金属物理学研究所 教授
2000年7月 ～03年6月	ヘルムホルツ・センター、ゲーストハッハト (Helmholtz-Zentrum Geesthacht) 材料研究所所長　「金属物理学」「新材料」「中性子の活動」という研究領域の責任者を務めるかたわら、クリスティアン・アルブレヒト大学キールの教授も兼任
2003年7月 ～現在	レオーベン鉱山業大学 教授 金属物理・材料試験学部長

■BORN

July 26, 1957 in Klagenfurt, Carinthia, Austria
(Austrian citizenship)

■EDUCATION AND TRAINING

1997:	Habilitation (Postdoctoral Lecture Qualification). Subject: Intermetallic Materials; Montanuniversität Leoben
1987:	Ph.D. (Dr. mont.), Montanuniversität Leoben, Materials Science
1983:	M.S., Montanuniversität Leoben, Materials Science

■EMPLOYMENT HISTORY

Montanuniversität Leoben, Professor, Head of the Department of Physical Metallurgy and Materials Testing, 7/2003 - present.

Helmholtz-Zentrum Geesthacht, Head of the Institute for Materials Research. Responsible for the areas “Metal Physics”, “New Materials” and “Neutron Activities” in a joint appointment as Professor at the Christian Albrechts University of Kiel, 7/2000-6/2003.

University of Stuttgart, Professor, Institute of Physical Metallurgy, 3/1997-6/2000.

Plansee AG, Head of the R&D group “Intermetallic Materials”, 2/1990-2/1997.

Montanuniversität Leoben, Research Assistant at the Department of Physics, 1987-90.

■略　歴

ヘルムート・クレメンス博士は構造用金属間化合物材料の分野において、国際的に最も高名な専門家の一人で、γ-TiAl 基合金と呼ばれる軽量チタンアルミ金属間化合物に重点を置いた研究をしています。TiAl 合金の最も重要な利点は、現在使われているニッケル基超合金と比べて重量がほぼ半分であることです。クレメンス博士の研究グループと彼の産業界のパートナーによって開発された合金および加工技術は、次世代環境対応燃焼エンジンの開発を実現するための重要な要素として考えられており、この合金はエンジン内の重い超合金の部分的代替を可能にします。クレメンス博士は、レオーベン鉱山業大学（オーストリア）金属物理・材料試験学部長を務めており、その科学分野における業績に対し、1983年にレオーベン鉱山業大学の修士論文学長賞（Rektor-Platzer-Ring）、1995年にドイツ材料科学学会のゲオルク・ザクス賞（Georg-Sachs Prize）、2006年にオーストリア産業連盟の産業による大学研究賞、2010年に B&C 財団（オーストリア）のヴォルフガング・ホースカ賞（Wolfgang-Houska Prize）など、多数の賞を受賞しています。

■BIOGRAPHICAL SKETCH

Helmut Clemens is one of the internationally most renowned experts in the field of structural intermetallic materials, with particular focus on light-weight titanium aluminides, so-called γ-TiAl based alloys. The most important advantage of TiAl alloys is their almost half specific weight, when compared to the presently used Nickel-base superalloys. The alloys and processing technology developed by the research group of Dr. Clemens and his industrial partners are considered as key elements to be used in the next generation of eco-friendly combustion engines, where they partly replace heavy superalloys. Dr. Clemens is the Head of the Department of Physical Metallurgy and Materials Testing at the Montanuniversität Leoben in Austria. For his scientific contributions, Dr. Clemens was awarded the Rektor-Platzer-Ring of the Montanuniversität Leoben in 1983, the Georg-Sachs Prize of the German Society of Materials Science in 1995, the University Research Award of the Industry of the Austrian Industrial Society in 2006, and the Wolfgang-Houska Prize of the B&C Foundation, Austria, in 2010, among others.

■主な出版物

Advanced Intermetallic TiAl Alloys:
(with S. Mayer), Advanced Engineering Materials, Review Article, 2012.

Technology and Properties of Advanced γ-TiAl Based Alloys:
(with several co-authors), Int. Journal of Materials Research and Advanced Techniques, 2009.

Neutrons and Synchrotron Radiation in Engineering Materials Science:
(edited with W. Reimers, A.R. Pyzalla and A. Schreyer), Wiley-VCH, Weinheim, Germany, 2008.

Gamma Titanium Aluminides 2003:
(edited with Y-W. Kim and A.H. Rosenberger), TMS, Warrendale, USA, 2003.

■MAJOR PUBLICATIONS

Advanced Intermetallic TiAl Alloys:
(with S. Mayer), Advanced Engineering Materials, Review Article, 2012.

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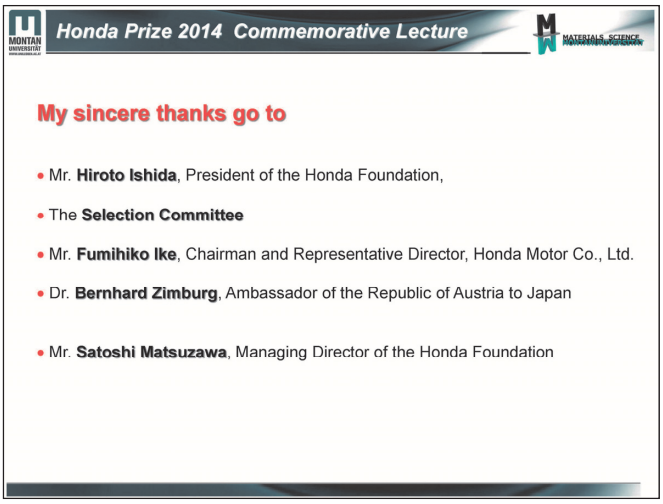
このレポートは、2014 年 11 月 17 日　東京、帝国ホテルにおいて行なわれた第 35 回本田賞授与式記念講演の要旨をまとめたものです。
This report is the gist of the commemorative lecture at the 35th Honda Prize Award Ceremony at the Imperial Hotel, Tokyo on 17th November 2014.

The role of materials in progress and limit of technological evolution

Helmut Clemens



Ladies and gentleman,

in my lecture I will talk about the "Role of materials in progress and limit of technological evolution".

I have tried my best to arrange the lecture as comprehensive as possible, because I know that not everybody in the audience has a background in materials science. As an academic teacher, however, I hope that after these 60 minutes all of you will be well-educated materials experts and you will understand the important role of materials in technical progress and human history.

Before I start with my lecture I would like to thank the Honda Foundation for this great honor. To be awarded with the Honda Prize and thus being a part of its remarkable tradition is the high point in my scientific life. I will never forget this extraordinary ceremony and the gathering of such distinguished guests.

My sincere thanks go to Mr. Hiroto Ishida, President of the Honda Foundation, as well as to the Selection Committee for selecting me and my scientific work for this award.

I want to thank Mr. Fumihiko Ike, Chairman and Representative of the Honda Motor Company.

In addition I thank Dr. Bernhard Zimburg, the Austrian ambassador to Japan, for attending this beautiful ceremony and for giving my wife and me a feeling of home.

I also thank all other distinguished guests who took their precious time to attend this special event.

Last, but not least I would like to thank Mr. Satoshi Matsuzawa, Managing Director of the Honda Foundation, and his team for their kindness, organizational talent and wonderful professional assistance.

Finally, I thank you all for attending this ceremony.

In my lecture I will show that the scientific and technological achievements by my partners and me fit very well with the eco-technology concept of the Honda Foundation, meaning to protect and preserve our ecological systems by advanced technological solutions.

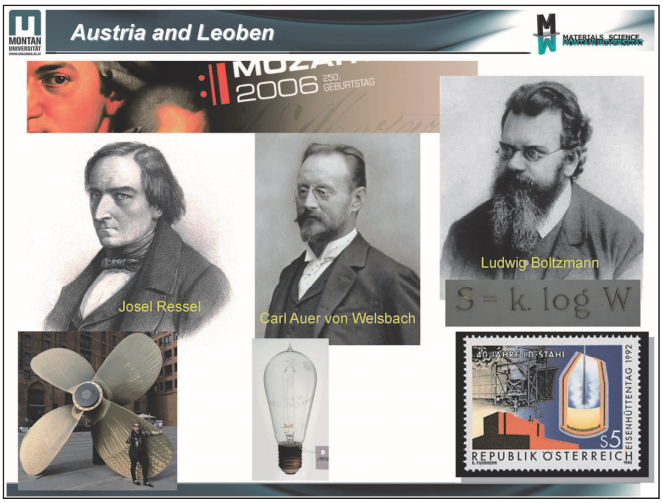


Fig 1

〈Fig 1〉 Even though Austria is a small country there are a number of Austrians which are known all over the world. One example is Wolfgang Amadeus Mozart and his music. However, if you do not like his music, you might like the so-called "Mozart Kugel" which is a delicious candy. And this is my first example of an advanced materials concept. If you cut such a candy into two halves you can see that it consists of layers of sweet materials. If you eat it, the different constituents start to mix in your mouth and a special taste is created.
Such an arrangement, where the layers consist of different technical materials, is called a composite material. Modern composite materials are used in many technical applications, but also in sport equipment.

Now I want to introduce some Austrians which are by far not as famous as Mozart, but whose inventions had an enormous influence on the development of our society.

Who of you knows the name of this person (left)? His invention is of a particular importance for Japan which has a heavy ship building industry. His name is Josef Ressel and he invented the ship propeller. Another Austrian invention, believe it or not, is the torpedo. The development of this weapon dates back to the time when Austria had its own navy.

The next person has contributed to the break-through of electric lighting (Center). His name is Carl Auer von Welsbach. He has not invented the light bulb, that was Thomas Edison, but he was the first who introduced a metal with a high melting point as filament material. The metal filament increased the working life of the light bulb considerably. This invention – which is an example of how materials determine technical progress and evolution – has not only illuminated the world, but also ignited the research on high-melting materials such as tungsten and molybdenum. With the need for high quantities of refractory metals a new technology was developed, namely powder metallurgy. In the beginning of the last century, all

over the world companies were founded for the manufacturing of high-melting materials. In Austria, for example, Plansee was founded which is still a leading company in the field of powder metallurgy. I am proud that I was working for Plansee for almost 8 years. During this period I started my research on intermetallic Titanium Aluminides.

The next Austrian I would like to introduce is a person whose scientific work had a great influence for physics as well as materials science. His name is Ludwig Boltzmann (right) and his main achievement is even carved in his gravestone. The entropy, marked with the letter S, is an important state variable in thermodynamics. Thermodynamic calculations, for example, can be used to establish phase diagrams for complex material systems. And this, of course, is important for materials development.

Finally, I would like to show an invention which has revolutionized steel making, the so-called LD process. L stands for Linz, also a city in Austria, and D stands for Donawitz, which is a district of Leoben. Leoben, in turn, is the location of my university.

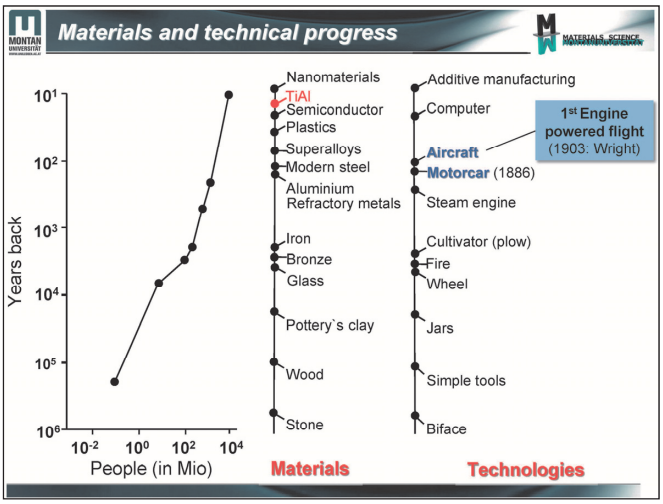


Fig 2

〈Fig 2〉 In this slide it is shown how the global population increased with time. A drastic increase took place during the last 200 years.

In the right part of the slide I will now demonstrate how materials have determined the technological progress of mankind.

In the beginning, stone and wood were used to produce the first simple tools, which, however, gave human beings an advantage over animals, but also over fellow men which had not yet reached such a step of development. With the manufacturing of jars it was, for example, possible to preserve food or liquids.

With the invention and use of the wheel the first big step towards a “mobile” society was done. Another giant leap was the start of metallurgy. For the first time metals and their alloys could be produced in larger quantities. There it was necessary to construct furnaces where the temperature was high enough to carry out reduction processes and melting operations. With the invention of a cultivator a step towards a settled society was done.

A complete change came to our society with the development of the so-called modern materials, such as Aluminum, refractory metals, modern steels, and superalloys, which were absolutely necessary to realize new inventions, such as a steam machine, an automobile or an aircraft, which of course have changed their appearance since their first introduction to the market.

For example, the first engine powered flight took place 1903. The weight of the aircraft was about 340 kg. Today, a fully loaded Airbus A380 has a mass of about 600 tons. However, you will hear much more about aircrafts and their engines during this lecture.

With the development of polymeric materials, the human society has entered the “Plastic Age”, with all its advantages and disadvantages.

However, only a few decades ago the properties of so-called functional materials have been discovered. The most prominent element is Silicon, which is a semiconductor and the base material of the transistor. Semiconductor technology was the foundation stone for computer

technology, which has changed mankind into an information-based and information-dependent society, creating a society without limits. And how long will it take until human brain cells will communicate directly with a computer via an implanted microchip?

In the 70s of the last century intermetallic Titanium Aluminides were considered for the first time as an innovative material for high-temperature applications, but I will leave this story for later.

Nowadays, the concept of nanomaterials has started to dominate world-wide research activities. A lot of success has been achieved, for example, by using self-organizing systems for drug delivery in medical applications.

In the last decade also new processing technologies, such as Additive Manufacturing, were introduced to the market. With such a technology, tailor-made components can be produced from pre-alloyed powder without any complex tooling.

From these examples it is evident that materials considerably determine the limits of technological progress.

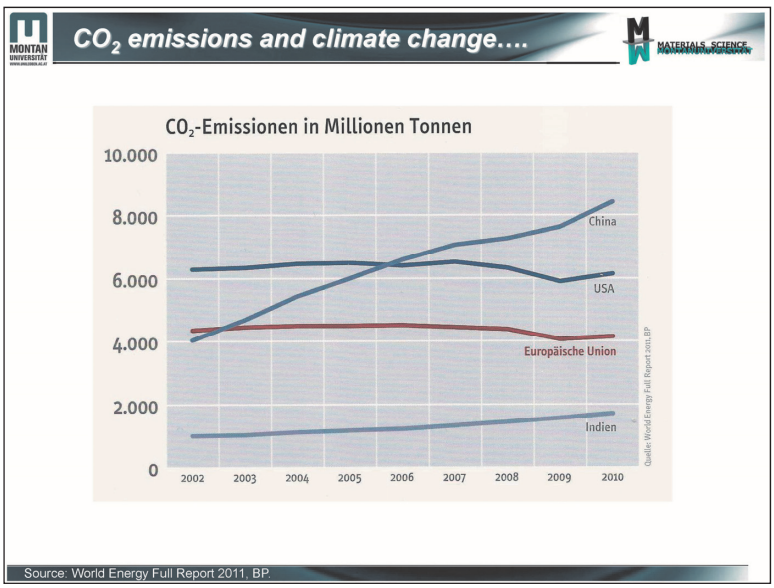


Fig 3

〈Fig 3〉 A serious type of pollution is the global increase of CO_2 in the atmosphere. In this viewgraph you can see that the European Union and even the USA succeeded in keeping the CO_2 emissions at a constant level, whereas the emission rate of China and India are still increasing. Emission of CO_2, however, represents a cross-border problem contributing to the global change in climate.

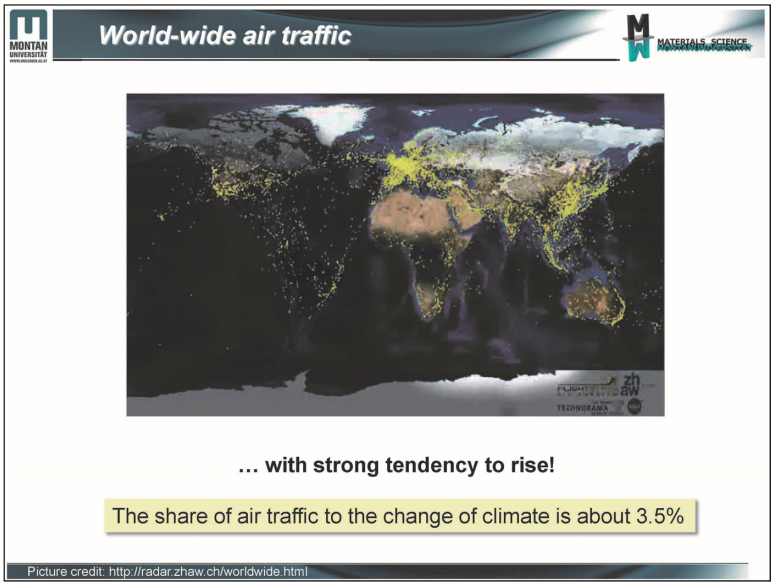


Fig 4

〈Fig 4〉 This slide shows the world-wide air traffic going on every day. Air traffic, in particular, shows a strong tendency to increase dramatically within the following years. In this movie every yellow dot represents one aircraft on its way.

The contribution of air traffic to the change of climate is estimated to be about 3.5%.

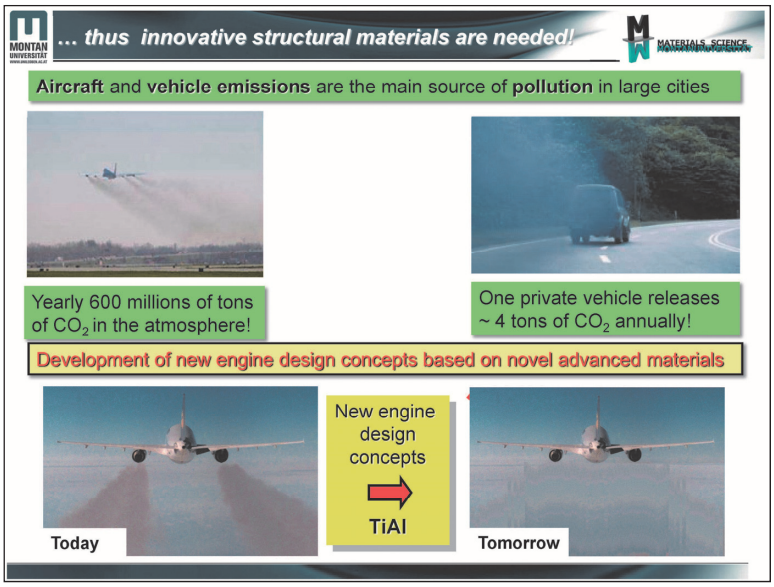


Fig 5

〈Fig 5〉 In large cities aircraft and automobile emissions are the main source of pollution. Each year more than 600 millions of tons of CO_2 are produced by air traffic, whereas the amount of each single car is much smaller. However, if you multiply this number with the number of cars in so-called mega-cities you get terrifyingly large CO_2 emissions.

These emissions contribute to the so-called green-house effect, leading to global warming of the atmosphere. If mankind is not able to stop global warming, the polar caps will melt and sometime in the future New York City will be flooded.

But what can be done? To forbid flying and driving cannot be a seriously-meant solution. What we need is the development of new aircraft engine concepts based on novel advanced materials, such as intermetallic Titanium Aluminides. On the computer this is easily done – with one click you can design an emission-friendly aircraft, which in reality takes many years of intensive and expensive research and development.

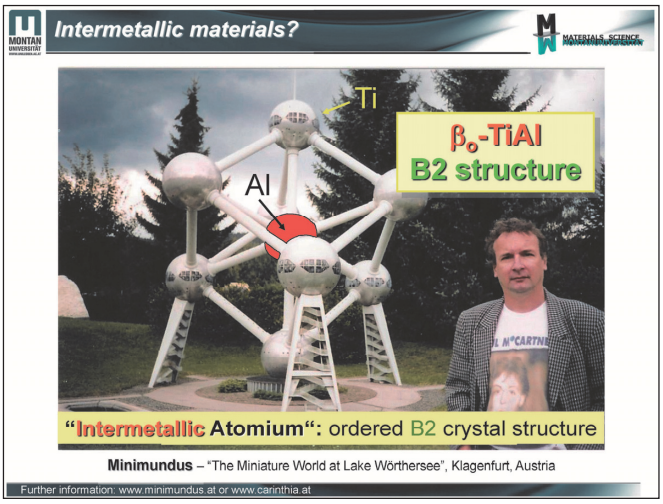


Fig 6

〈Fig 6〉 But what are intermetallic materials? Let me explain their most important characteristic feature by using this photograph. Here I am standing in front of the so-called "Atomium". It is not the original one, but a small-scale model, which can be visited in the city where I was born, Klagenfurt. The "Atomium" represents the crystal lattice of a metal exhibiting a so-called body-centered cubic structure.

Imagine all atoms are Titanium atoms - then you end up with the crystal structure of the so-called β-modification of Titanium. If you add, for example, only a few Aluminum atoms to Titanium then you end up with an Aluminum containing Titanium alloy. The Aluminum atom shown here can sit at every site in this lattice.

However, if you take the same concentration of Titanium and Aluminum atoms then a so-called intermetallic phase is formed. An important feature is the ordered crystal structure, meaning that every type of atom has a specified site where it is sitting. In our example the Titanium atoms are sitting on the corners, whereas the Aluminum atom is sitting in the center of the lattice. This particular intermetallic phase is called ordered β_o-Titanium Aluminide.

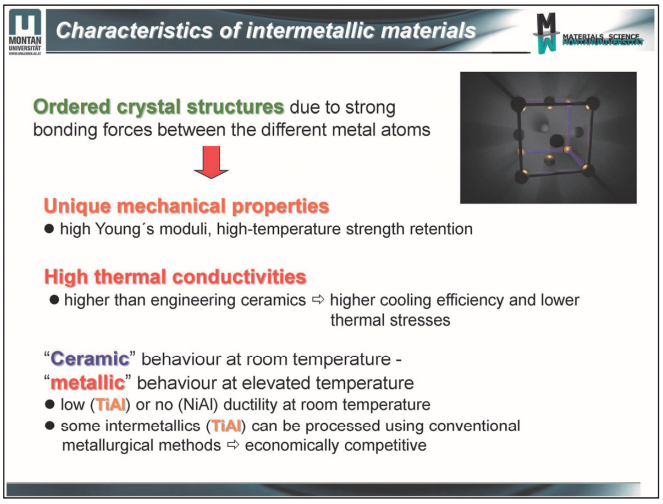


Fig 7

〈Fig 7〉 What are the characteristics of structural intermetallic materials in general?

As already shown on the last slide, intermetallic materials exhibit an ordered crystal structure due to strong bonding forces between the different species of metal atoms.

As a consequence they show high elastic moduli and high strength even at elevated temperatures.

In contrast to engineering ceramics, intermetallics exhibit higher thermal conductivities which can be used in components with higher cooling efficiency.

In general, intermetallic materials show a ceramic-like behavior at room temperature, but the characteristics of metals at elevated temperatures. This means that ductility is limited at room temperature, whereas at high temperatures some intermetallic materials, such as Titanium Aluminides, can be processed by conventional metallurgical methods, which make them economically competitive.

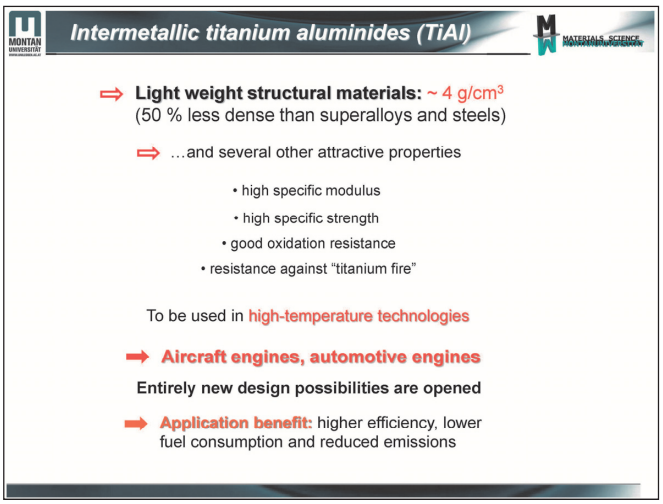


Fig 8

〈Fig 8〉 Now let us focus on the outstanding properties of intermetallic Titanium Aluminides, the material which made me win this year's Honda Prize.

The most important property is the low density which is about 50% less than the density of superalloys and steels. Exactly this low density makes Titanium Aluminide an interesting candidate for high-temperature light-weight design.

Besides its low density the material shows other attractive properties, such as

- A high specific modulus. "Specific" means that the value of the elastic modulus is divided by the mass density of the material.
- A high specific strength.
- A good oxidation resistance and
- Resistance against the so-called "titanium fire".

The combination of all these properties opens new possibilities for the design of aircraft as well as automotive engines.
The application benefits are higher efficiency, lower fuel consumptions and sustainably reduced emissions.

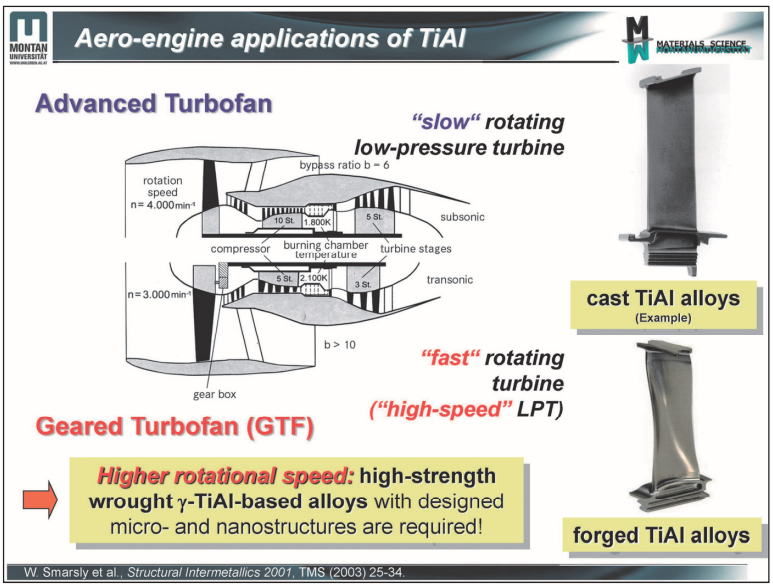


Fig 9

〈Fig 9〉 Due to their property profile, the application areas of intermetallic Titanium Aluminides are evidently in automotive and aircraft engines. By the way, the first implementation of Titanium Aluminides happened in Japan in the year 1999. Back then, Mitsubishi has equipped their turbo-chargers used for the Lancer Evolution VI with cast Titanium Aluminide turbine wheels.

A more challenging application, however, is the field of aero-engines. In the upper half of this schematic drawing you can see the conventional engine architecture of an advanced turbofan. The huge fan-blades are normally the part of the engine you see when an aircraft arrives at the gate. The mode of operation of a jet engine is not difficult to understand. The in-coming air is compressed in the compressor section. Then the compressed air enters the burning chamber where the kerosene is injected. The expanding burning gas is driving the high-pressure turbine and the low-pressure turbine. In conventional engine architecture, such as the advanced turbofan, the fan and the low-pressure turbine are mounted on the same shaft. Because of the relatively slow rotating low-pressure turbine and the lower temperature, cast Titanium Aluminides blades can be used here. An example is the so-called GEnX engine of General Electric which was in 2011 the first aero-engine ever where Titanium Aluminide cast turbine blades were used for the last stages of the low-pressure turbine. One can see that this kind of turbine featured a high number of stages.

The lower half of this drawing represents Pratt & Whitney´s "Geared Turbofan", or GTF to put it short. In contrast to conventional engine architecture it is equipped with a fast rotating turbine, termed "high-speed" low-pressure turbine. Due to this advanced type of turbine

concept, which has been developed by MTU Aero Engines AG (Munich, Germany), the propulsion system is much lighter than a conventional engine, as it has fewer stages, and hence consists of fewer parts. However, due to the higher rotational speed a gearbox must be interposed between fan and low-pressure turbine. This means that both components run at different speed, which leads to a higher efficiency of the whole system.

However, due to the higher mechanical stresses and temperatures cast Titanium Aluminides blades cannot be used. For such service conditions high-strength forged turbine blades with designed micro- and nanostructures are required!

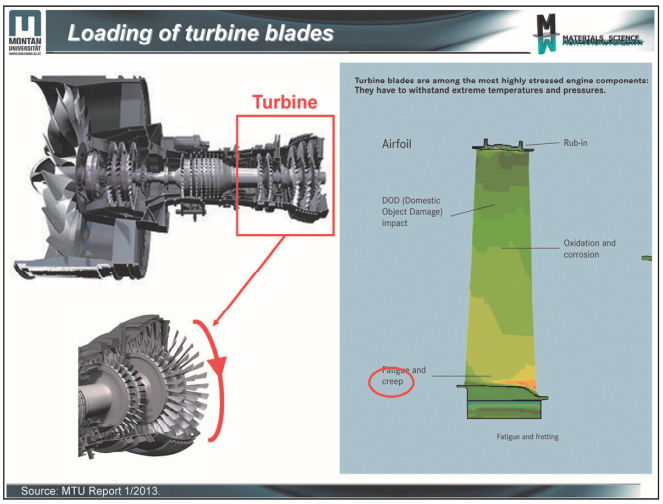


Fig 10

〈Fig 10〉 Turbine blades are among the most highly stressed engine components. They have to withstand extreme temperatures and pressures.

Let me explain the very high mechanical stresses by using a simple example. When the turbine is rotating, a centrifugal force is acting on the blade. This force corresponds to the weight of a huge car. A high stress is not the only problem. In addition, the hot gas from the burning chamber has a high pressure and heats the turbine blade to a certain temperature. The combination of mechanical stress and temperature leads to a process which is called creep. Creep, however, has the consequence that the blade starts to deform during operation. Simply said, the blades start to elongate. Therefore, it is obvious that turbine blade materials must exhibit high creep strength to minimize their elongation in order to ensure a safe life-time. Additionally, the blade material must be resistant against oxidation and corrosion.

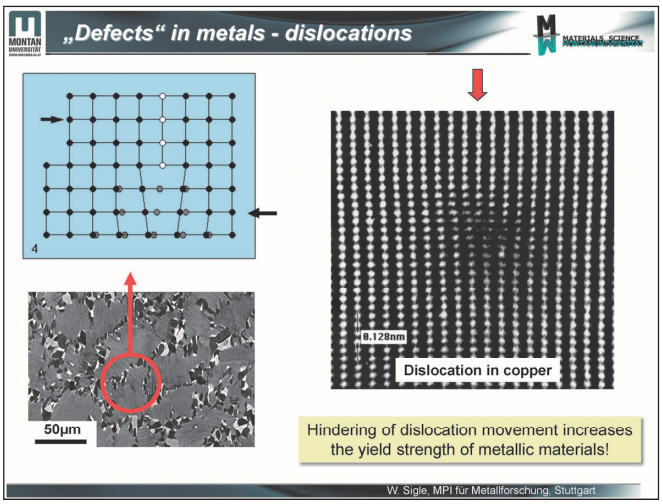


Fig 11

〈Fig 11〉 The strength of a material is a decisive property; therefore, we have to ask ourselves the question what determines the strength and also the plastic deformability of a metal. To answer this question we have to look at the microstructure of a material. This picture shows the microstructure of a Titanium Aluminide alloy taken by scanning electron microscopy. Now we increase the magnification to such extent that we can see the atomistic structure of the crystal lattice. Obviously, there is something wrong, because the local symmetry of the crystal lattice is disturbed. If you take a closer look than you see that an extra plane of atoms is inserted in the lattice as indicated by the red line. Materials scientists call such defect a dislocation. You may ask yourself why it is necessary to mention defects, whose dimensions are extremely small. The answer is that these little defects control the plastic behavior and the strength of metallic materials. At this point I want to emphasize that without the presence of dislocations shaping of metals by rolling, forging and drawing would be practically impossible - metals would be too strong!

If you apply a certain stress on the material dislocations start to move and the material starts to deform plastically and changes its shape. The stress which is necessary to start plastic deformation is called the yield stress. In order to show you a proof that a dislocation is not only a theoretical model, this transmission electron micrograph shows a dislocation in Copper.

Now the strategy is clear how to increase the yield strength of a material – you have to find a way to hinder the movement of dislocations.

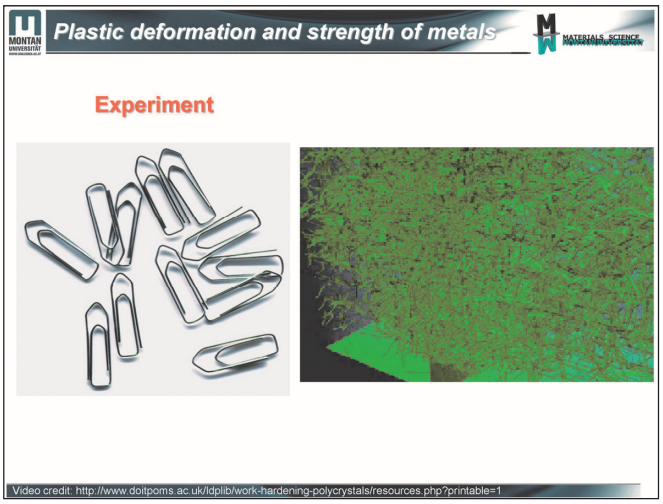


Fig 12

〈Fig 12〉 Maybe you were surprised that you have received a paper clip at the reception. As a materials scientist I am used to do experiments. Now I invite you to perform an experiment with me.

Please take the paper clip and straighten it. After you have done this, there are now three undeformed sectors on the almost straight wire.

Now we will perform a so-called three-point bending test. To do this please take the straight line in the middle of the wire and bend it like I am doing it. Bend the wire very slowly and "measure" the force you need for a plastic deformation to occur.

After you have done this, please re-bend the wire slowly to a straight line. Again, measure the force you have applied.

Now we are coming to the evaluation of the experiment and therefore I ask you for your results.

I congratulate those of you who have measured a higher force during re-bending! Obviously, the material became harder during the first deformation step.

The reason for this behavior is explained in this computer simulation. Here you see the cross-section of the wire of such a paper clip. As soon as the wire starts to deform plastically, a lot of dislocations are formed inside the material, in this simulation represented as lines. These dislocations strengthen the materials by mutual hindrance. When the wire is then re-bent, even more dislocations are generated which further increase the strength of the metallic paper clip material.

This technique, the strengthening of a metallic material by cold deformation, has been known for several thousands of years and is still applied by the metal working industry. Today the process is called strain hardening or work hardening.

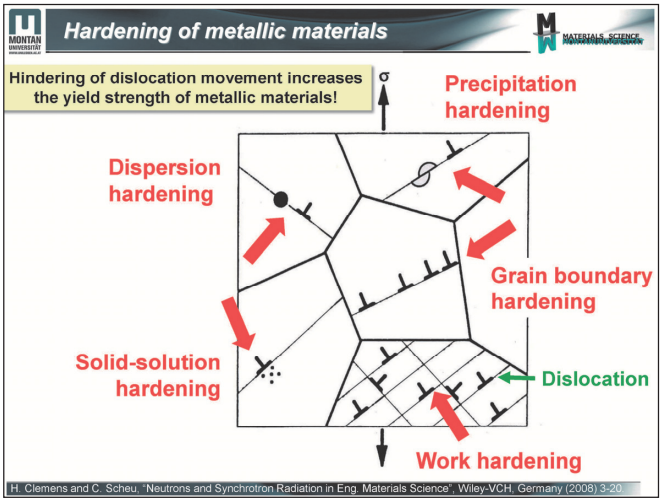


Fig 13

〈Fig 13〉 Which concepts can be used by materials scientists to increase the strength of metallic materials? In this schematic drawing of a polycrystalline microstructure all possible strengthening mechanisms are shown. All mechanisms are based on hindering the movement of dislocations.

One strengthening mechanism is already known to you: work hardening which is based on the formation of dislocations which hinder themselves in their motion.
Another mechanism is to decrease the grain size and thus to increase the number of grain boundaries, which are obstacles for dislocations. Such a mechanism is applied in many fine-grained steel grades.
A very important strengthening concept which is applied in all technical alloys is solid-solution hardening. Usually, the diameter of an alloy atom is smaller or larger than that of the matrix atoms. As a consequence, stress fields are generated which interact with the stress field of the dislocations.
Two very important mechanisms which can be exploited in particular in high-temperature materials are precipitation and dispersion hardening. Here, the movement of dislocations is blocked by very fine and homogeneously distributed particles.

All these mechanisms can be also used to increase the strength of intermetallic Titanium Aluminides. However, you should keep in mind that not all of these concepts are suitable for elevated temperatures and that an increase in strength will lead to a decrease of ductility, especially at room temperature. In particular for Titanium Aluminides, which naturally show a limited ductility at room temperature, it is a challenge to develop alloys exhibiting balanced mechanical properties, which means high strength, but also sufficient deformability at room temperature.

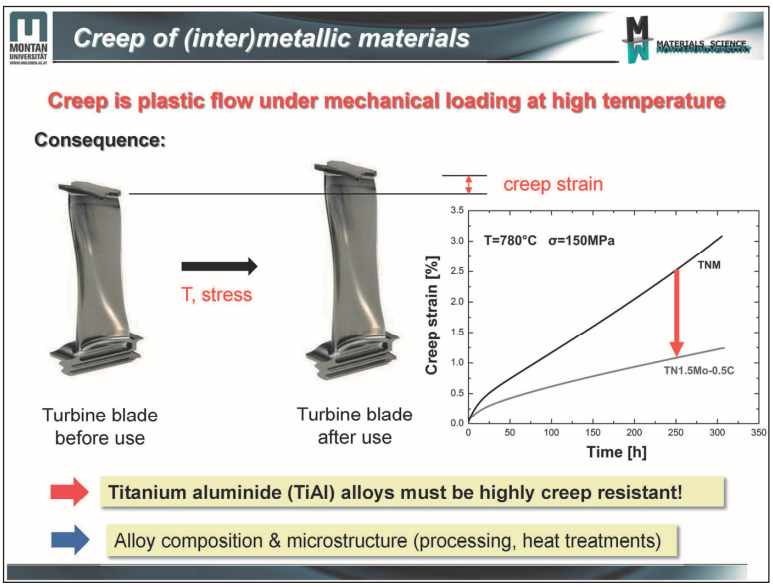


Fig 14

〈Fig 14〉 In one of the previous slides I have indicated that creep is a serious problem when metallic components are subjected to high stresses and temperatures.

For a turbine blade the consequence is shown here, which, of course, is a big exaggeration as far as the shape change shown here is concerned.

Here you can see a turbine blade after fabrication. During its use in the engine for many thousands of hours creep processes start to occur, leading to an elongation of the turbine blade. This elongation is termed creep strain. The creep behavior can be measured on test specimens and an example of a so-called "creep curve" is shown on the right side of the slide. It is clear that for a safe application the creep strain must be as small as possible and, therefore, Titanium Aluminide alloys must be highly creep resistant. The creep properties depend on the alloy composition and the microstructure. Here you can see how the creep strain can effectively be reduced when the composition of the alloy is suitably changed.

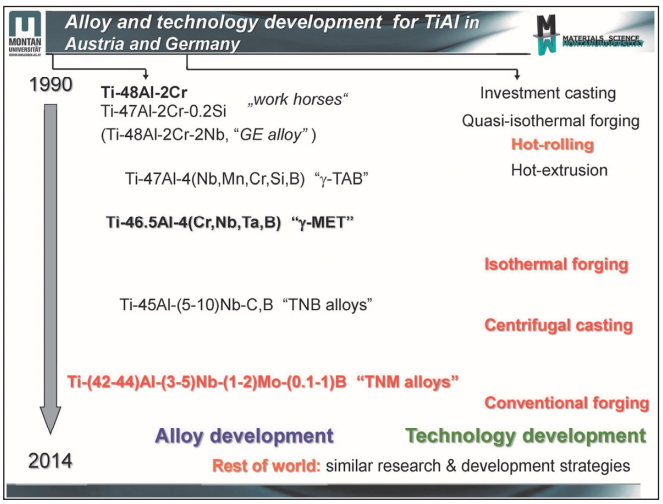


Fig 15

〈Fig 15〉 In this compilation the alloy and technology development for Titanium Aluminides in Austria and Germany is shown. However, the so-called rest of the world conducted similar development strategies.

In the early 90s the development started using simple alloys, very similar to that of the so-called "General Electric" alloy which was invented in the 80s of the last century. This alloy, however, has seen application as a cast material almost 30 years later in the GEnx-engine.
When I was working for the Plansee I have developed the "Gamma-Met" alloy. This alloy, representing a medium-strength alloy was developed for sheet products, but was also used at the end of the 90s as valve material in Formula 1 engines.

Then there was an intensive period of alloy development. The target was to increase the strength of Titanium Aluminides significantly, while maintaining certain ductility at room temperature.
In this context I would like to mention the pioneering work of Dr. Fritz Appel and his team at the GKSS Research Center in Geesthacht, Germany. He was one of the first to use increased Niobium contents and small additions of Carbon to achieve so-called high-strength Titanium Aluminides.

It has not yet been ten years ago when we started the development of the TNM alloy. Here, T stands for Titanium Aluminide, and N and M for Niobium and Molybdenum as the main alloying elements. The targets were to develop an alloy which can be economically forged to turbine blades and which can be heat-treated to exhibit balanced mechanical properties, meaning high-strength at elevated temperature and sufficient fracture strain at room temperature. At that time the vision was to get this material into the engine which should

soon power a high-efficient aircraft - the Airbus 320NEO. Here, NEO stands for new engine option.

The process technology which is now applicable for Titanium Aluminides is summarized on the next slide.

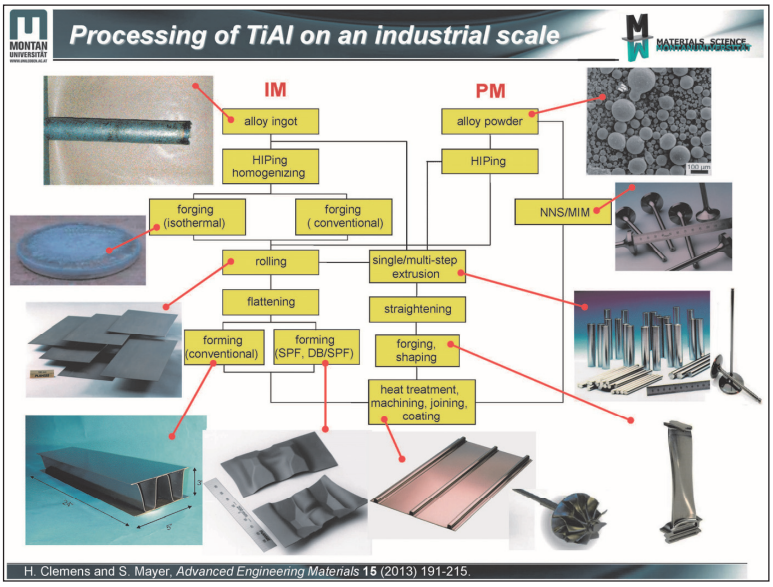


Fig 16

〈Fig 16〉 This slide shows the processing route for Titanium Aluminides on an industrial scale which has been developed in industrialized countries all over the world. In fact it is possible to apply all technologies which are used for Titanium alloys when they are adjusted to the particular properties of the intermetallic materials.

As can be seen, starting from ingot material or densified alloy powder, processing steps such as rolling, extrusion as well as forging can be conducted. In addition, joining and machining technologies were developed. Especially joining is important when Titanium Aluminides must be connected to other materials, such as steel or a superalloy. One challenging example is the turbo-charger application, where the turbine wheel must be connected with the steel shaft.

Besides the wrought processing routes, several near net shape casting processes have been developed for Titanium Aluminides components, such as turbo-charger wheels and turbine blades. One of the leading companies is Daido, who have been the first in casting turbo-charger wheels for series application.

For those of you who are interested and want to get further information, the printed version of this lecture contains a recent review article, wherein all technological details are explained.

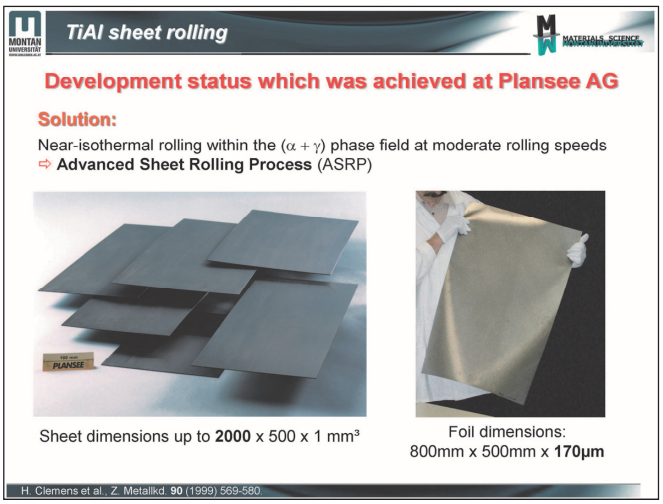


Fig 17

〈Fig 17〉 It was during my time at Plansee in Austria when I came in contact with intermetallic Titanium Aluminides. My task was to develop a hot-rolling process on an industrial scale for this material.

In the beginning I was very skeptical if rolling of large sheets would ever be possible, because of the limited deformability of this type of material even at elevated temperatures.

However, in the framework of a fundamental research project we determined the necessary conditions, which are required to process Titanium Aluminides on a commercial hot-rolling mill.

We called our near-isothermal rolling process the "Advanced Sheet Rolling Process". This process was internationally acclaimed as a major break-through in the manufacturing technology of Titanium Aluminides. The sheets which were rolled at Plansee are still the largest which have ever been produced. Even foils were processed, which was another major progress.

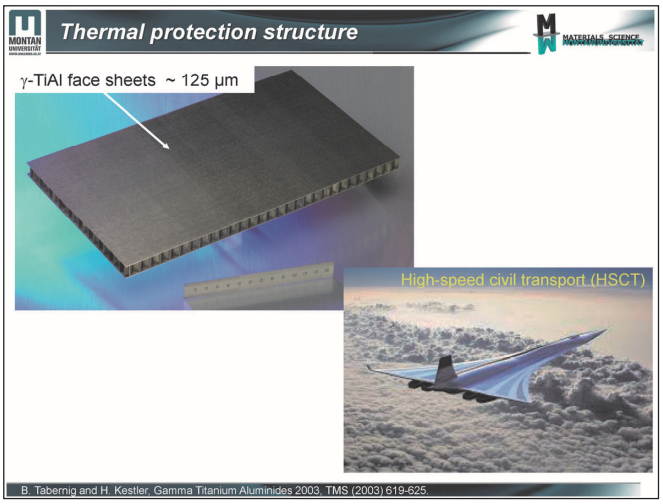


Fig 18

〈Fig 18〉 Here you can see one most important result of Titanium Aluminide sheet and foil technology. In the framework of a US "High speed civil transport" project, Plansee was able to produce so-called Thermal Protection Structures. For the realization of such a structure, where also the development of suitable joining technologies was conducted, Plansee and the project partners NASA and Pratt & Whitney were awarded with the prestigious "R & D 100 Award".

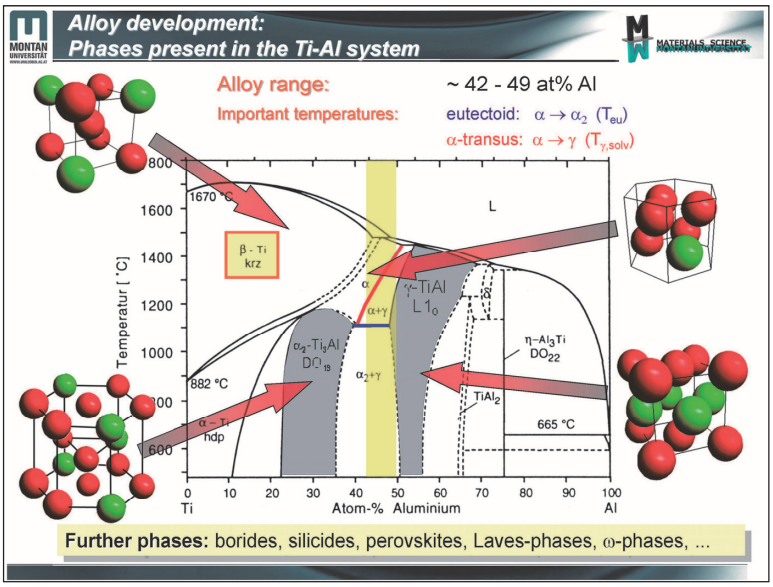


Fig 19

〈Fig 19〉 Now I will explain in a simple way the development strategy for Titanium Aluminide alloys which should show good hot-workability on one hand, and balanced mechanical properties on the other hand. As you have already seen in the Opening Video, it was Dr. Wilfried Smarsly from MTU Aero Engines who initiated the development project almost 10 years ago, after we had discussed the probability of its success for a long time. At this point I thank Wilfried Smarsly from all my heart that he had always believed in this project and never stopped the support even at times of setback.

At conferences and workshops Prof. Masao Takeyama always emphasizes that "we need phase diagrams". I fully agree with him, because phase diagrams provide the fundament to understanding microstructural development and they help to adjust process parameter.

In this slide you see the binary Titanium - Aluminum phase diagram. For those of you who are not familiar with phase diagrams just a short explanation. A phase in a metallic alloy is a certain region with a specific crystal lattice and chemical composition. A phase diagram describes the appearance and stability of the phases present in a certain alloy system as a function of temperature and composition.

For example, in the Titanium - Aluminum system, the following phases are important for understanding the behavior of advanced multi-phase Titanium Aluminide alloys.
The most important phase is the ordered γ-TiAl phase which we have already got to know. The second most important phase is the so-called α_2-Ti_3Al phase, which has an ordered hexagonal lattice. Engineering Titanium Aluminide alloys show Aluminum contents in the range of 42 to

50 atomic percent, note the yellow indicated area. For this reason binary alloys consist of Gamma- and α_2-phases at room temperature as well as at application temperature.
At elevated temperatures the ordered α_2-phase disorders to α-phase and forms a simple α-hexagonal lattice. However, even when the α-Ti(Al) phase is brought to elevated temperatures, it is still very difficult to deform.
In the range of low Aluminum concentrations there is still one important phase left: this phase is the cubic-body centered β-Ti(Al) phase, which shows – in contrast to the α-phase – an excellent deformation behavior. For this reason, hot-working of difficult-to-process Titanium alloys is conducted in a temperature range, where a high volume fraction of β-phase is present.

It was the merit of Prof. Takeyama to show that this concept also works for Titanium Aluminide alloys.

The trick is now to shift the existence range of the β-phase to the right side of the phase diagram. To this end, β-stabilizing alloying elements such as Niobium, Molybdenum or Vanadium must be used.

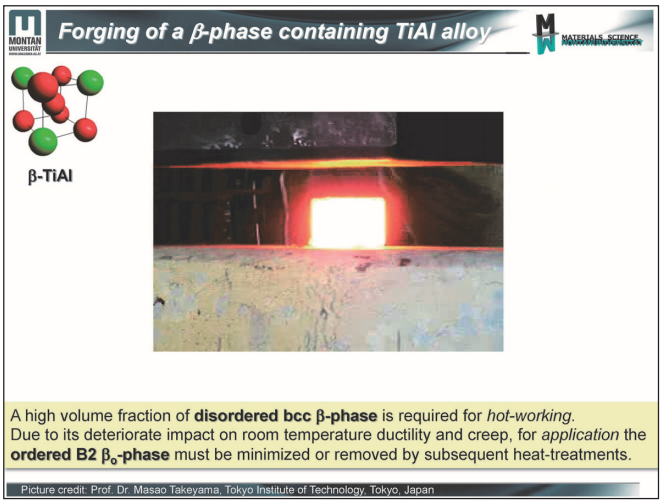


Fig 20

〈Fig 20〉 In this impressive movie, provided by Prof. Dr. Masao Takeyama, you can see how easily a β-containing alloy can be deformed. However, due to a relatively large mass of the object shown in this video no heat loss occurs during the forging process. As soon as the parts are becoming smaller, such as turbine blades, heat loss becomes a serious problem. However, state-of-the-art forging machines offer a sufficient range of freedom to select forging parameters appropriate for Titanium Aluminide alloys.

However, the success of forging is one point; the other is to obtain balanced mechanical properties in the final component. It is known that the β-phase, which improves the forging behavior, degrades the mechanical properties of the component, for example, causing embrittlement at room temperature and deterioration of the creep properties at service temperature.

Therefore, the alloy design must be chosen in a way that the β-TiAl phase can be eliminated after the forging process by means of a heat treatment.

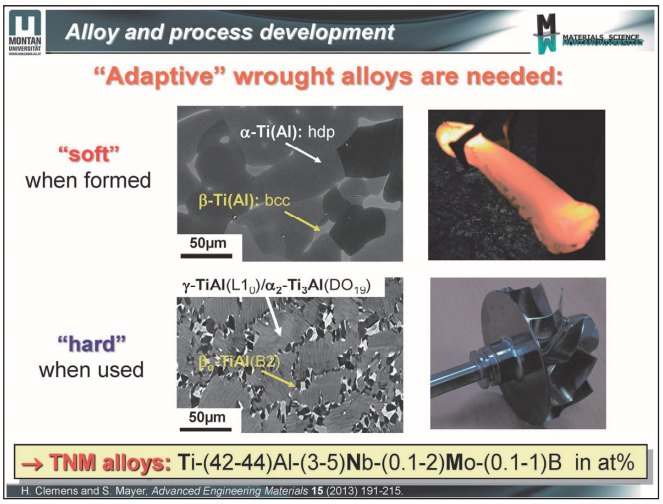


Fig 21

〈Fig 21〉 From the requirement profile defined in the last few viewgraphs it was clear that an "adaptive" wrought alloy is needed.
This means that the material should be soft when formed, but hard when in service.

In order to meet this target, for the first time thermodynamic simulations were conducted to obtain the chemical composition of the new Titanium Aluminide alloy. I will not bore you with details concerning Computer-Aided Alloy Design; just let me show the final result: the chemical composition of the TNM alloy.

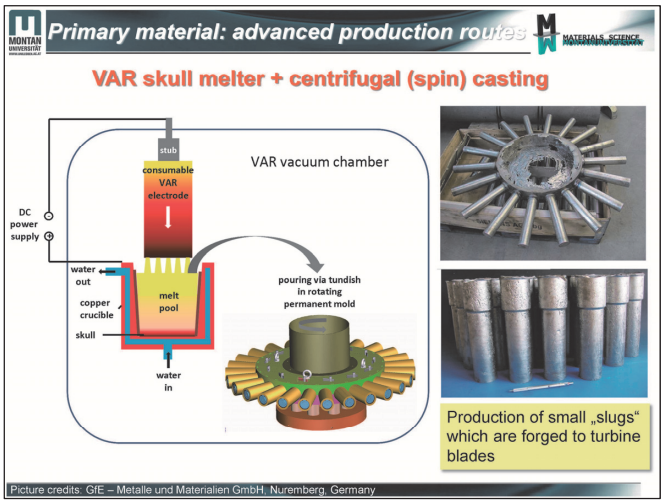


Fig 22

〈Fig 22〉 As soon as the material composition was defined, the next logical step was to produce primary material for the subsequent forging step using a process which is cost-effective and leads to sufficient materials quality.
Here I would like to thank Dr. Volker Güther and his team at "GfE – Metals and Materials" in Nuremberg, Germany, who have developed an advanced production route which suits the solidification and phase transition characteristics of the TNM alloy.

This schematic drawing shows the principle how the process is working. At first a large ingot is produced by vacuum arc re-melting, which is a technique world-wide used for the fabrication of Titanium alloys. This ingot is then introduced into a vacuum chamber and re-melted in a Copper crucible which is induction heated. As soon as the melt is chemically homogenous, it is poured into a rotating permanent mold, where the solidification takes place.

On the right side is shown the casting after removing the mold. Below you can recognize that this production route leads to small ingots, so-called "slugs", which can be directly forged to turbine blades after they were subjected to hot-isostatic pressing.

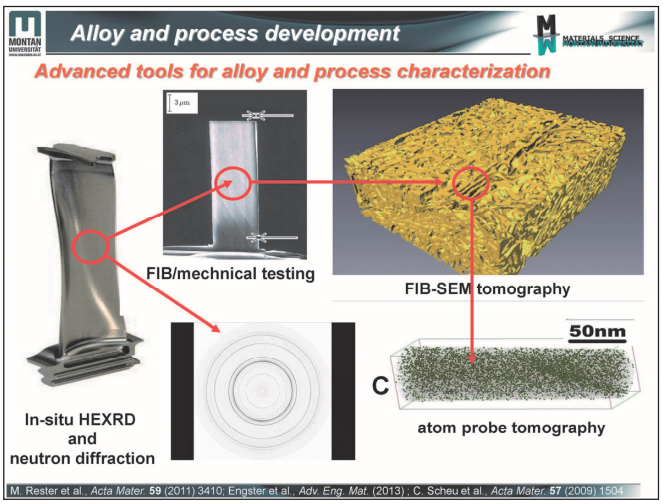


Fig 23

〈Fig 23〉 In this slide I have summarized the advanced tools we have applied for alloy and process characterization. In order to understand the mechanical behavior of the material on the micrometer scale, very small specimens had been produced which were then tested in the scanning electron microscope.

In order to understand the complex arrangement of the constituting phase we have also analyzed the microstructure of the material by tomographic means.

To analyze the chemical composition on the atomic level, high-resolution techniques such as atom probe tomography were used. In this image you can see the distribution of Carbon atoms in a more advanced Titanium Aluminide alloy. Each green dot corresponds to a Carbon atom.

From the scientific point of view, the use of in-situ methods, such as high-energy X-ray diffraction for understanding the hot-deformation behavior of Titanium Aluminides was an innovative step, which I will demonstrate in one of the next slides.

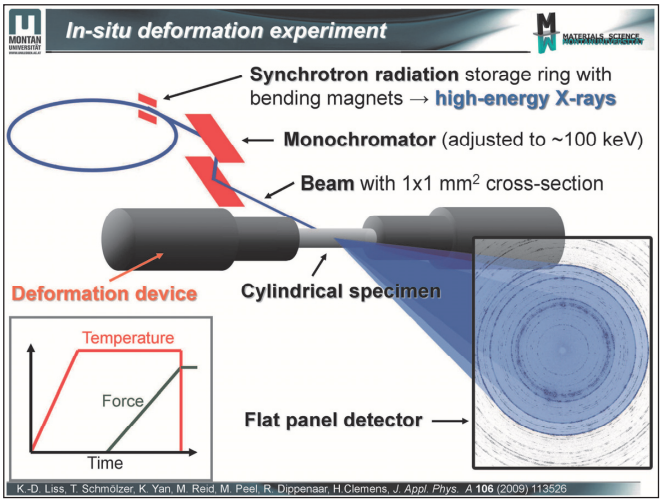


Fig 24

〈Fig 24〉 For the forging of the TNM alloy to turbine blades, in principle two forging processes are suitable, which are "Isothermal Forging" or "Near Conventional Hot-Die Forging". In the following I will not discuss the details of the different forging processes, because they are subject to utmost secrecy.

As a materials scientist, however, I would like to see in-situ and "live" what is going on in the material during deformation at very high temperatures and which mechanisms and processes contribute to plastic deformation and microstructural evolution. To this end I started to collaborate with Dr. Klaus-Dieter Liss. Klaus-Dieter was working at the GKSS Research Center when I first met him and when we defined the first experiments on Titanium Aluminides. Later he joined the ANSTO in Australia, where he and his teams are doing pioneering work to study thermo-mechanical processing of several classes of materials by using synchrotron radiation.

In this slide the set-up of an in-situ deformation experiment is shown. At first you need access to a synchrotron, which normally is linked to a major research institution. In simple words, a synchrotron is a huge ring where electrons are moving synchronized in a circle. During their circular movement they emit high-energy X-rays. These X-rays, when leaving the ring, are adjusted to an energy of about 100 kilo electron volt and focused to a beam which exhibits a cross-section of 1 mm².

The other important equipment is a deformation device where the cylindrical specimen with a diameter of 4 mm and a length of 8 mm can be deformed at a defined temperature and force. The goal is to simulate the entire industrial forging process on a small scale.

I am sure that not all of you are experts in X-ray diffraction, therefore, I will give you a little introduction. When an X-ray beam hits a fine-grained polycrystalline material, so-called Deybe-Scherrer rings are recorded on the detector. On some rings you can see big dots, which originate from diffraction at larger grains. It must be kept in mind that different phases and their atomic planes create different sets of rings. However, with experience it is relatively easy to allocate the different rings to the different phases.

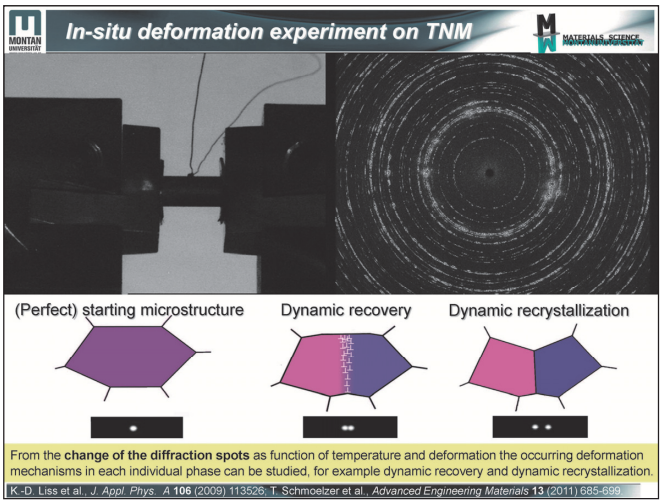


Fig 25

〈Fig 25〉 In this slide you can see the deformation equipment on the left hand side, whereas on the right hand side the corresponding Debye-Scherrer rings are shown.

The TNM specimen is located in the center of the deformation device. The wires belong to the thermocouple which is used for temperature control. During heating of the sample some of the rings vanish, because the corresponding phases are dissolved in the matrix and thus are not present anymore.

From the change of the diffraction spots, as indicated below, the occurring deformation mechanisms in each individual phase can be studied, for example, dynamic recovery and dynamic recrystallization.

The effect of dynamic recrystallization, meaning the formation of a new, fine-grained microstructure, can be seen when you observe these diffraction spots which belong to rather large grains. With increasing deformation these huge spots vanish and very homogeneous rings are formed, which means that grain refinement during hot-deformation has taken place.

Besides recrystallization, additional information can be gained from the evaluation of Debye-Scherrer rings. Some of them are indicated here.

The final message regarding this topic is that in-situ experiments are powerful tools for alloy and process development, which can solve many scientific and technological questions. It is very nice to see that nowadays also industry starts using such advanced characterization methods more often in order to optimize their materials and processes.

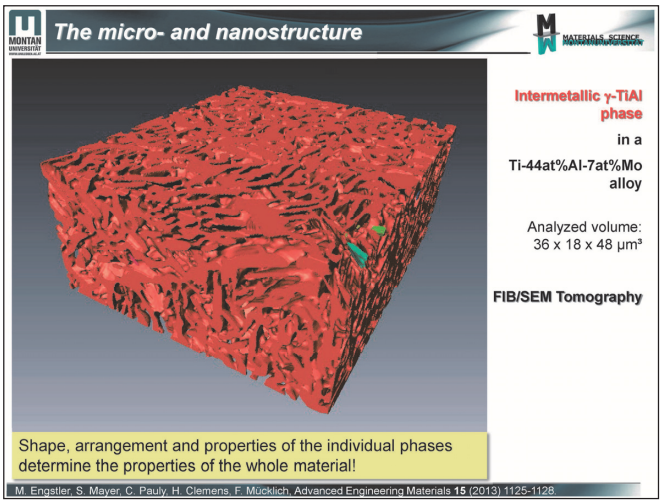


Fig 26

〈Fig 26〉 This slide brings me to the last episode of my lecture. Here I will shortly describe how the shape, arrangement and properties of the individual phases determine the mechanical properties of the material.

The object shows the three-dimensional arrangement of the γ-TiAl phase in a Titanium Aluminide alloy which consists of two phases at room temperature. In order to see the presence of the γ-phase more clearly, in this tomographic picture the second phase was blanked, which creates the illusion of a Swiss cheese.

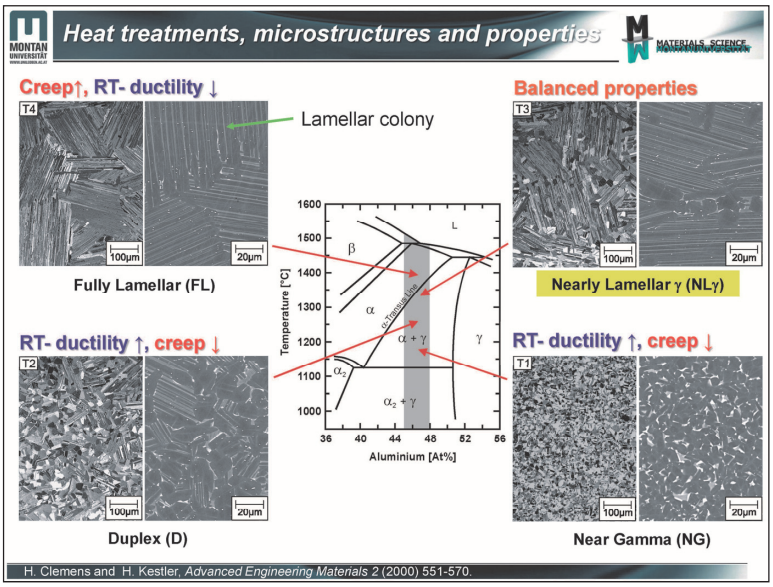


Fig 27

〈Fig 27〉 In order to understand the microstructure - property relationship in engineering intermetallic Titanium Aluminides I have prepared this slide.

In the center of the slide is a section of the binary Titanium-Aluminide phase diagram. The composition range of technical alloys is indicated by the grey rectangle. Also the TNM alloy is a three-phase alloy, which in reality exhibits a much more complex phase diagram, but the fundamental relationship between the microstructure and the mechanical properties can also be derived from this rather simple phase diagram.

Left and right from the phase diagram you can see the microstructures obtained after annealing in different phase field regions. The left image was taken by light-optical microscope, whereas the right image was taken by scanning electron microscope. Here, the γ-TiAl phase shows a dark contrast, whereas the α_2-Ti_3Al phase appears brightly.

After forging, the material shows a homogeneous fine-grained microstructure. This microstructure is termed “Near Gamma”. Such a type of microstructure shows good ductility at room temperature, but poor creep properties as a consequence of the fine grain size.

In contrast, when the forged material is annealed at a very high temperature, which is within the single α-phase field region, the grain size starts to coarsen rapidly. Upon cooling to room temperature the γ-phase is formed and so-called α_2/γcolonies exist at room temperature. Such a “Fully Lamellar” microstructure shows excellent creep properties, but, as a consequence of the large colony size, a very low ductility. Here, it is important to note that the creep strength depends strongly on the spacing of the lamellae.

In the case of the TNM alloy balanced mechanical properties, meaning good creep properties at elevated temperatures and sufficient ductility at room temperature, are achieved when the forged alloy is annealed in the upper temperature region of the ($\alpha + \gamma$) phase field region. The final microstructure consists of lamellar colonies, which determine the creep properties, and globular γ-grains which are arranged at the colony boundaries and whose volume fraction controls the ductility at room temperature.

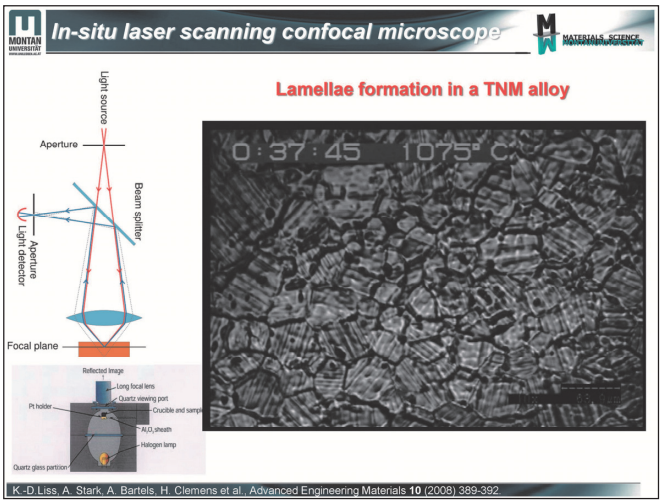


Fig 28

〈Fig 28〉 Material scientists like to observe the evolution of a microstructure directly. This movie shows the devolvement of a lamellar microstructure in a TNM alloy using laser scanning confocal microscopy. For this experiment a specimen is cooled from the α-phase field region and the surface of the sample is scanned by a laser beam. The experimental set-up is schematically shown on the left hand side of this slide. At a certain temperature the γ-TiAl laths are nucleated and grow within the α-Ti(Al) grain, forming a lamellar microstructure. Such experiments are very helpful to understand the evolution of a microstructure and the findings can be used to optimize the heat-treatment parameters, such as heating and cooling rate as well as annealing temperature and holding time.

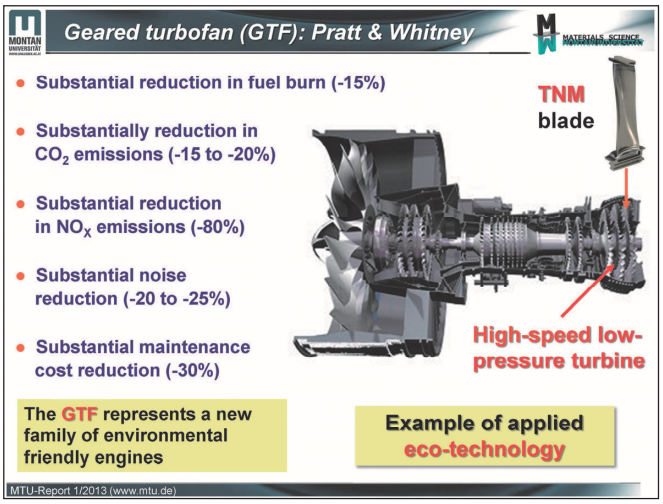


Fig 29

〈Fig 29〉 After having developed the TNM alloy, the forging process of the turbine blade as well as the heat-treatment to obtain balanced mechanical properties the material is ready for application.

The TNM alloy will be used as turbine blade material in the high-speed low-pressure turbine which was designed and developed by MTU Aero Engines for the so-called Geared Turbofan, which is manufactured by Pratt & Whitney.

If you take a look at the performance data it is evident that this next generation aircraft engine represents a new family of environmentally friendly engines and is an excellent example for applied eco-technology. And the TNM alloy contributes significantly to this advanced aero-engine concept.

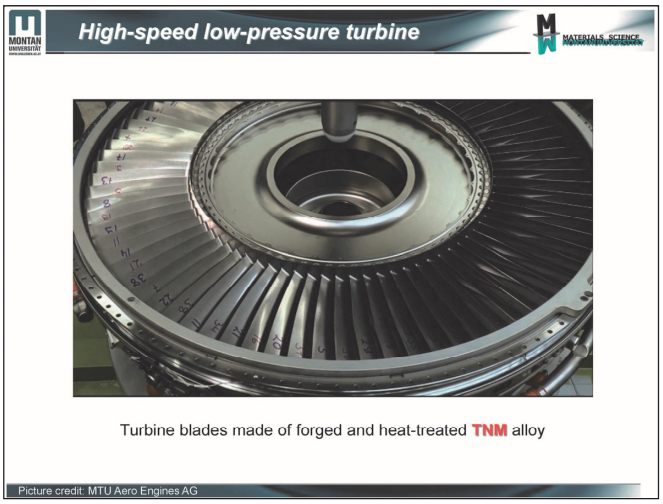


Fig 30

〈Fig 30〉 In this image, taken from a movie clip, the TNM-blades inside a high-speed low-pressure turbine can be seen which was used for test purposes.

Fig 31

〈Fig 31〉 The highlight in a materials scientist's life is when his development proves its applicability. Cutouts of this movie you have already seen in the Opening Video.

It shows the new Airbus A320neo during its maiden flight which took place in Toulouse, France, on September 25, 2014. The aircraft was equipped with two GTF engines which contained forged TNM turbine blades.

The first flight took about two and a half hours and after landing the aircraft returned safely to its parking position.

Fig 32

〈Fig 32〉 All the scientific and technical achievements would not have been possible without the privilege to work and exchange with a large number of colleagues all over the world for the last 20 years. Although this list is still incomplete, the persons highlighted in red color have escorted me through my scientific life and some of them have deeply and sustainably contributed to the TNM project.

In addition, I like to thank my Department, my research team and my university for never ending support and creating an atmosphere which makes research successful. I am very thankful that the Rector of the Montanuniversitaet Leoben, Prof. Wilfried Eichlseder, is participating in this Award Ceremony.

Last, but not least the most sincere thanks are going to my family, my wife Ruth, my son Roland and his girlfriend Tamara. Their love, sympathy and balancing backbone were always the true driving forces.

Fig 33

〈Fig 33〉 This is the last slide of my lecture. Just after I had received the news that I would be awarded with the Honda Prize 2014, I saw this small piece of art.

This figure which completes the puzzle could be me, who developed a new material to be used in the next generation of eco-friendly aero-engines.

In general this figure could be everybody of us, meaning that everybody must do her or his share to create a truly humane civilization and thus fulfilling the vision of Soichiro Honda!

With this final statement I would like to thank all of you for your kind attention.

公益財団法人 本田財団

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