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# Complex Material Science Projects Solved by System Engineering Methods

by

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**Abstract**

Complex engineering problems, such as micro-system-technology, nano-technology or other material science problems, are solved with the aid of structural maps. Such a system engineering approach clarifies the dependences of physical parameters and solves the complexity by visualization. After explaining the methods of system engineering the development and heat treatment of an aluminum alloy for aircraft application is explained. The described method can be used for investigating other development problems.

***Keywords:*** Complexity, Material science, Al-Li alloy, Structural maps, Aircraft development

## 1. Introduction

System engineering has become a popular method in industry in order to solve complex engineering problems, which expanded not only in quantity, but also became more and more interdisciplinary, in our days referred to as emerging engineering or converging technologies[1]. Companies strongly demand teaching this subject at universities and students should know the main terms and methods when they graduate. This paper was written as a preparation for a lecture at the material science department to be given soon. So, it focusses on materials science, but other fields of engineering are touched as well, as new materials are the base for many engineering fields.

Looking back in history, the ancient Egyptians organized building their pyramids, not only a challenge for managing so many workers, but also with a lot of technical innovations. The most popular example for system engineering, however, is usually addressed to the Apollo program in USA[2], which was crowned by the success on 20. July 1969 by Armstrong's first walk of the mankind on the moon[3]. At that time computer abilities were rather poor. The large success was possible through the collaboration of many engineers from different disciplines. As the handbook is available in the internet[2], it became a detailed base for system engineering. Other examples for early system engineering achievements were the organization of railways[4], aviation, telephone[5] or semiconductor-based micro-system technology (MST).

After explaining systems engineering methods, this paper applies them to a problem in material science, as it is the base of many engineering applications. The main aim of this paper is to figure out, in which way system engineering approach can be used to solve unknown and complex questions of science.

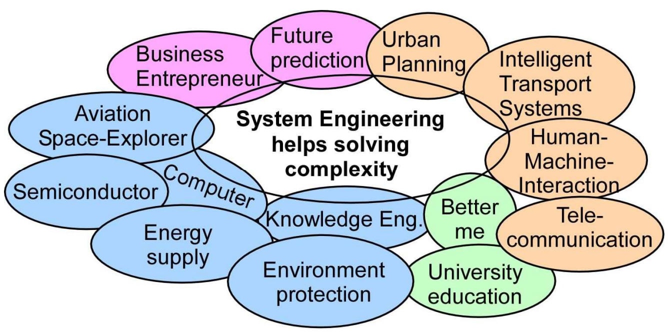


Fig. 1 System Engineering helps solving complex dependences in several areas of science and engineering (blue), business (purple), society (orange) and education (green).

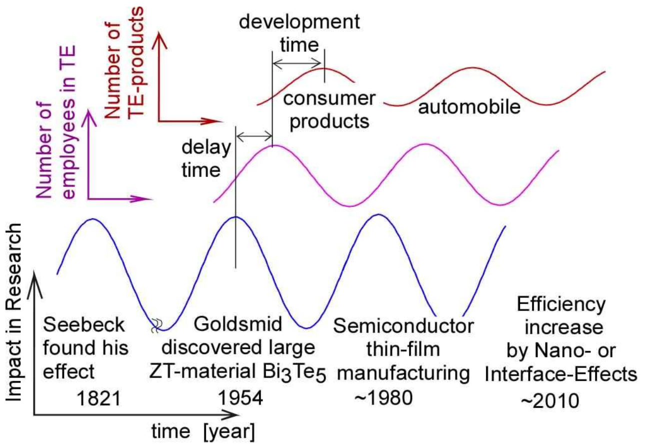


Fig. 2 Schematic drawing of business cycles shown for the example of thermoelectric (TE-) materials (Data adapted from[4])

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## 2. System Engineering

### 2.1. Areas of application

Meanwhile, many fields of science solve complex management problems by using system engineering methods as shown in fig. 1, where the blue areas refer to engineering problems. The main concerns in present days are the energy supply and the environmental protection. After computer became easy accessible in the early 1980-ies, system analysis took over many methods form programming and vice-versa, many fields of science used data management and later simulation methods from computer science and informatics. Treating complexity needs the aid of computer, because "every factor depends on every other factor, even the unknown", and hence it is also used for managing knowledge. Planning of business requires future prediction, shown in purple in fig. 1. Also, for managing of social aspects (orange color in fig. 1) or even for education, carrier planning, gap analysis, or potential analysis (green color), whether "better me" can be achieved, recently system engineering methods have been applied[1].

System engineering in a narrower meaning is focused on research and development of technical products in industrial companies. But even this field has diverged into several areas[1], such as: (a) Program management and project management has a broader meaning than systems engineering. (b) Concurrent engineering (CE) [1] designs the interfaces and find solutions for integration for the four main project components, namely people, process, tools and facilities. (c) Software engineering shapes modern systems engineering practice, either when a large amount of data is processed or when complexes of large software-intensive systems are handled. New programming is also necessary, when new technical processes are implemented. Three subsections of software engineering have recently been developed. The goal of meta-modeling tries is to find similarities between models and used them for different applications. Knowledge management organizes data structures in such a way to access knowledge easily. Cliodynamics is the mathematical modeling and simulation of dynamic processes in sociology, demography, economic, evolution, and history. (d) Risk management, reliability engineering, also called security engineering, is the discipline of ensuring a system will meet the customer's expectations for reliability throughout its life within the limits of failure probability. The failure modes and effects analysis (FMEA) focuses on critical components and hazard fault tree analysis, and of Reliability engineering relies heavily on statistics, probability theory and reliability theory for its tools and processes. (e) Safety engineering means to identify "safety hazards" in emerging designs, and may assist with techniques to mitigate the effects of (potentially) hazardous conditions that cannot be designed out of systems. (f) Quality management or performance engineering focus on the ensuring a system will meet the customer's expectations for performance throughout its life. Performance is usually defined as the speed with which a certain operation is executed or the capability of executing a number of such operations in a unit of time. (g) Human factors engineering or design of the human-machine interface (HMI) considers the influences of pilots, operators or passengers in systems, in four categories, biomechanics, the physical size, shape, and strength of the humans, visual, hearing or sensing abilities, environment such as noise, vibrations, room climate, or psychological factors, signal detection, memory, or stress. (h) Life cycle assessment (LCA) or eco-balance is the investigation and evaluation of the impact on environment caused by a process, product, or service. The demand of raw materials, the consumed energy, as well as the emission of greenhouse gases is calculated as costs, ecological footprints or ecological backpacks. There are other areas of system engineering, such as cost management, which this paper does not describe, they can be found in the literature [1, 2].

### 2.2 Complexity

As a system is a set of parts, elements or particles, system engineering clarifies the relations and dependences among them. Many famous scientists found their physicals laws or equations by such an approach. Hence, system engineering deals with description or clarification of complexity, in usual language we would say, find charts or diagram in order to understand the relations, predict the system behavior, and create new paradigms, algorithms or machines. The original meaning of complexity is used for many parts in intricate arrangement[1], or in other words for problems too difficult to understand. Such examples in physics are: (1) Sets of partial differential equations: for example of non-linear waves, which cannot yet be solved analytically. (2) Dependences of many parameters: As human beings live in a three-dimensional world, we can understand the dependence of three parameters, but need a lot of effort to understand more and think in higher dimensions. (3) Phenomena due to large amount of particles: Traffic flow simulation deal with classical particles and the basic equations are known, but new multi-particle phenomena occur, like the suddenly occurring Nagel-Schreckenberg congestions on highways[1]. (4) In many cases of complex problems, however, relations between particles are yet unknown. (5) Further demand for system engineering came from the convergence of technologies, also called emerging technologies. Material science, physics, chemistry, and biology grow together as new products such as sensors, actuator, lab-on-the-chip, micro-system- or nano-technology were established. Furthermore, the environmental problem forces the mankind to find a urgent solution for solving the severe $CO_2$ problem and protecting the ecosystem on Earth. This can only be done by analyzing and solving complexity by system engineering methods.

### 2.3 Business cycles

The search for a new trend or unsolved problem is the base for a new project, which can later lead after a successful feasibility analysis or market analysis to a business chance. Three methods are common. (a) The first is a survey, enquire, or the most sophisticated the Delphi method[1], which is a systematic, interactive forecasting method named after the Greek oracle. Based on a representative selection of people, new business trends can be evaluated. (b) The second method is the scenario method, in which certain influence factors and their dependences are modeled by experts. As one can imagine, it depends on assumptions. Nevertheless, such an investigation in 1970 by the Club-of-Rome[1] emphasized for the first time the present environmental problems and attracted remarkable attention. (c) The third method is "learning from history". Future prediction can be extrapolated from business cycles (as shown in fig. 2). Four periods with in average 4, 9, 25 and 50 years have been distinguished, the later one is called Kondratiev wave[1] after its discoverer. The reasons for such periods of business cycle waves can be found by the length of one generation (25 years, as in fig.2), the time for building an infrastructure (9 years), or market niche (4 years). Future prediction, also called the science of futurology, has the goal to collect data about question such as which field of science, or which city area will grow or shrink. Such data about future development are necessary for prediction trends in society (orange color in fig, 1), such as urban planning, transport system, or new communication systems or robots with speech recognition. Similarly, young university graduates, who want to start a business as an entrepreneur, need to obtain a good forecast about their business. Four topics for start-up business are important, high amount of innovation, the proper start time, a reliable business partner, right decisions and of course knowledge of the market by operations research, and trade studies.

A material science example for the 25-years-business-cycle is shown in fig .2, namely the development of thermoelectric materials[6]. After the discovery of the Seebeck effect[1] in 1821 it took a long time until Goldsmid found a good material. $Bi_3Te_5$ is yet the material with the highest figure-of-merit ZT for converting waste heat into desired electricity, and for this reason thermoelectric materials are considered as environmental energy sources.. After the development of the semiconductor- and thin-film-technology in 1980, companies started their development after a certain period of delay, until new products were available with another delay time. These two time periods after a large discovery last usually 3 to 5 years. Since the discovery of enhanced figure-of-merit for nano-structured thermoelectrics, nanotechnology boosts another cycle. Such discovery will be followed by new products after the delay time, for which some people think it will become shorter and shorter due to sophisticated system engineering methods.

### 2.4 Method and Procedure

The main method of system engineering is visualization of complex behavior in structural maps, the partition of a complex problem into several sections. The data flow diagram (DFD) shows, how different sub-systems treated the data. Symbols from programming such as and- , or- , decision-, input-, output-symbols are often used. Three basic configurations are (fig. 3). (a) System-in-system: A large system incorporates another, smaller system, which again contains another subsystem. (b) In a sequential system each process follows another, for example the mechanical, thermal, or chemical. treatment of a material. (c) A hierarchal type consists of several subsystems in a parallel arrangement. Examples are the organization of a company or the fabrication of car parts, which can be done simultaneously. (d) Of course in reality, a large system can consist of a complex combination of all of these three subsystem variants. The next step in system engineering is drawing of a concept map. A new project is initiated by a certain vision or target of the stakeholders, who have a vision what the project should target on. These can be companies, a corporate interested in a new business, their customers, governmental organizations, citizens, or researchers, etc. Fig. 4 shows the progress of a project in material science using the definition.

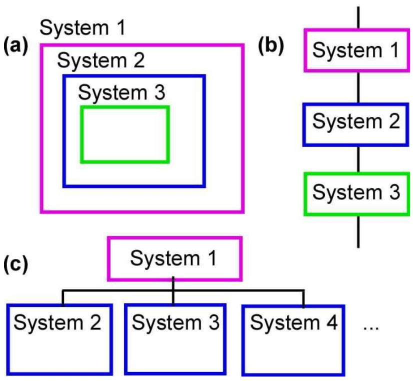


Fig. 3 The combination of sub-systems can be either of (a) inclusion or subset type, also called system-in-system (b) sequential type, or (c) parallel, hierarchal type.

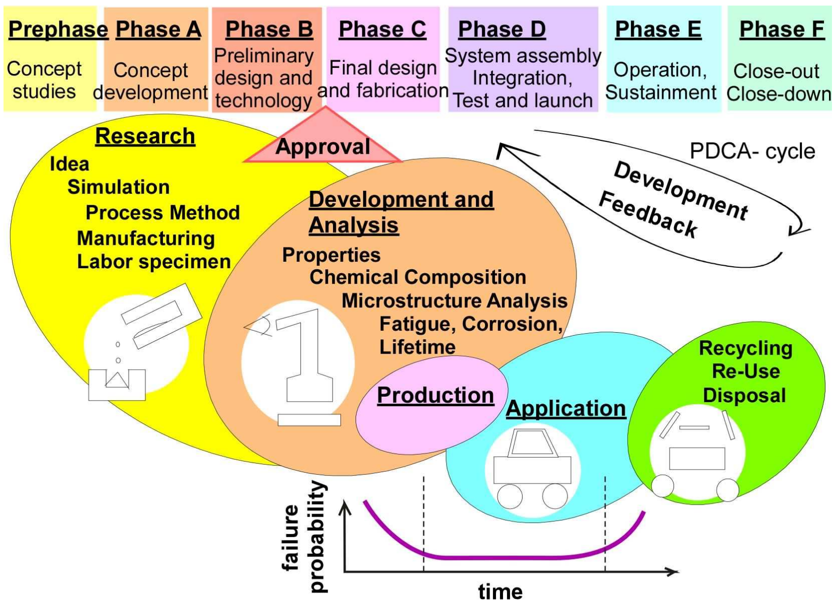


Fig. 4 Scheme of system engineering for the example of material development showing the different project phases, the Plan-Do-Check-Action (PDCA) cycle, and the failure probability of the final product.

of phases from literature[3]. After the request for proposal (RFP) is announced, concept and design studies occur (phase A, and B)and the targets are specified precisely by setting certain benchmarks, for example concerning performance, energy demand, weight, costs, etc. Then, after an appropriate research, first labor specimens are manufactured and tested. At this stage of the project, the main key decision point (KDP) has been reached, and an approval is necessary, whether the project should be continued or stopped. At the end of each phase, of course, also such key point decisions are necessary, as well as continuous improvement. This so-called kaizen[1] consists of Plan-Do-Check-Action (PDCA) cycles of development and feedback, another interpretation is Problem-finding, Display, Clarification, Acknowledge [1] or simple continuous improvement process (CIP).

Whether a project will be approved, whether it is feasible or not, this decision is a tradeoff between expectations, budget, and practicality. Until the approval point is reached, several different alternatives are discussed, but digging deeper and deeper in the level of complexity (see fig. 5) the clearer only one solution becomes feasible. This step-wise decision process is also called water-fall model in system engineering, because it decomposes the definition into a sequences of smaller steps. Sometimes it is drawn in Vee-shape and called V-model. In cognitive science or knowledge management, the same feature is called the hour-glass model, which illustrates the narrowing down on one topic, and once the decision about one way of realization is made, it widens, because more and more details need to be discussed, particularly how it is realized part by part. Now the system engineers define the concept of operations (ConOps), in which the stakeholder expectations, requirements, and the architecture of a project are capture. Involving stakeholders in all phases of a project for example by self-correcting feedback loops will significantly enhance the project success.

The technical requirements definition (TRD) transforms the stakeholder expectations into a problem definition followed by a complete set of validated technical requirements, which define a design solution for the product breakdown structure (PBS) mode. Then, the integration, verification and validation sequence starts (Phase C in fig. 4), at which the functional flow block diagrams (FFBD) shows the dependence of each process. The system requirements document (SRD) describes the needs and duties of each product. After the system functional review (SFR) and the preliminary design review (PDR), the critical design review (CDR) decides the final design. Finally, the work breakdown structure (WBS) is established, which means that the system development activities at the end of phase C are now well organized and described.

Before the fabrication in phase D starts, the measures of effectiveness (MOE), technical performance measures (TPM) and Maintainability, Producibility are checked and improved if necessary. Recent environmental concerns also require the life cycle assessment (LCA), which is a detailed description of the input of raw materials and energy as well as the emission of greenhouse gases. During phase D, the assembly and test, there is the final chance for alternative design concepts, until a solution with improved performance is found.

Phase E is the sustainable operation of the system during its lifetime. The failure probability curve versus time is shown on the bottom of fig. 4, and due to its shape, it is called bathtub curve. In the beginning of operation malfunction of parts or design faults can causes failure of the whole system, and sometimes costly reconsidering of the design or even callbacks of delivered products might become necessary. The failure probability curve drops after eliminating the weak points, and after operation it increases, when material fatigue or failure of electric parts occur. Then it is time to consider phase E, the end of the project. Dismantling, disassembly and re-use of the parts is recently included in the project calculation. Valuable raw materials can be recycled for other processes, and such urban mining becomes more and more popular in order to save costs or the environment.

Fig. 4 shows this project cycle for the example of materials. Concept studies and research are followed by development and checking materials properties as a function of the microstructure, before production, application and recycling occurs. How important recycling has become, shows the following example. Later on in this paper, light Al-alloys for aviation applications are considered. For railways also weight reduction by using Al-alloys was considered, but since steel alloys have the advantage that they can be recycled easily and production costs are cheaper, they are now used preferentially.

The methods in system engineering are summarized in the snail-shaped map, adapted from[2] and modified for material science (fig. 5). The spiral shape indicates that thoughts usual circle around a problem several times and digging deeper and deeper, until an engineering decision is found, a process sometimes as slow as a snail movement. In each level of deepness design selections, concept verifications, and validations are required. When the implement decision is successful, the engineering of this part is completed and the spiral can be left. When the decisions are not satisfied, refinements on a deeper level become necessary.

The example shows the development of an electro-car driven by the urgent need of greenhouse gas reduction. Industry companies distinguish a finer graduation of the first section of this map, namely the system is divided into segments, elements, subsystems, assemblies, subassemblies, parts, and then finally the material compounds and other material science categories as shown in fig. 5. From this scheme researcher, who decide about a new finding or a physical model, can learn that they have to check complex physics similarly as complex system engineering problems. They need to check all the steps including verification and validation until they finally publish a new paper.

## 3. Application on a material science problem

The following example illustrates system engineering approach on some unpublished results during the development of aluminum alloys for

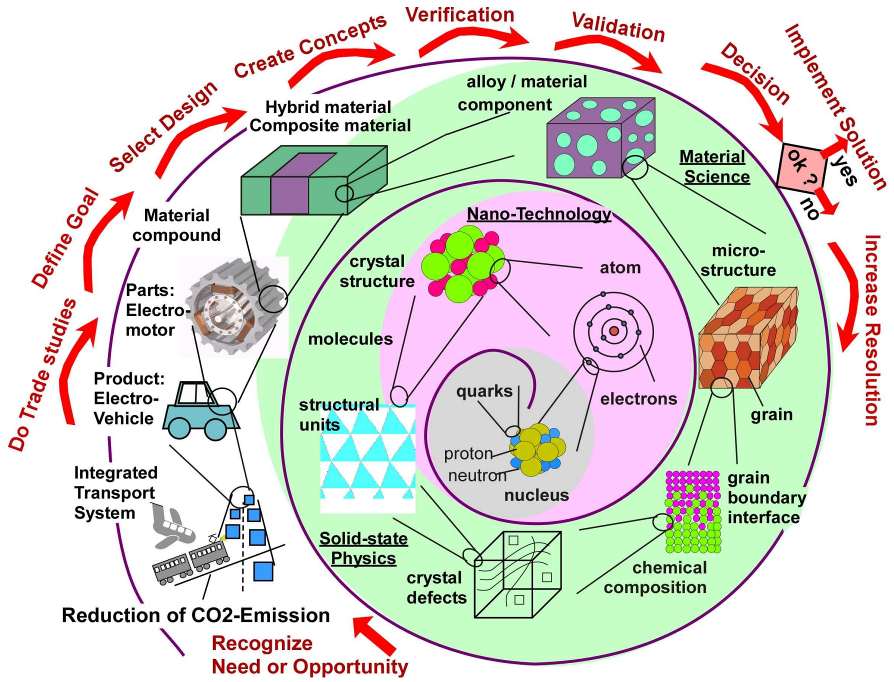


Fig. 5. The system-engineering focus map (structure adapted from[2)]) shows the development of materials for an electro-vehicle. The red arrows indicate, that on each level of resolution trade studies, design selection, verification, validation, and decisions about new concepts are required. The green area refers to material science or solid-state physics, the pink area to nano-technology.

aircraft application from late 1980-ies. The goal of this research is the decrease of the weight further by alloying the elements Li with a smaller atomic than aluminum. The data flow diagram in metallurgy is the temperature-profile as a function of time (left side of fig. 6). While the chemical composition was fixed at Al-8.5%Li, the annealing program was changed as drawn in the time-temperature-profile on the left side of fig. 6. The usual heat treatment for aluminum alloys is shown in the middle, after a homogenization treatment at 565 °C 30min, the treatment for forming the δ‘-$Al_3Li$ precipitations occurs at 200 °C 48h. The reason is seen in next row of fig. 6 showing a part of the phase diagram. When cooling from 200 °C to room temperature, the curvature of the solidus lines lead to a super-saturation of the aluminum matrix, which means that after a certain incubation time the remaining Li dissolved in Al will form new precipitations[7, 8)]. This effect was clarified by microstructure observations (second row from the left in fig. 6). In fig. 7 the 30 nm sized $Al_3Li$ precipitation formed at 200 °C 48 h are clearly visible by their doubled lattice spacing (blue arrows in fig. 7), while the 4 nm small sized precipitates (red arrow in fig. 7) form at room temperature by the fast Al-diffusion. They are smaller than the specimen thickness and hence show less contrast. Knowing this effect, the formation of small precipitates can be suppressed by very slow cooling from 200 °C

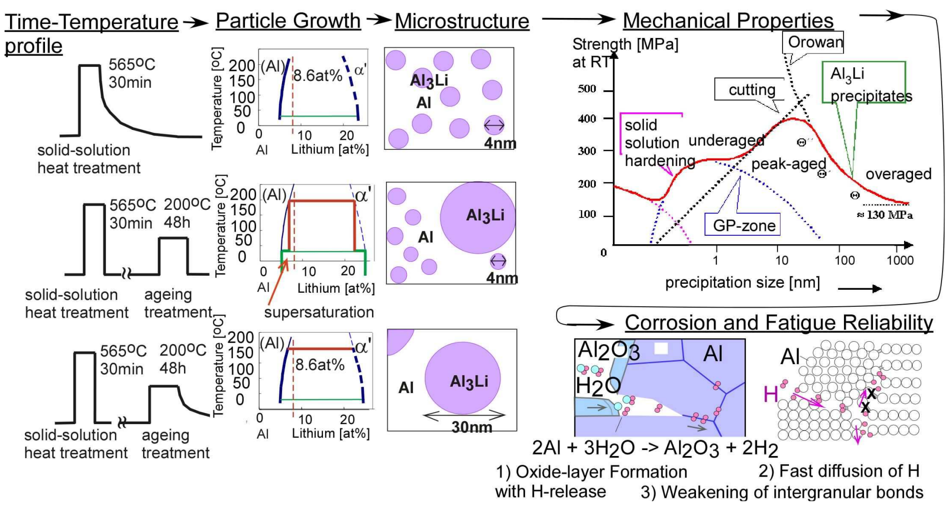


Fig.6 This flowchart of materials development for Al-Li-alloys shows for three from the left to right the time-temperature profile, particle growth, microstructure, mechanical and corrosion properties.

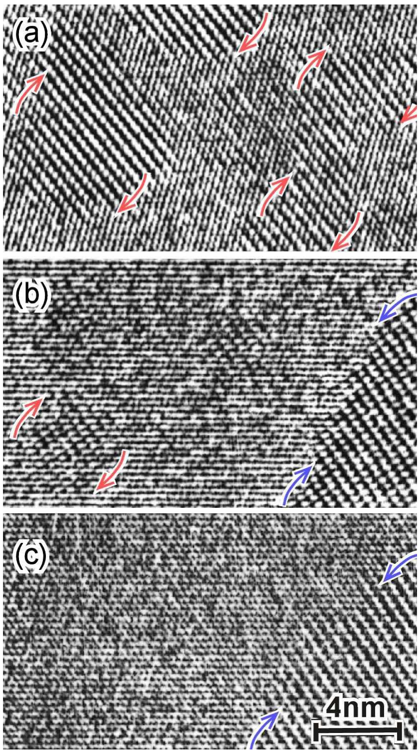


Fig.7 HRTEM micrograph showing the $Al_3Li$ precipitates in the Al matrix. This micrograph was used to deduce the three different growth modes of 40nm particles marked with blue arrows and 4nm particles marked with red arrows during different heat treatments as shown on the left side of fig. 6.

from 200 $^{o}$C (bottom row in fig 6 or 7.). On the other hand, the formation of large precipitates is suppressed by slow cooling from 565 $^{o}$C and only 7 nm sized precipitates are formed (upper row in fig 6 or 7).

The precipitation hardening effect on mechanical properties is shown on the right hand-side of fig. 6. While the 30 nm sized particles have the optimal size for hardening this alloy (peak-aged), the 4 nm sized particles affect only a small contribution to hardening[7)]. After knowing this effect, a third step at the heat treatment for the Boeing 777 and Airbus 380 alloys is added. The last step in testing a new alloy is the fatigue test. At Al alloys the crack propagation rate in the last step of fatigue increases remarkable, when the atmosphere contains a large amount of humidity. This stress-corrosion cracking is caused by three effects: (1) Oxide layers are formed with hydrogen release at fresh crack surfaces, (2) Hydrogen atoms diffuse very fast along grain boundaries. (3) Intergranular Al atomic bonds are weakened by H-substitution. This effect was confirmed on these Al-Li alloys[10)], and a micro-structural model of flattened grain boundaries suggested[11)].

The development of aluminum alloys with its complicated dependence of heat treatment, microstructure, mechanical and fatigue properties can be visualized by structural maps showing the dependences. How system engineering has influenced material science is documented buy the fact that complex grain boundary structures are called complexion [11)].

## 4. Conclusion

This paper gives an introduction to system engineering by comparing the procedure of establishing a new production process with the research and finding new phenomena in material science. The main principles are very similar: (a) Curvature of time dependences initiates new effects, either new business chances or products. (b) Thinking in higher dimensions or meta-models helps to find relations and integration. (c) Visualization and clarification of the dependences require the drawing of structural maps. These topics were outlined and applied on a problem of aircraft material development.

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