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ADVANCES IN MANUFACTURING SCIENCE AND TECHNOLOGY
Vol. 41, No. 2, 2017
DOI: 10.2478/amst-2017-0007

# BIOLOGICALLY INSPIRED DESIGNING AND MANUFACTURING OF ELEMENTS WITH SPECIAL FUNCTIONAL DEMANDS – SELECTED EXAMPLES FROM AUTOMOTIVE AND AIRCRAFT INDUSTRY

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S u m m a r y

This paper presents a comprehensive literature survey of the potential applications of bionic achievements related to both design and manufacturing of machine elements with required functional properties. The motivation is that any machine tool or manufacturing process designed even by experienced engineers are not as excellent as the functional behaviour of plants, animals or processes occurring in natural surroundings, i.e, which have been created by nature in the evolution process. Special attention is paid to producing lightweight parts for machine tools and aerospace and automotive applications. The main aspects of design methodology, mathematical modelling, experimental testing and manufacturing are taken into account.

**Keywords***:* bionics, bionic design, manufacturing

**Inspirowane biologicznie projektowanie i wytwarzanie elementów o specjalnych właściwościach mechanicznych**

S t r e s z c z e n i e

W pracy przedstawiono analizę danych literaturowych kierunkowanej na ocenę możliwości zastosowania osiągnięć bioniki w projektowaniu i wytwarzaniu elementów maszyn o specjalnych właściwościach. Motywacją prowadzenia analizy jest przyjęcie założenia, że zarówno konstrukcja maszyny oraz procesu wytwarzania zaprojektowane nawet przez doświadczonych inżynierów nie są doskonałym w porównaniu do wytworzonych przez naturę. Dotyczy to roślin, zwierząt i procesów występujących w środowisku naturalnym podczas jego ewolucji. Uwagę szczególnie zwrócono na projektowanie lekkich elementów dla przemysłu obrabiarkowego oraz dla lotnictwa i motoryzacji. Przedstawiono również podstawowe zagadnienia metodyki projektowania, modelowania matematycznego, badań doświadczalnych oraz procesów wytwarzania.

**Keywords:** bionika, bioniczne projektowanie, procesy wytwarzania

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## INTRODUCTION

A very intensive technological development motivates mechanical engineers focussed on design and manufacturing challenges to develop intensively new and original solutions. One of possible and unconventional sources of such engineering inspirations is localized in our natural surroundings. The bridge which links solutions available in natural surroundings and real technology creates the area of knowledge named the *bionics*. Bionics means the application of biological function and mechanics to machine design [1].

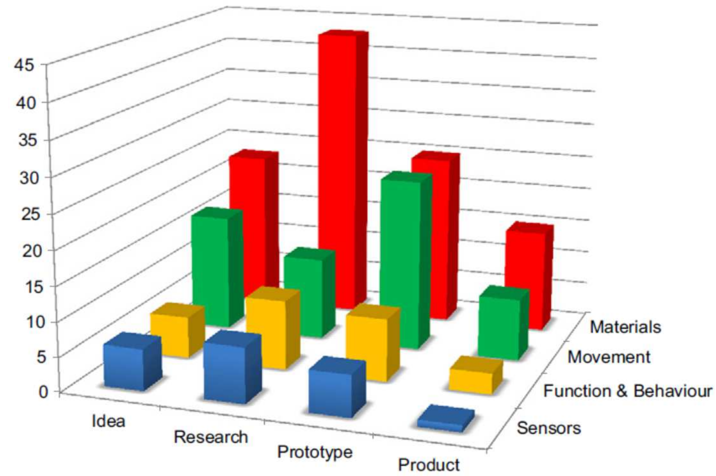



Fig. 1. Different areas of biomimicry applications, based on [2]

Moreover, *Biomimicry*, *Bioinspiration* or *Biologically inspired design* are synonyms which emulate or seek natural models, systems and processes to solve a wide range of human problems [1, 3]. Taking into account the overall object of bionics it could be structured into three main fields, i.e. construction (structures of nature), processing (methods and processing of nature) and information (data transfer, developmental and evolutionary strategies) bionics [2]. The most successful areas of biomimicry applications are specified in Fig. 1. Although the largest area of biomimicry research is material development (accounted for 50% of all references), the areas of prototypes and new products in terms of their functional behaviour also seem to be important. The bionic inventions were successfully applied in the design of lightweight aircraft parts and units of precise machine tools [1-3]. There have also been worked out very interesting inspirations for precise grinding process including grinding wheel properties, machine tool accuracy and organization of the machining process. It is worth underlining that in grinding process usually properties of surface layer of many parts with demanded functionality are created. Nowadays, biologically inspired design is applied in AI research on computational sustainability [4]. In this paper some interesting applications of bionic achievements in production engineering are presented and discussed.

## 2. Biological inspirations in technique and technology

It is worth unnderlining that animals and plants in natural surroundings have been developed in a visible evolution process lasting millions of years. Apart from this fact the structures and processes which are performed in the nature are very efficient but usually they are too complicated and difficult for direct copying in technical applications. It is possible to design advanced construction with very high mechanical properties but the obstacle for its building are excessive costs. In the design of machines and tools engineers can first use multiple inspirations resulting from investigations of all birds and mammals skeletons, structures of plants such as bamboo, bulrush, Mexico cacti, Brazilian giant horsetail, grass or ordinary trees [1-3, 5-8].

Another level of inspirations can be taken from the inner structure of bones, tree branches, stems and leaves of plants presented exemplarily in Fig. 2 and 3. This is because that in service usually strong correlations occur between surface layer properties and functionality of parts. As a result, design engineers can also find inspirations in improving both surface and structure properties and their functional behaviour. For example, the macro property of a bamboo stem shown in Fig. 2, which is determined by the micro gradient distribution of fibre bundles, seems to be one of the most efficient load-bearing structures.

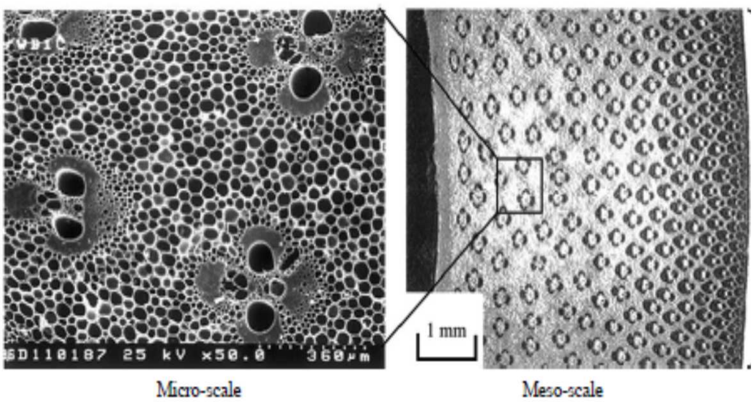



Fig. 2. Bamboo’s cross section structure in micro and mezo scales, based on [5]

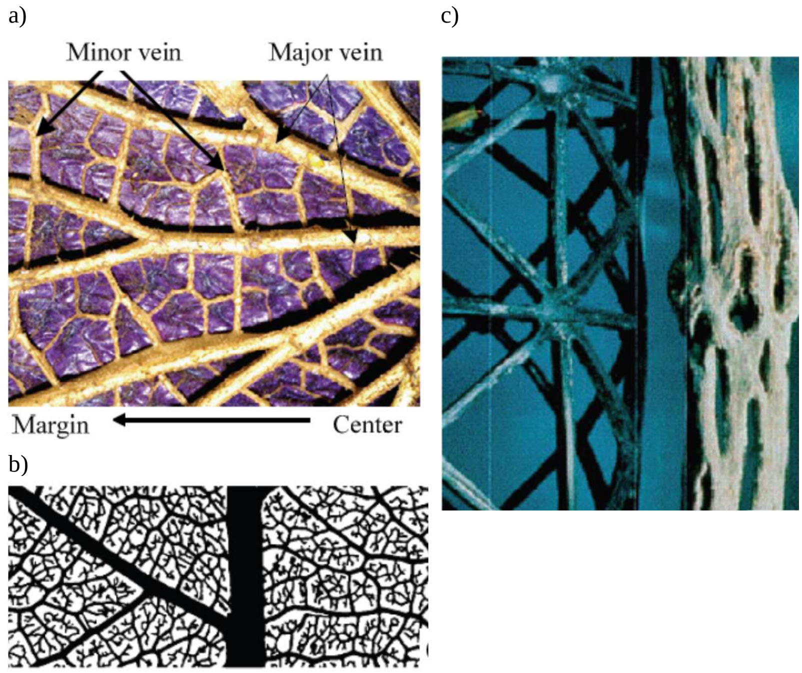



Fig. 3. The networks of giant water lily leaf (a) and *Gloeospermum* leaf veins (b) and Mexico cacti stem (c), based on [9]

It is well known that veins (Fig. 3) can provide the adequate model for the external load to keep their surfaces flat and stiff. Two kinds of veins shown in Fig. 3a include the major radial and minor ones which form a powerful supporting network of the leaf surface. Moreover, a *Gloeospermum* leaf shown in Fig. 3b and the Mexico cacti stem shown in Fig. 3c are other examples of ideal load-carrying structures. These biological configurations provide extreme stiffness in conjunction with maximum efficiency and minimum use of materials.

Another example of biomimicry is the use of tubercles on the pectoral flippers of humpback whales shown in Fig. 10a for the design of windmill turbine blades. Hence, the bionics is able by the use of nature to improve and emphasize the design of new technological systems, processes and products including environmental sustainability [4]. Moreover, the biologically inspired products can cover spatial scales ranging from nanometers (e.g. biomolecules) to hundreds of kilometres (e.g. ecosystems). Summarising these analogises between the nature and real engineering efforts it should be noticed that nature not only offers inspirations for solving complex technical problems but at the same time reminds that men are part of natural surroundings.

## 3. Design of lightweight constructions

Lightweight constructions have significantly lower mass in comparison with conventional ones but no worse other properties such as functionality, mechanical strength, stiffness, distortions or vibration resistance. The manufacturing processes of bionic parts must be also friendly to natural surroundings. Designing of lightweight units using conventional design techniques is intuitively related to the application of light materials (Li, Mg, Be, Al), theirs alloys and special composite materials. Lightweight constructions are being more and more widely applied in industry [6]. They have numerous applications in space, aircraft, automotive, train industries and in the area of machines building. For instance, a significant decrease of mass of aircraft engines was achieved by using other alloys such as nickel or titanium –based superalloys. Also the mass of a Volkswagen XL -1 car was significantly decreased by the use of only 25% of steel. The rest of the materials are light metals and their alloys (22%), special composite and advanced plastic materials (53%) [6]. The mass of parts (units) can be significantly decreased by their special design. For instance, in order to replace conventional aircraft turbines consisting of turbine blades mounted on the ring, monolithic turbine blade discs (blisks) are used [8]. This is a conventional way of decreasing the mass of construction. The most efficient mass decreasing can be achieved by using biologically inspired design characterized in Section 4. As a result, some exemplary solutions which have been worked out by nature in the evolution process in the form of “bionic” constructions are presented.

## 4. Methodology of biologically inspired design

The scenario of the bionic design usually includes the following five stages [1, 3, 5, 7]:

- Technical general aim formulation. Here, the flexibility in technical aim definition is very helpful. It is also useful to take into consideration different ways of reaching the best technical solutions. It could be very useful in the next steps of design process.
- Biological structures, analyses of materials or processes in order to find out biological model for technical problem solving and primary evaluation of this model. Typical tools applied are methods based on theory of similarity and fuzzy logic. In this step the primary bionic model should be built but also the flexibility is very useful.
- Taking into account the obtained results of steps 1 and 2 and after discussion the mechanical model of the designed part is created. For this purpose usually the FEM method is used and, as a result, modelling process allows the designer to find out the appropriate mass, stiffness, strength, stresses and distortion distributions. In modelling parts with known both dynamic load and

the vibration characteristics are very valuable in model evaluation. When results of calculations are promising the material model of the part is build in scale 1:1 or 1: X (the choice of X depends on part dimensions).

- Using material model the complex experimental investigations should be carried out in order to verify the results of mathematical modelling. When the comparison of mathematical calculations and the results of experiments and measurement are not satisfactory the relevant corrections in steps 1, 2 or 3 should be made.
- When the results of mathematical calculations and experimental tests of the bionic model are satisfactory the decision to build a prototype can be taken. By carrying out experiments using the prototype (stiffness, stresses and distortions distribution, weight, fatigue resistance, wear resistance) the evaluation of the fulfilling level of technical demands is possible.

It is worth to underline that the very important research tool is natural human intuition

## 5. Practical applications of lighweight design

Practical applications of the research in the bionic area is very wide. As leading examples, its applications in the field of machine tools and the aircraft industry are presented. Taking into account the presented bio-inspired design methodology and some biological inspirations it was possible to work out the bionic design of some units of machine tools (Fig. 4) with the following advantages achieved: increase of strength in the range of 53-124%, increase of stiffness of 21-43%, weight decrease of 3- 43%, distortion decrease of 16-44% [5,7-9]. The results of conventional and bionic design of machine-tool body and aircraft parts are presented in Fig. 5-9.

Taking into account bionic structures presented in Fig. 2 and 3 and the design methodology presented in Section 4 the bionic construction of the crossbeam of a vertical machining center shown in Fig. 4 was completed. The differences between the results of classical and bionic structural models can be distinguished in Fig. 5.

As reported in Ref. [9] a new optimized bionic structural model presented in Fig. 5b allows reducing the mass by 3.31 %, mechanical distortion by 16.23 % and increase specific stiffness by 23.29 %. This effects result from the fact that the parallel ribs characteristic for the conventional structure presented in Fig. 5a were modified into additional diagonal ribs using the analogy to the veins distribution of Mexico cacti stem shown in Fig. 2c.

Figure 6 shows the results of bionic modelling of a lighter working table for high-speed machining (HSM) applications (Fig. 6a) and the relevant FEM model generated in ANSYS FEM package with visualization of the static deformation in the improved model (Fig. 6b). The construction improvements resulting from a new lightweight bionic concept of the working table include the hollow stem between constrained and loaded areas and additional diagonal ribs in the middle deformation area. As a result, both the machine tool performance for a higher acceleration and the machining precision were improved.

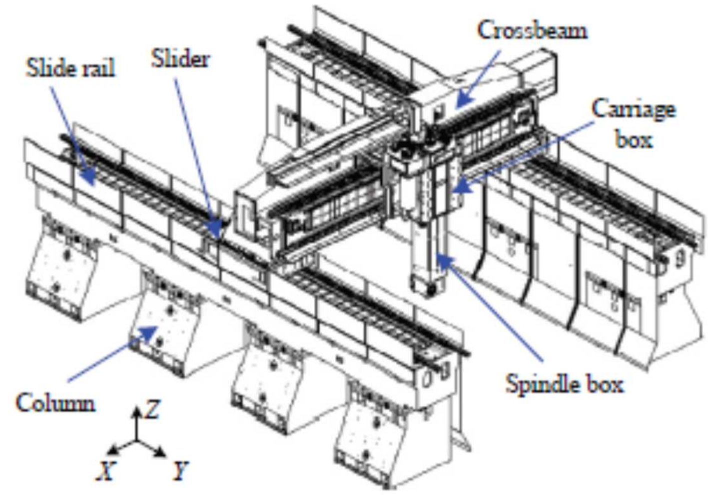
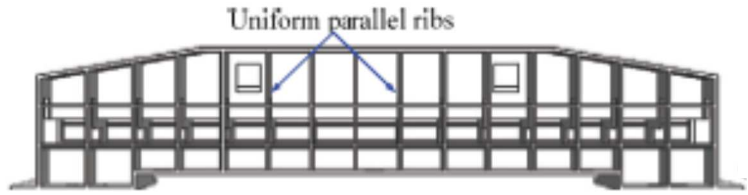



Fig. 4. The major modules and the coordinate system
of a vertical machining center, based on [9]

a)




b)

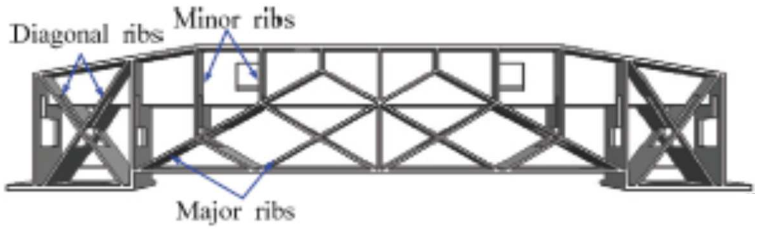



Fig. 5. The conventional parallel and uniform ribs of conventional model (a)
and improved bionic model (b), based on [9]

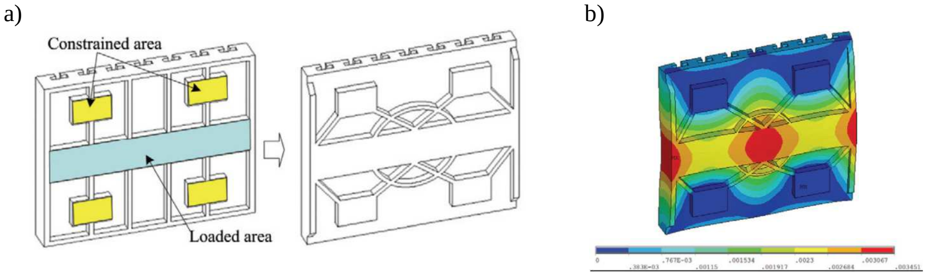



Fig. 6. The conventional and bionic models of a working table of a HSM machine tool (a) and its FEM model with the distribution of static deformation (b), based on [5]

Aircraft industry offers a wide spectrum of very important problems to be solved urgently. First of all, because of distinct increase of passengers number and the amount of goods for airplane transportation the production of aircrafts must be significantly increased in a near future. Secondly, the new aircrafts must be significantly modernised and improved. Important parts in a new airplane construction are lightweight ones. Using biologically-inspired design and modelling some parts have been modified as shown in Fig. 7 or brand new parts with bionic inspiration have been designed as illustrated in Fig. 8 and 9.

Taking into account the vein structures of bamboo, rhubarb, honey comb and diatom the bionic design of bracket (Fig. 7), crossbeam (Fig. 8) and aircraft reinforced frame (Fig. 9) using the bionic design procedure have been performed. The obtained results are presented in Figs 7, 8 and 9 respectively. As shown in Fig. 7b the aircraft bracket designed by means of the bionic design is significantly lighter in comparison to the conventional design but because of complicated shape it must be manufactured using Laser Additive Manufacturing, which generates additional costs. However, savings of material (its mass is about three times lower) and operational costs during aircraft lifecycle are significantly higher. The bionic lightweight design gives possibility of important improvements in the next aircraft generation [10].

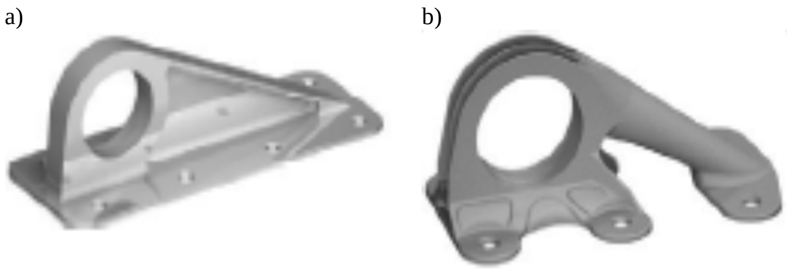



Fig. 7. The bracket design: (a) conventional solution and (b) bionic design manufactured using laser additive method, based on [10]

It can be noticed based on dimensions of the brackets shown in Fig. 7a and b respectively that the volume of conventional bracket made of aluminium 7075 grade was decreased three times from $12 \times 10^4$ $mm^3$ to $4 \times 10^4$ $mm^3$ when it was replaced by titanium Ti6Al4V grade, while its mass was decreased from 330 g to 90 g.

Fig. 8. A new bionic model of aircraft crossbeam fabricated by investment casting, based on [5]

Fig. 9. A new bionic model of an aircraft reinforce frame produced by CNC milling, based on [5]

A new bionic model of a crossbeam presented in Fig. 8 was obtained using a precision casting process (called investment casting) of a cast aluminium alloy ZL 101 grade. As a result, a very complex structure with differently shaped hollows was manufactured. For the same delicate textured structures, as this shown in Fig. 9, CNC milling can be used as a rapid prototyping process to obtain models with high accuracy, lower costs and fast manufacturing.

In all cases presented in Figs. 7, 8 and 9 the dead-load is reduced without sacrificing static and dynamic mechanical properties. The tests revealed that the anti-vibration performance of bionic models has also been improved [5].

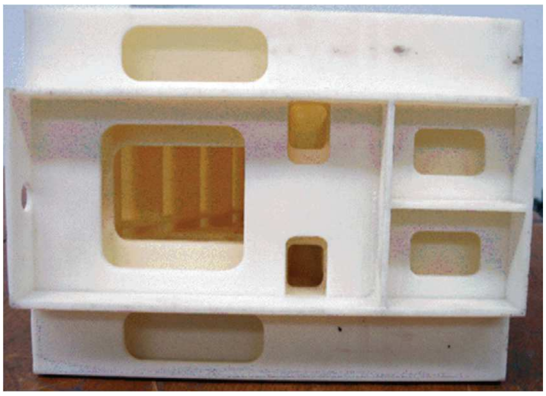


Fig. 10. Bionic model of a column obtained by RP, based on [5]

a) b)

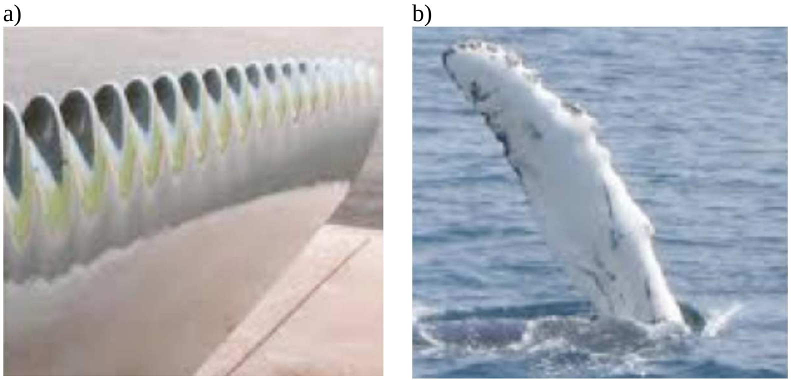


Fig. 11. Design of windmill turbine blade (a) inspired by tubercles of humpback whale flippers (b), based on [4]

Another example of the bionic model obtained by rapid prototyping is shown in Fig. 10. In this case a column was fabricated using Selective Laser Sintering (SLS) technique [5]. The negative effect is that the material used is ABS engineering plastic which can bring some problems during mechanical testing. However, this RP technique allows fabricating three-dimensional parts with a relatively high efficiency and low costs.

Fig. 11a shows the result of the design of windmill turbine blades when using tubercles on the pectoral flippers of humpback whales presented in Fig. 11b. As shown in Fig. 11a tubercles are copied in the form of large bumps on the leading edges which create fast-moving channels for air flowing (water flowing in case of whales). The result of such bionic-based construction modifications is that wind turbine blades work with better lift and reduced drag and the energy efficiency of the turbine with modified blades is improved.

## 6. Problems with manufacturing of bionic structures

Bionic structures are quite different from conventional solutions. This is the reason why the use of the advanced manufacturing systems which are developed by engineers for conventional parts, is limited for manufacturing bionic details. Because of usually complicated structures the best methods for manufacturing bionic details are additive manufacturing methods. However, sometimes it could be very difficult when some bionic details are very large, as for example body of large machine tool shown in Fig.4. In this case the welding technologies are very useful. For medium precise parts (see Fig. 7) it is reasonable to apply investment casting technology. In case of structurized surfaces shown exemplarily in Fig. 8, the CNC milling, laser structurizing (LBM) or electrodischarge machining (EDM) can be efficiently applied [5, 6, 11, 12]. For smaller parts the application of Laser Additive Manufacturing could be more efficient way for their fabrication. In this case very helpful could be equipment produced by Nanoscribe Company [13] dedicated to manufacturing small parts with the resolution of a few micrometers.

## 7. Summary

Bionics builds a bridge between “world of plants, animals and processes “ developed by the Nature in evolution process and innovated technical applications. By using bionic models and solutions it is possible to solve a range of difficult technical problems connected with:

– building of precision machine tools, designing their functional units and parts. Lightweight constructions with improved mechanical properties such as stiffness, strength or distortions are very promising solutions.

– improvement of surface layer and part properties by creation on the regular surface patterns analogous to those worked out by the Nature which result in higher stiffness, better wear resistance and increased fatigue strength.

In some cases improvement of mechanical and functional properties of parts is possible only when complicated bionic structures are applied. In this case applications of such machining processes as grinding, drilling, milling, electro-discharge or laser beam machining, investment casting, welding or additive manufacturing are necessary

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*Received in December 2017*