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Simulation-Based Determination of Disassembly Forces

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Abstract

While joining tolerances, and therefore forces, are known in the assembly process, the determination of disassembly forces is not possible. This is caused by changes of the product properties during the product operation, which has multiple reasons like thermal or mechanical stress on the product. Regarding the planning of disassembly tasks, disassembly times and tools cannot be planned properly. They have to be determined in the process or stay undefined, which can result in damaging of the product.

This article shows an approach to describe the necessary disassembly forces without having to investigate the complex physical influences caused by the usage of the product. A solidifying force that has to be overcome in the disassembly process is defined. To make the solidifying force transferable within the huge amounts of individual products, it is split into a usage factor (e.g. hours of operation) and a product specific factor (e.g. geometry of connection), which specify the influences on the joint properties. The transferability of usage factor to product variants is investigated using a FEM-Simulation.

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Keywords: Disassembly, Automation, Process Planning

1. Introduction

The disassembly of a product initiates its regeneration. Therefore, the planning of the disassembly is critical to the unobstructed process of the entire regeneration cycle. Particularly in the case of complex capital goods such as an aircraft engine, a planned disassembly process is essential for maintaining the components. A systematic disassembly is only possible, if all product properties are taken into account. However, uncertainties about the state of the product prevent a detailed planning, what is symptomatic for disassembly processes.

In a product life cycle the disassembly is arranged directly after the product operation. As a result of the operation, the product properties and assembly connection properties of the assembled parts change. The component tolerances, defined in the assembly, are thus no longer valid, which is particularly evident for heavily stressed components. In contrast to the assembly process, where joining forces are known due to defined product properties, disassembly forces are typically unknown. The unknown connection properties lead to unknown disassembly forces, which effect a lack of the tool dimensioning. As a result, manual processes are currently predominant in disassembly strategies and process times can only be estimated imprecisely.

To make the disassembly, and thereby the entire regeneration cycle, plannable, cost efficient and component-saving, it is necessary to be able to estimate needed disassembly forces. Knowledge of the disassembly forces is essential to the planning of an automated process. However, it is difficult to quantify and simulate the physical effects during the product operation, especially in the case of highly stressed components. For example high forces or high temperature loads lead to complex changes in the product properties and the interaction of the individual influencing factors makes it even more complex. Thus, the analytical description or the simulation of the physical influences would be an approach to the determination of the disassembly forces. Nevertheless, such strategies are very laborious and, due to the complexity, very imprecise.

An alternative approach, which seems more promising, is the assignment of the disassembly forces to the history of the product (eg. operating hours). Thus, the physical processes during the operation are not explored, but only the stationary

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state before and after operation. However, such experiences of process forces always depend on the constructive properties like the connection geometry, material, or contact surfaces. Thus, disassembly forces comprise internal (construction properties) and external influences (operational properties) (Fig. 1).

Fig. 1. Influences on disassembly forces.

In order to plan disassembly forces, the transfer of internal connecting forces to other construction properties is the aim of this research. To this end, experiences one gained from a disassembly force for a particular assembly connection and its load properties are decoupled from the constructive properties of this connection. These information can then be transferred to a connection with different construction properties (Fig. 2).

A typical sample application with solidified assembly connections is a blade in a disk of a high-pressure turbine of an aircraft engine. Here, the disassembly is especially worthwhile, due to high costs of the components. Internal connection forces (and thus disassembly forces) occur in a particularly high degree and lead to solidified connections as shown in Fig. 3.

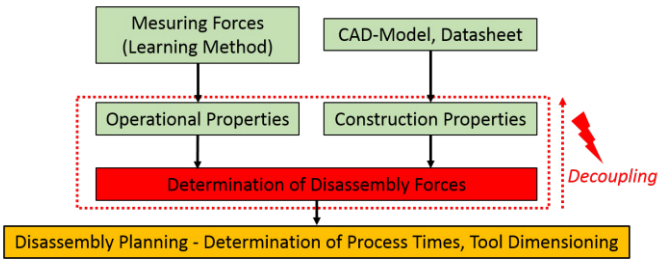

Fig. 2. Splitting of the disassembly forces to determine process parameters for disassembly planning.

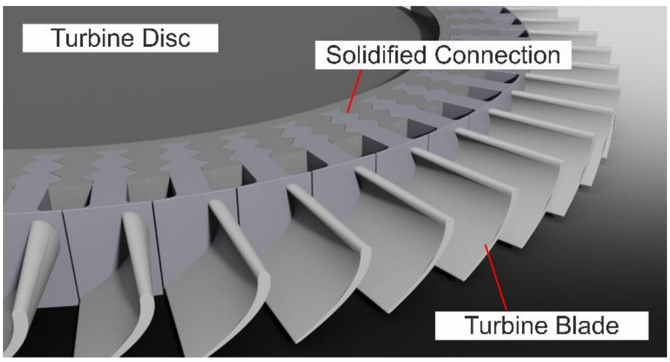

Fig. 3. Model of high-pressure turbine disc and blades.

2. Related Work

The disassembly is characterized by manual operations as well as in case of aviation engine disassembly. This is due to unknown product properties and joining properties of each component. With regard to plannable or even automatized processes, knowledge of the product condition is necessary. In order to describe the physical effects of all the several influences on the connection state, a big effort would be required, which remains unsuccessful in the worst case [1]. This complexity of individual influences, and interactions are illustrated in the next section, in order to motivate the alternative approach of this research.

The operating phase of a product has a strong influence on the assembly connection properties, especially heavy stressed components solidify to an unknown degree. This process of solidification can have various causes. By considering the example of a turbine blade, hot gas corrosion and adhesion are major wear mechanisms. Hot gas corrosion is caused by components of the fuel and the air (e.g. sea salt) flowing through the engine and produces solidifications in the contact surfaces of a connection. Surface corrosion can increase the loosening torque of a screw, for example, up to 45% [2]. In contrast adhesion is caused by molecular interactions on the boundary surfaces of the assembly connection. Deformations of roughness peaks and the separation of material fragments can increase the adhesion forces and thereby the solidification [3]. Besides the solidification, which is caused by separated particles of the connection itself, foreign particles can cause additional blockades in the connection, e.g. sand of a desert flight.

In his research, Müller [4] developed a method to determine the maintenance intervals of an aircraft engine using a probabilistic modelling method. Müller considers various influences on the wear of a jet engine to predict default probabilities.

In this work, the focus is not on the determination of the maintenance intervals, but on the determination of the disassembly forces of the turbine blades. Various causes and their interaction make it very difficult to calculate the necessary disassembly forces beforehand. This requires highly flexible processes, so that the turbine blades are therefore disassembled manually, using simple tools like a hammer. However, high manual forces are difficult to control, and thus damage can occur. Especially during the regeneration of products, it is necessary to use methods that save the components from damages.

Rather than beating the blades out of the disc with a hammer, controlled impacts are generated by a piezo-stack actuator to reduce the disassembly force [5].

The disassembly force $F(z)$ and the weight load mg of the turbine blade have to exceed a solidifying force $R_Z(z)$, which acts contrary to the disassembly force, see Eq. (1). A slight exceeding enables component-saving disassembly.

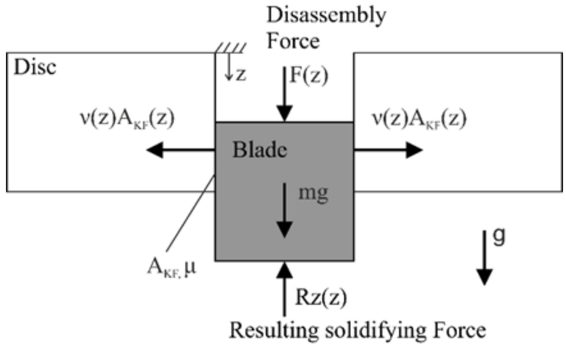

Fig. 4. Simplified solidification model

$$F(z) > R_Z - m \cdot g \quad (1)$$

Since the weight of the turbine blades is usually very low in comparison to the solidifying force, the centre of attention is the solidifying force $R_Z(z)$. The solidifying force is determined by the contact surfaces A_{KF} of the joined components, the solidification pressure ν between the components and the coefficient of static friction coefficient μ. Following from the simplified model shown in Fig. 4, the solidifying force can be described as:

$$R_Z(z) = \mu \cdot \nu(z) \cdot A_{KF}(z) \quad (2)$$

Nevertheless, the solidifying force is not only dependent on the absolute amount of the contact surface, but also upon the geometry of the connection. Fig. 5 shows two types of connections that are common in the aviation industry, along with FE-simulation of the solidifying force over the disassembly length for an exemplary solidification. All boundary conditions such as the contact area and material properties are the same. It becomes obvious, that the solidifying force changes with the geometry of the connection between the blade and the turbine disc.

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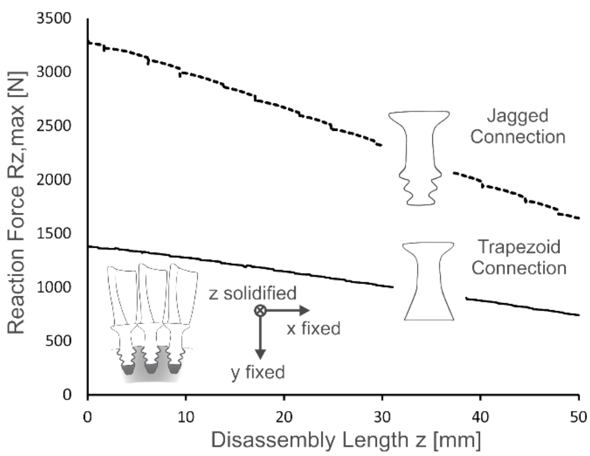

Fig. 5. Course of solidifying force in FE-Simulation.

Within the FE-simulation, the pressure between two components can be simulated by implementing an interference fit [6]. The solidification pressure ν correlates with an interference e and the length of the area affected by the interference. In an one-dimensional interference (e.g. lengthwise compression of a beam) the effective length is easy to determine. In the example of a turbine blade connection with at least two dimensions, is considered the problem becomes more complex. Nevertheless, since the approach in this work aims at the approximation of disassembly forces, a one-dimensional approach is used in the following. The pressure, determined by the interference, describes the level of solidification of the connection.

In this research an approach is shown to decouple the solidification of the product properties, like the geometry or the material. Thus, if experience values of a solidification state of a connection are known, the state can be transferred to products with different constructive characteristics.

3. Decoupling the Force of Product Specific Parameters

The idea of the following concept is to determine the solidifying force of a particular turbine blade by parameterizing the solidifying force of an already determined reference product. The solidifying force is determined as described in Eq. (2).

While the contact surface and the static friction are determined by the geometry, surface and the materials of the connection partners, the pressure can be further split. In previous simulations, the pressure has been modelled by creating an interference fit e (Fig. 6).

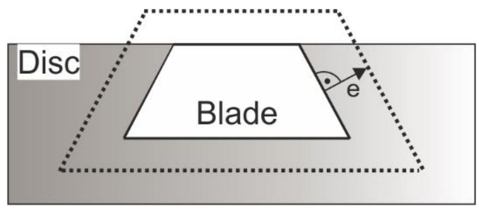

Fig. 6. Modelled interference fit between blade and disc.

Taken into account, that the material of the blade has to be elastically deformed to fit into the connection, an internal connecting force F_{int} emerges, so that the deformation of the blade can be described in the elastic case with a constant stiffness parameter c_{Blade}.

$$F_{\text{int}} = c_{Blade} \cdot e \quad (3)$$

With the component pressure, the modulus of elasticity, the contact area and the change of length it follows:

$$\nu \cdot A = \frac{E \cdot A}{l_{eff}(G)} \cdot \Delta l \quad (4)$$

The dependency of the contact surface disappears:

$$\nu = \frac{E}{l_{eff}(G)} \cdot \Delta l \quad (5)$$

The effective length $l_{eff}(G)$ is defined as a parameter that depends on the connection geometry G. It can be seen in Fig.

7, that the effective length, a scalar, can easily be determined in an one-dimensional case.

$$l_{eff} = l_i \tag{6}$$

In the two-dimensional or three-dimensional case, the determination becomes a more complex problem, because there is an infinite amount of effective lengths.

In this case, the strains overlap and influence each other. In addition, a mechanical determination in narrowing (P1) or free ends (P2) of a geometry, shown in Fig. 8, is very complex. An analytical determination would not be effective for the application and certainly only reflect the reality limitedly as described in the state of the art.

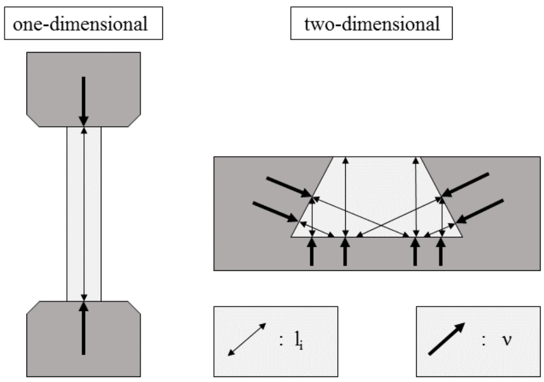

Fig. 7. Schematic illustration of the effective length in an one- and a two-dimensional case.

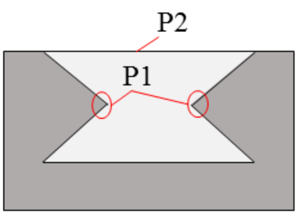

Fig. 8. Overlaps and free ends in a connection geometry.

Thus the sum of all one-dimensional strains, which is referred to as the effective length, is not determined analytically. In order to estimate the disassembly forces for geometries without experimental data, a geometric-specific effective length is determined. In comparison the change in length, Δl does not depend on the geometry and equals the interference e, which is specified as a constraint condition of the solidification properties. Equation (5) changes to:

$$\nu = \frac{e}{l_{eff}(G)} \cdot E \tag{7}$$

Substituting ν in Eq. (2) with Eq. (7), the solidification and thus a minimum force, which has to succeed by the disassembly force, can be described as:

$$R_Z(z) = \mu \cdot \frac{e}{l_{eff}(G)} \cdot E \cdot A_{KF}(z) \tag{8}$$

4. Dependency of the Connecting Geometric Form

Since the aim is to decouple the geometric parameters from the solidification of the connection, it is necessary to isolate the main parameter which is responsible for differences in the disassembly force of different connection geometries. The parameters μ and E are determined by the used materials and surfaces, the interference e describes the solidification of the connection. The contact surface A_{KF} can easily be measured and decreases linear during the process analogous to Δz. Thereby the effective length $l_{eff}(G)$ is isolated as a parameter, that contains specific geometric information:

$$l_{eff}(G) = \frac{\mu \cdot E \cdot e \cdot A_{KF}(z)}{R_Z(z,G)} \tag{9}$$

The solidifying force R_Z is now set in relation with material and geometry variables as well as the connection geometry with the parameter $l_{eff}(G)$. In order to compare the geometry in the manner of a parameter variation, it is described as simply as possible, thus only two variable parameters are used. Fig. 9 shows two different, simplified types of connections, which are used as an example in this work. The connection seen at the top will be referred to as Type A connection, while the connection at the bottom will be referred to as Type B connection. Both connections are described by the parameters L1 an L2.

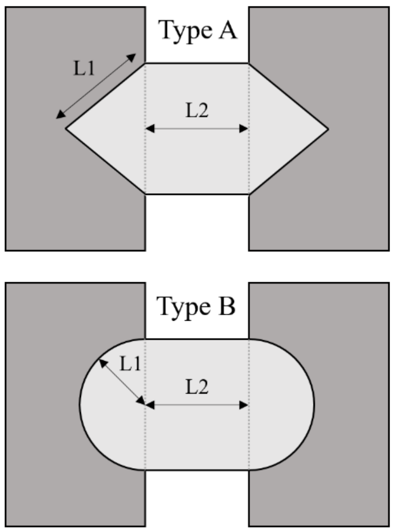

Fig. 9. Geometric parameters L1 and L2 at a Type A connection (top) and a Type B connection (bottom).

The simulation of the solidifying forces of the Type A and B connections showed, that, with all other parameters, like μ, E, e and A_{KF}, set equal, the solidifying force R_z changes with the alteration of $L1$ and $L2$. This means that the geometry parameter $l_{eff}(G)$ depends on the lengths $L1$ and $L2$.

Keeping in mind that, the idea of this work is, to define a parameter that makes different connection geometry, but a similar usage factor and therefore solidification, comparable, a quotient K of two geometry parameters $l_{eff,A}$ and $l_{eff,B}$ is introduced:

$$K_{B,A} = \frac{R_{Z,A}(z)\cdot\mu_B\cdot E_B\cdot e_B\cdot A_{KF,B}(z)}{R_{Z,B}(z)\cdot\mu_A\cdot E_A\cdot e_A\cdot A_{KF,A}(z)} \quad (10)$$

$$K_{B,A} = \frac{l_{eff,B}(L1,L2)}{l_{eff,A}(L1,L2)} \quad (11)$$

The usage of the parameter $K_{B,A}$, as intended in theory, will be described in the following. First, a turbine blade with a known usage factor (operation hours, flights over sea and desert) and a Type A connection must be disassembled, so that R_Z can be determined by means of a force sensor and Eq. (1). With an known usage factor e the geometry parameter $l_{eff,A}$ can be determined. If a turbine blade connection with a different geometry (e.g. Type B) but a similar usage history is disassembled, the geometry parameter $l_{eff,B}$ can be determined, analogous to $l_{eff,A}$. A valid simulation can also provide this relationship, if the material and geometric properties are known.

5. Simulations

In the following section, the idea, that the difference in the solidifying force of two geometrically different connections with a similar usage history can be quantified with only one factor, will be verified by simulating the solidifying forces of the Type A and B connections.

For the simulation, the connections of the Type A and Type B are modelled using a CAD-System and then transferred into the FEM-System. Fig. 10 illustrates the joined components of a Type B connection.

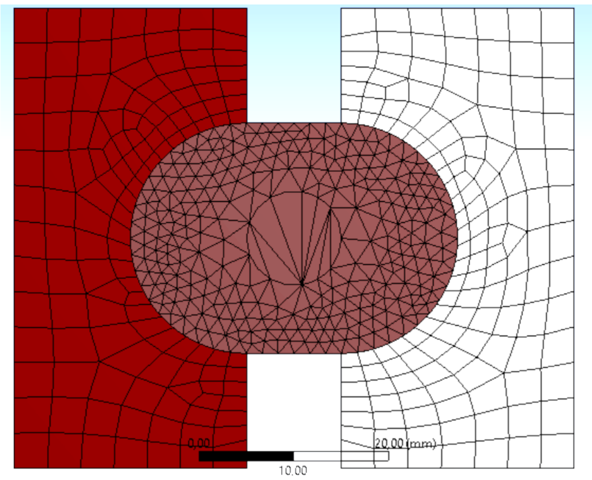

Fig. 10. Net used in the FEM-Simulation of a Type B connection

Table 1 shows the results of the simulation of the solidifying forces and the geometry parameter as a function of the lengths $L1$ and the contact surface for the Type A connection. The length $L2$ has a constant value of 20 mm. Analogous, Table 2 shows the results for the solidifying forces and the geometry parameter for the Type B connection geometry.

In Fig. 11 the geometry parameters $l_{eff,A}$ and $l_{eff,B}$ are illustrated. The values are taken from the highlighted columns in Table 1 and Table 2. The blue graph represents the Type A connection and the orange graph shows the Type B connection. Since the two graphs are approximately linear, they can be slid over each other by multiplying all of the geometry parameters of the Type A connection with a factor. In Fig. 11 the factor is 1.56.

Table 1. Solidifying force and geometry parameter as a function of the length L1 for a Type A connection (E=96 GPa, e=0.005 mm, μ=0.2).

L1 [mm]	A_{KF} [mm²]	$R_{Z,A}$ [N]	l_{eff} [m]
17.77	2844	9651	0.028
26.67	4267	10937	0.037
35.56	5689	11366	0.048
44.44	7111	11747	0.058
53.33	8533	11259	0.073
62.22	9956	11377	0.084
71.11	11378	11432	0.096

Table 2. Solidifying force and geometry parameter as a function of the length L1 for a Type B connection (E=96 GPa, e=0.005 mm, μ=0.2).

L1 [mm]	A_{KF} [mm²]	$R_{Z,B}$ [N]	l_{eff} [m]
12.22	3072	10008	0.029
18.33	4608	10722	0.041
24.45	6144	10637	0.055
30.56	7680	11359	0.065
36.67	9216	11543	0.077
42.78	10752	11230	0.092
48.89	12288	11789	0.100

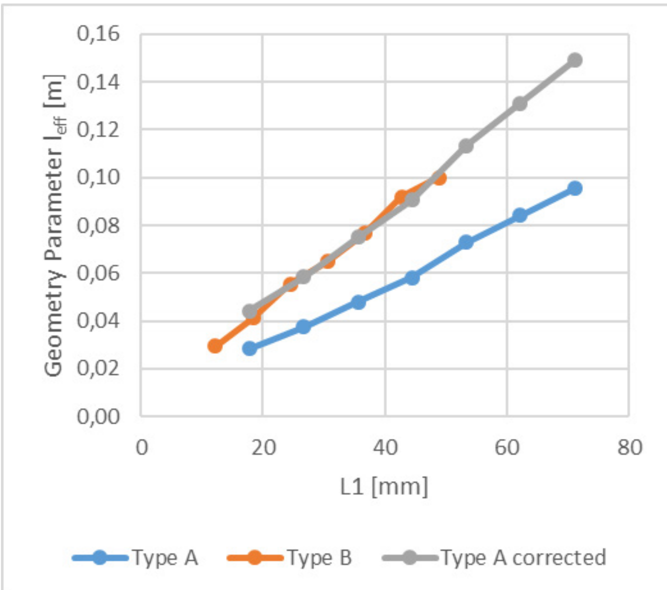

Fig. 11. Geometry parameters $l_{eff,A}$, $l_{eff,B}$ and $l_{eff,A,corr}$ as functions of $L1$.

The factor of 1.56 is equal to the geometry quotient $K_{B,A}$. Eq. 12 illustrates this relation:

$$K_{B,A} = \frac{l_{eff,B}(L1, L2)}{l_{eff,A}(L1, L2)} = 1.56 \qquad (12)$$

The length *L1* of the Type A and Type B connections as shown in Table 1 and Table 2, are not the same, which is also shown in Fig. 11. Nevertheless, once the geometry quotient of two geometrical connection types has been determined, it can be used for the comparison of any of these connections with a similar length *L2*.

In the following, an example of how the geometry quotient $K_{B,A}$ can be used in practice shall be given. It is assumed that a disassembly company has already disassembled various turbines with different blade-disk connection geometries and documented the disassembly forces needed in each case. By using this data, it is possible to determine the geometry parameters l_{eff} of each connections at different levels of solidification. If is given a new geometry, usually the solidification, respectively reaction force had to be experimentally determined for each usage scenario (e.g. hours of operation, flight over sea or desert) with the risk of damaging the components. With the use of the geometry quotient *K*, only the geometry parameter has to be determined once. For this, the disassembly of a “new” blade with a known usage factor has to be compared with the disassembly of an “old” blade with an equal usage factor. Using this data, the geometry quotient $K_{new,old}$ can be calculated. In the future, the solidifying force of all turbines with the new blade geometry can be estimated by comparing them to a blade disassembly of the “old” geometry with a similar usage factor.

Transferred to this example, Eq. 12 results to:

$$K_{new,old} = \frac{R_{Z,old}(z) \cdot \mu_{new} \cdot E_{new} \cdot e_{new} \cdot A_{KF,new}(z)}{R_{Z,new}(z) \cdot \mu_{old} \cdot E_{old} \cdot e_{old} \cdot A_{KF,old}(z)} \qquad (13)$$

With the assumption, that both have a similar usage factor and therefore a similar solidification, it results:

$$\frac{e_{new}}{e_{old}} \approx 1 \qquad (14)$$

$$R_{Z,new}(z) = \frac{R_{Z,old}(z) \cdot \mu_{new} \cdot E_{new} \cdot A_{KF,new}(z)}{K_{new,old} \cdot \mu_{old} \cdot E_{old} \cdot A_{KF,old}(z)} \qquad (15)$$

The friction and the elastic modulus are material properties that are known before the disassembly and the contact surface can easily be calculated from CAD data. The solidifying force $R_{Z,old}$ and the geometry quotient $K_{new,old}$ have been determined as described in the previous paragraph.

6. Conclusion and Outlook

In contrast to the assembly in a joining task, unknown fits are typical in a disassembly of joined components. This problem is illustrated exemplary by the disassembly of turbine blades, which are solidified in a turbine disc during the operation cycle. The unknown parameters such as the solidification or disassembly force prevent a reproducible disassembly process. The estimation and transfer of these parameters is part of the approach in this paper. It was shown that two blade connections with a similar usage history but different geometries can be compared by using a constant parameter. Two basic connection geometries were compared by calculating the solidifying forces of different versions of each connection. Graphical representation of the calculated geometry parameter showed a linear correlation between the solidifying forces of the simulated connections.

Future research is aimed at finding a usage parameter, which describes the correlation of the solidifying force of two connections with a similar geometry, but a different usage history. The subsequent step is to combine both parameter to make the comparison of assembly connections with different geometries and different usage factors possible. This would be a very important step towards more effective and less defective disassembly processes.

Of course, the reliability of the geometry parameter (and later on the usage parameter) has to be verified in practice. To do so, a test stand built for the disassembly of turbine blades will be used. It uses vibrations produced by a piezo-stack actuator to disassemble solidified connections, while being able to measure and regulate the applied disassembly force [5].

Acknowledgments

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References

[1] Selinger, G.: Sustainability in Manufacturing – Recovery of Resources in Product and Material Cycles, Heidelberg, Springer-Verlag, 2007, pp 217-311

[2] Kahmeyer, M.: Flexible Demontage mit dem Industrieroboter am Beispiel von Fernsprech-Endgeräten, Faculty of Engineering Design and Production Engineering Stuttgart, Springer-Verlag, 1995, pp 50-60

[3] Ahgary, A.: Eine Analyse der Verschleißmechanismen in der Anwendung der Hüftgelenkendoprothetik unter realistischen Randbedingungen, Berlin, diplom.de 2002

[4] Müller, M.: Untersuchungen zum Einfluss der Betriebsbedingungen auf die Schädigung und Instandhaltung von Turboluftstrahltriebwerken, Institut für Luftfahrtantriebe, Universität Stuttgart, 2013

[5] Wolff, J.; Yan, M.; Schultz, M.; Raatz, A.: Reduction of Disassembly Forces for Detaching Components with Solidified Assembly Connections, Institute for Assembly Technology, Leibniz Universität Hannover, 6th CIRP Coneference on Assembly Technologies and Systems, 2016

[6] Shen, J.; Chen, D.; Liu, G.; Zhou, D.; Du, X.: FEM Analysis of Stress on Shaft-sleeve Interference Fits, Hefei University of Technology, Advanced Materials Research Vol 668, 2013, pp 495-499