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MATERIAL BEHAVIOR UNDER DYNAMIC MONO- AND BIAXIAL LOADING

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This paper gives an overview of different testing methods and the mechanical material behavior including mono-axial and multi-axial testing under high rate loading. Special emphasis is laid on difficult loading conditions and loading states such as a high temperature and high strain loading ($\vartheta > 1200^\circ$C, $\varphi > 1$) and multiaxial impact tests. The impact behavior of selected materials is shown and compared for different loading conditions. Furthermore, a distinction is made between virgin and manufactured material behavior (e.g. welding) or pre-damaged materials. Specifically, if the influence of the manufacturing history is investigated. Under certain loading states the impact material properties show a dramatic difference compared to the virgin state of the material. Some examples of different material behavior under the conditions previously mentioned are given.

1. Introduction

It is well-known, that the material behavior of construction materials is dependent on strain, strain rate and temperature. Moreover, the knowledge of the dynamic behavior of materials is of interest, if such processes like cutting or forming operations are investigated. For many engineering applications, the mechanical impact behavior of materials and components also play an essential role.

For example, consider a deployed naval ship operating in rough sea conditions: the loading of this ship‘s structure by a canon fire can be described as a time-dependent strain loading (Fig. 1). In reality, the loading is measured by strain gages. If the amplitude of the strain-time signal is multiplied by Young’s modulus (Hooke’s law), one may find a stress value significantly exceeding the material flow stress as known from quasistatic and standardized experiments. Hence, if the assumption is valid, the ship must be deformed plastically. However, an examination of the strain-time signal shows a complete return to its initial state, which clarifies that the whole event was purely elastic. Investigations under dynamic tensile loading, using a universal hydraulic testing machine, show that the large strain-rate sensitivity of the flow stress of the ship building steel, during the impact by canon firing, is enhancing the flow stress above that

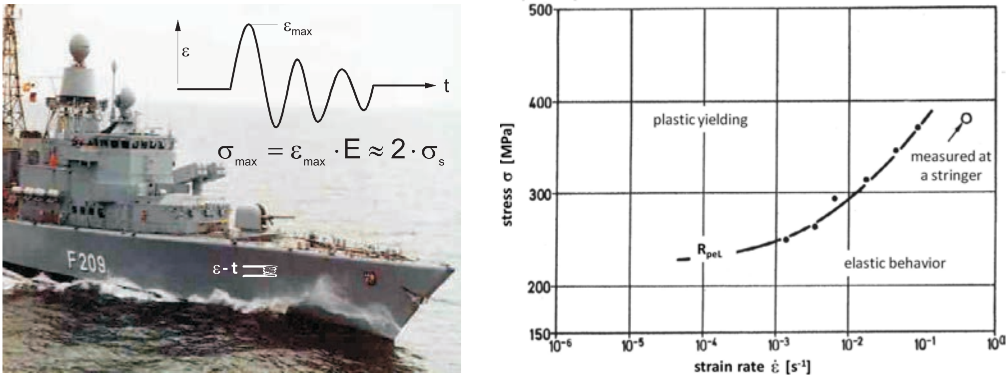

Fig. 1. Dynamic loading of a canon shooting on a Navy ship structure.

(elastic) value, what was measured on the stringer at the high strain rate. Thus, the ship is not being deformed plastically during maneuver operations or its deployment.

However, the knowledge of the material behavior under loading conditions matching the intended use, is of special importance in design and construction. Thereby, the material behavior must be known over a wide range of strains, strain rates and temperatures. A variety of different experimental techniques exist to determine the dynamic behavior of materials under the defined loading conditions and loading states.

2. Impact testing capabilities

Of the experimental work on impact material behavior described in the literature, mostly the Hopkinson bar testing is mentioned. However, a variety of different experimental techniques exist to determine the dynamic behavior of materials under the defined loading conditions and loading states.

For characterization of the mechanical behavior of material investigations over a wide range of strains, strain rates and temperatures are required. Additionally, different loading types may lead to different material behavior, even if only monoaxial loading is mentioned and must be considered in material investigations and constitutive modeling. In Fig. 2, a summary of different loading types under monoaxial and multiaxial loading is given.

For dynamic impact testing of materials, only a small amount of universal testing machines in comparison to quasistatic loading is available. Especially, accurate force-time measurements are a great challenge for such type of machines. Due to the large mass, which has to be accelerated during testing, the force-time signals often show large ringing and lead to increased uncertainties in

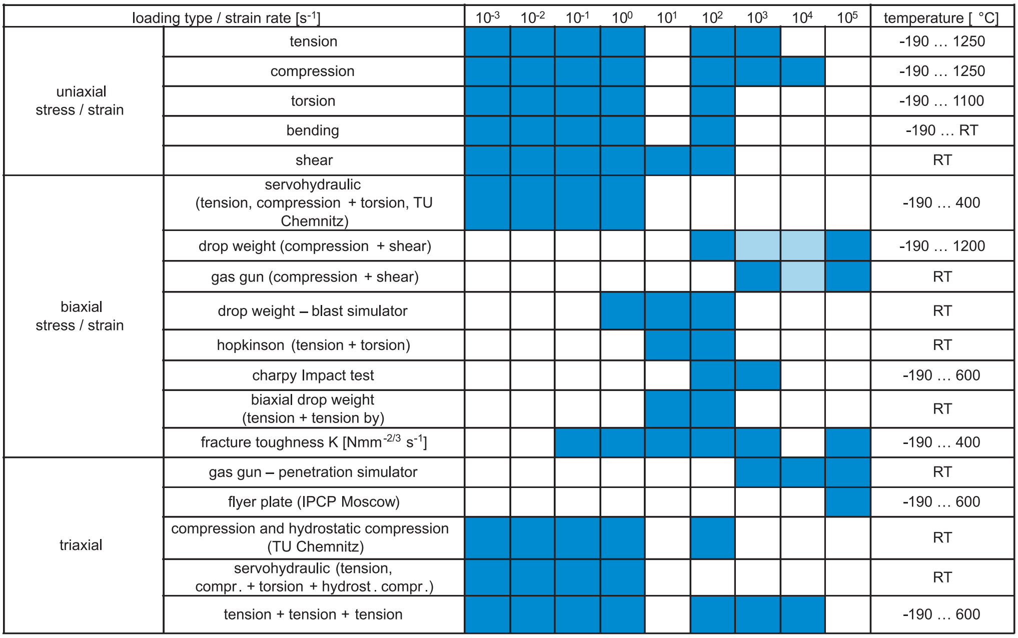

Fig. 2. Testing capabilities needed for impact dynamic material characterization. Testing facilities in blue are available at Nordmetall GmbH.

the determination of the real material behavior. However, different special designed devices for certain applications of dynamic testing of materials exist, e.g. Hopkinson bars for compression and tensile testing, rotating wheels for tensile loading or drop weight towers for compression or flexure loading.

For modeling of the constitutive behavior of materials, uniaxial data are mostly sufficient for the application of simple phenomenological equations and for the description of flow stress and strain hardening behavior (e.g. [1, 2]). If failure is going to be considered, uniaxial experiments are not sufficient for characterization of the material behavior. Both the flow stress and failure are significantly influenced by strain, strain rate and temperature. Therefore, the material must be investigated using a broad range of loading conditions. In addition, compared to flow stress behavior, failure is largely influenced by stress state (especially by stress triaxiality). Hence, multiaxial testing by using stress concentrators like notches (Charpy impact test) or cracks (fracture toughness) are necessary. Additionally, complex and defined stress states, e.g. those observed during forming processes, have to be considered using combined loading states, e.g. multiaxial tensile testing superimposed by hydrostatic pressure, whereby all the tests have to be performed at high loading rates (Fig. 2).

Additionally, most of the materials studied under impact dynamic loading are not loaded monoaxially in later use. Most applications are characterized by a complex geometry which normally leads to a complex loading state showing stress concentrations and high stress triaxialities. To investigate the impact component behavior, high quality dynamic measurement data (especially for force and deformation measurements) is required. Additionally, a large amount of impact energy is needed for the dynamic deformation of components. This has lead to the design and development of new testing facilities which are capable of meeting the new demands of dynamic component testing.

The following sections demonstrate how special emphasis is put on high strain, high strain rate and high temperature testing, using high speed torsion loading and multiaxial material and component testing using high energy mechanical testing devices for tensile and compression/flexure loading.

3. High speed torsion testing

The parameter identification of constitutive equations used nowadays in finite element analysis of forming or cutting processes, are mostly based on monoaxial experimental data from high rate and in some cases high temperature compression or tensile tests. Thereby, the strain reached in tensile or compressive deformation of materials is limited and does not match real forming or cutting process, where plastic strains larger than $\varphi = 2$ or 3 can be observed (e.g. [3, 4]). Especially the stress softening behavior due to recrystallization processes during deformation cannot be measured by compression or tensile tests.

Using torsion loading, this mismatch can be overcome, because no geometrical instability or friction effects lead to limited plastic deformation of the material, only the deformation capability of the material itself. Performing torsion tests to reach high plastic strains is familiar in material testing and characterization. To ensure a good predictability of material behavior in real engineering processes like rolling or turning, the material behavior has to be known at high strain rates and high temperatures. To solve this challenge, a new universal torsion testing machine was designed in cooperation between the Nordmetall GmbH and Chemnitz University of Technology (Fig. 3). The machine can be used for quasistatic tests by means of an electrical drive for loading the specimens, as well as for impact dynamic tests using an integrated flywheel construction.

For quasistatic tests, the specimens are fixed at both ends. Using a high power electrical drive, the specimen is loaded until failure of the material occurs. The torque during deformation is measured using a calibrated and adjusted load cell. The deformation is measured either by strain gages applied directly to the specimen and/or by an incremental gage of the machine. Dynamically, the force measurement is based on the principles of one-dimensional wave propagation effect and the Hopkinson principle. Thereby, the specimen is fixed directly on the Hopkinson bar containing strain gages. The lower end of the specimen

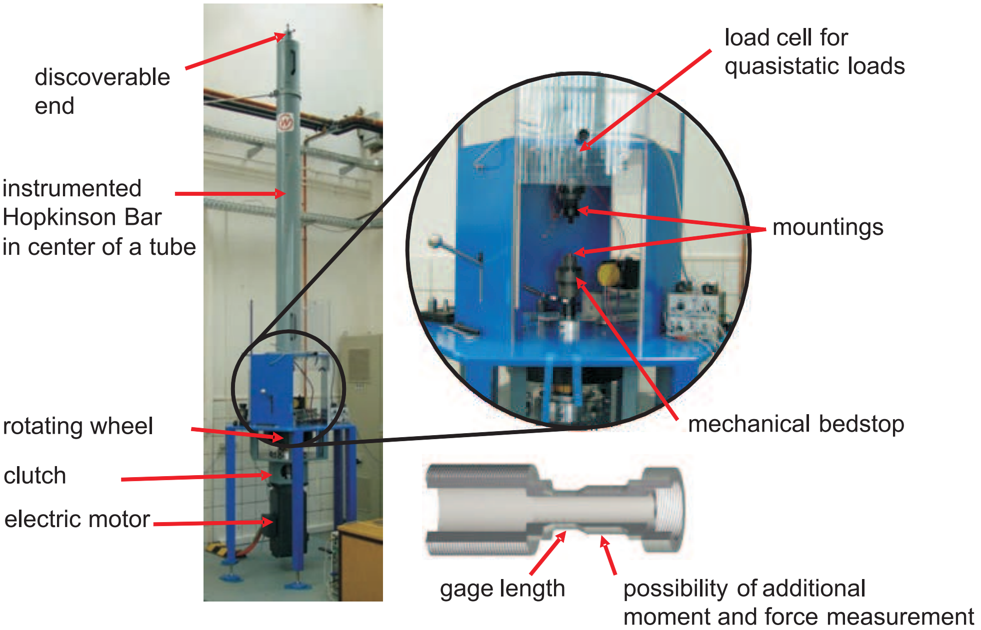

FIG. 3. Combined static and impact dynamic universal testing machine.

remains free. To ensure an impact loading of the specimen, a rotating wheel is accelerated by an electrical drive until a desired velocity is reached. Using a specially designed clutch device, the rotation is launched to the lower end of the specimen and the material is loaded by an impact torsion load. Due to the high mass of the flywheel and its rotation, the stored energy is sufficient to deform the specimen until fracture. Thereby, shear rates of approximately 200 s^{-1} can be reached, whereby a high signal quality of the load measurement can be assured. For both experimental setups, an inductive heating system can be integrated into the process, and high temperature investigations up to 1300°C can be performed. Hence, high strain, high strain rate, and high temperature data, leading to material behavior matching real cutting or forming processes, can be obtained.

In Fig. 4, an example for the behavior of a low alloyed steel at high strain rate and high temperature torsion loading is shown. It can be seen that the plastic deformability of the material is increased significantly from $\varphi = 2$ at 800°C to $\varphi = 10$ at 1200°C. From the experimental data, the transition from elastic to elastic-plastic behavior as well as strain hardening behavior can be evaluated. One of the great advantages of the torsion test is shown in Fig. 4. After reaching a stress maximum, the onset of recrystallization in conjunction with decreasing measured flow stresses can be found. This demonstrates that the onset of softening is strongly dependent on strain, strain rate and temperature.

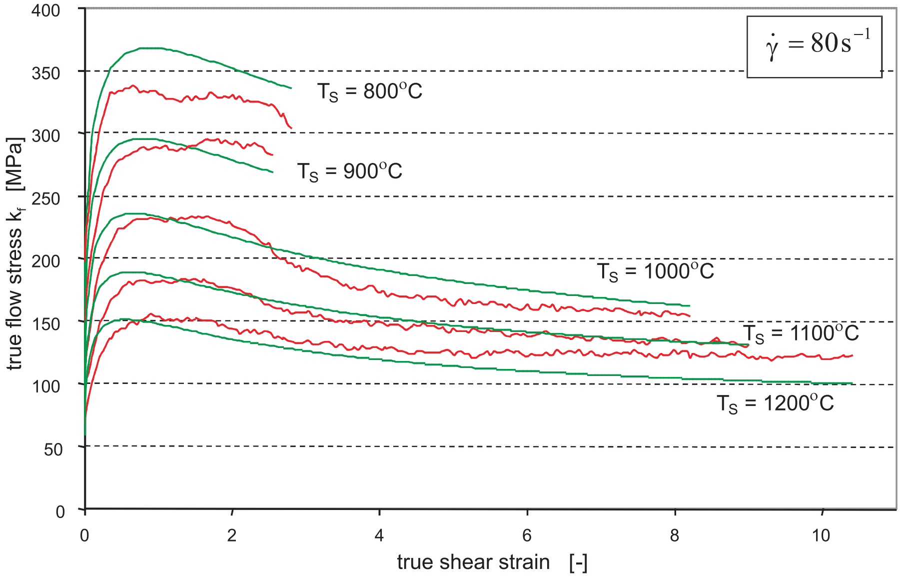

FIG. 4. Flow stress evolution of a low alloyed steel at high strains, high shear rate and high temperatures: comparison of experimental data and modeled data using the Hensel-Spittel approach [5].

Additionally, from Fig. 4 a comparison between experimental measured and modeled data, using Hensel-Spittel [5] (Eq. (3.1)) approach, can be evaluated as described in their publication.

$$k_f = A \cdot e^{m_1 T} \cdot T \cdot \varphi^{m_2} \cdot e^{m_4/\varphi} \cdot (1+\varphi)^{m_5 T} \cdot e^{m_7 \varphi} \cdot \dot{\varphi}^{m_8} \dot{\varphi}^{m_8 T}. \tag{3.1}$$

It can be seen that experimental and modeled data show a good agreement over the whole range of plastic strains and temperatures. Even the flow stress decrease due to recrystallisation processes can be predicted using the Hensel-Spittel approach. Based on these data, a good prediction of the process behavior e.g. in rolling processes using finite element analysis, can be expected. It should be emphasised, that most of the common constitutive equations used in finite element simulations, like Johnson-Cook or Zerilli-Armstrong, cannot predict dynamic recrystallisation phenomena. Hence, not only experimental data are required, what matches real process behavior, but also equations used for the constitutive description of the material behavior under such conditions must fulfill these requirements.

4. High speed multiaxial testing

Until now only monoaxial material behavior of a virgin material was investigated and discussed. In real engineering applications usually multiaxial loading occurs. Additionally, materials used in technical products and components normally pass through a variety of different manufacturing steps including forming, as well as cutting and joining technologies. Furthermore, the material or component behavior might be changed during its life cycle use. This may be caused by alteration or fatigue processes, especially in automotive and automobile industry, processes like welding or glueing play a key role in manufacturing today‘s innovative products. However, less is known about the dynamic behavior of components under a multiaxial dynamic loading.

A new experimental test setup was designed and built at Nordmetall GmbH (www.nordmetall.net) to investigate the material behavior under a multiaxial dynamic loading condition, and to include the influence of manufacturing history (welding etc.) and pre-damaging, due to fatigue in life cycle use compared to virgin material properties. Special focus is laid on a critical biaxial tensile-tensile stress state, which might occur for example under blast loading of structures and vehicles, or even under crash conditions. Normally, component testing under such conditions for automotive applications is performed at high impact velocities (10–20 m/s) that are obtained by a drop weight device having large drop heights. Thereby, high quality force-time measurements during deformation can not be obtained. This is because the large ringing of the signals that are superimposed on the output signal cannot be filtered out. Therefore, we enhanced the weight and reduced the drop height and the impact velocity and get undisturbed signals. The falling weight of 5 t provides sufficient energy during the test to deform most of the components to fracture.

The test setup used for dynamic biaxial tensile-tensile loading of steel plates is shown in Fig. 5. The plate is fixed on the top of a steel tube and impacted by a semi-spherical punch on the top site. During deformation, the deflection is measured by an incremental gage. The force-time characteristic is measured directly on the punch. A high-speed deformation field measuring system technique was applied in order to measure the real deformation behavior of the steel plate during impact loading. Thereby, the three-dimensional local deformation field at the bottom of the steel plate is measured during the entire process, from onset of plastic flow to fracture.

For the tests, three different states of the steel plates (plain, pre-notched and cracked, welded stringer) of the same thicknesses and two different materials were used. The results of the dynamic biaxial tensile-tensile tests are summarized in Fig. 6 and Fig. 7.

Shown in Fig. 6 are the recovered, biaxially loaded specimens. For both materials, no failure was observed for the plain steel plate. All the energy provided by the falling weight was absorbed by the material as plastic deformation. If the material is pre-damaged, either by a mechanical or a metallurgical notch (1 mm deep fatigue crack or welded stringer), both materials fail during biaxial

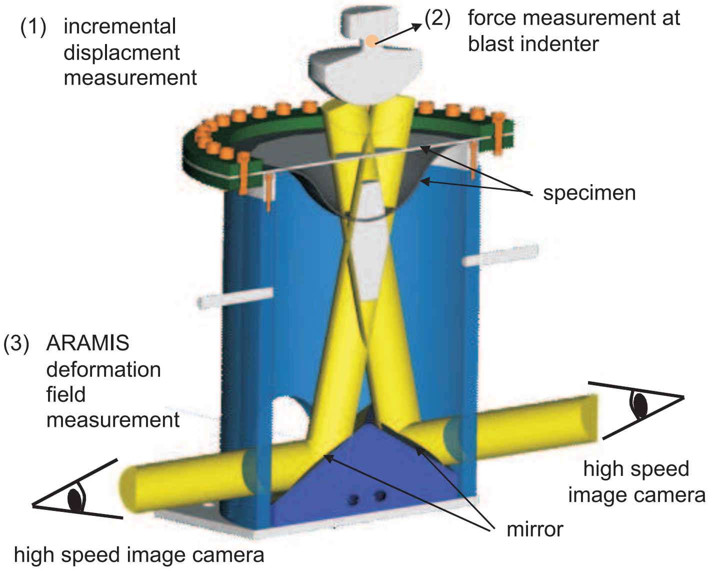

FIG. 5. Experimental test setup for high speed biaxial tensile-tensile-tests of steel plates, including high speed deformation field measuring system.

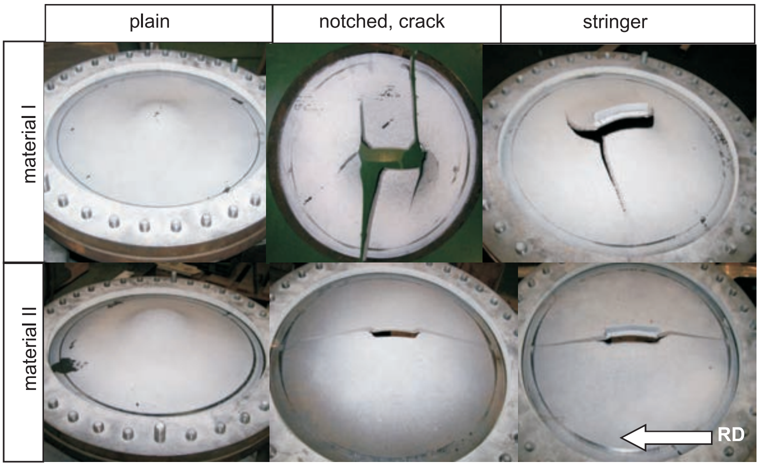

FIG. 6. Failure characteristics for two different materials at different pre-treatment states after biaxial testing.

tensile-tensile loading. For material II, a straight crack propagated through the whole specimen, whereas for material I branching occurred during crack propagation. If the measured force-time signals are compared (Fig. 7), one finds the highest strength for material I, if the material is tested in this virgin state (plain

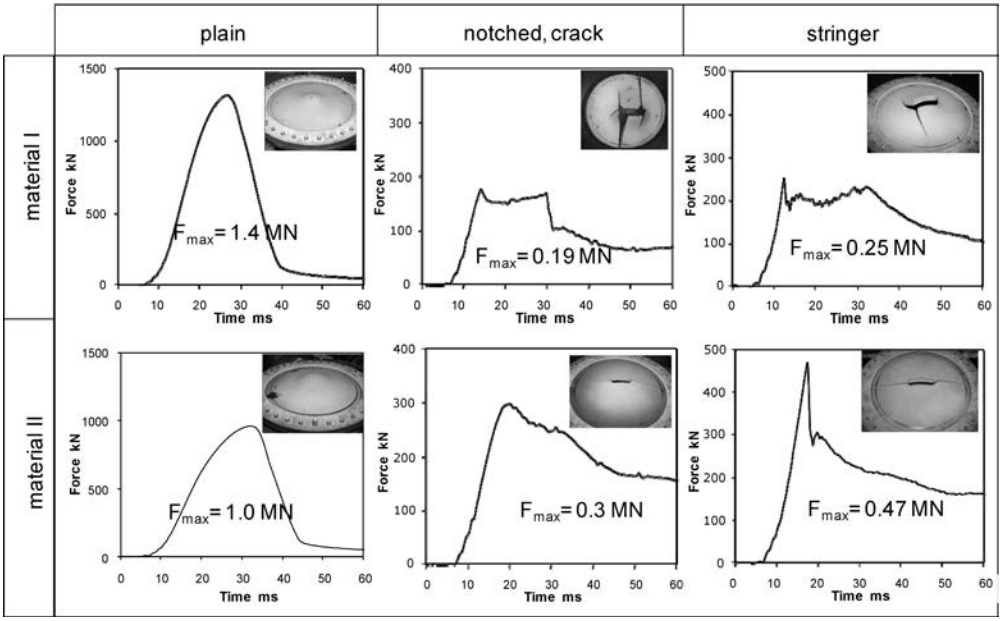

Fig. 7. Force-time behavior of two different materials with different stress-states at dynamic biaxial loading.

condition). If pre-damaging of material I occurs, the measured maximum forces are decreased dramatically. Only a sixth to a seventh of the initial maximum load can be sustained until the material fails. For material II, a similar decrease of the maximum load was observed. However, although material II is weaker in plain condition, it can be observed that the smaller influence of mechanical or metallurgical notches of material II leads to a better performance compared to material I.

Until now, material behavior is mostly considered in its virgin and undamaged condition. To ensure a high level of reliability and safety of engineering products and systems, the influence of manufacturing processes and their influence on the final mechanical properties of engineering materials have to be considered as well.

5. High speed tensile testing using a flywheel with a high stored energy

Based on the experience obtained from drop weight tests with high stored energy, the principle was transferred to a new flywheel device. This rotating wheel with a comparably low velocity, but a high stored energy due to a 10 t mass flywheel, can impact specimen with a maximum velocity of 12 m/s.

This new innovative testing machine at Nordmetall GmbH enables dynamic investigations of large engineering components, ensuring that a high quality measurement of the force-time signal is obtained. A schematic picture of the machine is shown in Fig. 8. The functionality follows the principles of commonly known rotating wheel devices (e.g. [6]), but provides a high amount of energy for the dynamic deformation of high strength and/or high deformable and/or large parts and specimens. Hence, a new quality of material and component input data for finite element analysis, as well as for the experimental verification of numerical results, can be expected.

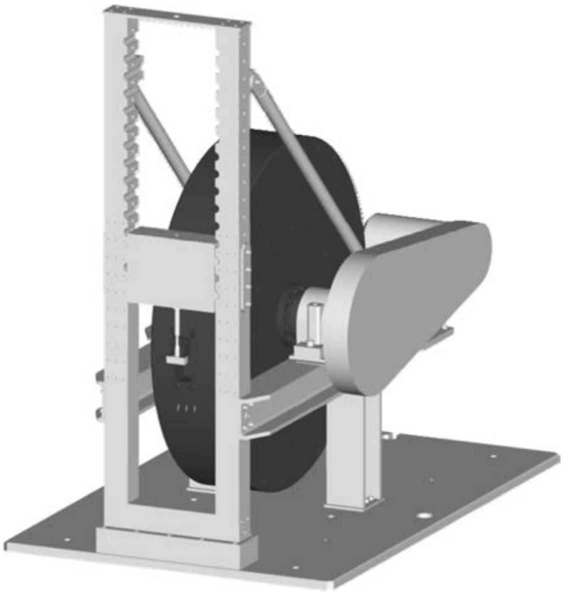

Fig. 8. Rotating wheel device of Nordmetall GmbH with a high amount of stored energy, by a 10 t flywheel (∅2 m) for dynamic component testing of engineering materials.

6. Conclusions

This paper contains a short overview about different testing facilities and the material behavior, including monoaxial and multiaxial testing under high rate loading. Specifically the overview concerns discussions of difficult loading conditions and loading states such as high temperature and high strain loading ($T > 1200°\text{C}$, $\varphi > 1$) and multiaxial impact tests. Special emphasis was laid on the influence of the manufacturing history of a material, on the dynamic properties under biaxial tensile-tensile loading. A dramatic decrease of the deformability and loading capacity was observed, if the material being tested contains a pre-damaged state by a metallurgical or mechanical notch.

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