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The role of the modified taylor impact test in dynamic material research

Frank Bagusat[a] and Ingmar Rohr

Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Eckerstrasse 4, 79104 Freiburg, Germany

Abstract. Dynamic material research with strain rates of more than 1000 1/s is experimentally very often done with a Split-Hopkinson Bar, Taylor impact tests or planar plate impact test investigations. At the Ernst-Mach-Institut (EMI), a variant of an inverted classical Taylor impact test is used by application of velocity interferometers of the VISAR type ("Modified Taylor Impact Test", MTT). The conduction of the experiments is similar to that of planar plate impact tests. The data reduction and derivation of dynamic material data can also be restricted to an analysis of the VISAR signal. Due to these properties, nearly each highly dynamic material characterization in our institute done by planar plate investigations is usually accompanied by MTT experiments. The extended possibilities and usefulness of a combined usage of these two highly dynamic characterization methods are explained. Recently, further developed MTT experiments with very small specimen sizes are presented. For the first time, Taylor impact and planar impact specimen can be used for which the load directions even in case of thin plate test material are identical and not perpendicular to each other. Consequences for testing construction elements are discussed.

1. Introduction

1.1. Taylor-test setup

Taylor-test investigations can be an important component in research examining material under dynamic loads. In terms of strain rate, Taylor-tests are a very useful addition to split Hopkinson and planar plate impact experiments. The classical method of execution [1–3] catapults the specimen perpendicularly onto a fixed flat target with a defined impact velocity. The impact process causes a deformation only on the impacted side of the specimen. Dynamical material data is calculated by using geometrical properties of the finally deformed specimen. In the past, changes of this setup have been introduced. One point was the inversion of the test, so that the specimen is staying at rest and serves as a target in an impact experiment. As impactor, a rod with identical shape ("symmetric test" [4]) or a large and heavy projectile is used ("anvil on rod test"). Furthermore, instantaneous data collection, i.e. during the experiment, has been made possible by adaption of strain gauges.

It is a very common idea already described by Taylor in his article introducing a new method for the determination of the dynamic yield stress [1] that due to the impact, elastic and plastic wave propagation processes are occurring in the specimen. Strain gauge technique can measure surface waves [4,5] on the specimen, from which dynamical material data can be calculated.

1.2. The modified Taylor-test (MTT)

Wave propagation processes can also be recorded by interferometric techniques. These have the advantages that they are contact free without any mechanical influence on the specimen and that they can measure continuously with high time resolution. At the EMI a free beam VISAR (velocity interferometer system for any reflector [6–10]) system is used [11–16], but in principle also fiber based VISAR setups are known to be used [4,17–19] in connection with inverted Taylor test experiments.

The inverted Taylor-Test with VISAR is denoted as modified Taylor-Test (MTT) in the following.

MTTs at the EMI are typically executed with a length-(L)-to-diameter-(D) ratio of the specimen of $L/D = 10{:}1$. The typical diameter of the specimen is 6 mm, but also much smaller specimens can be used [16], which will be demonstrated and discussed at the end of this article.

As a projectile, a sabot carrying a maximum hardened C45 steel cylinder with flat polished surface is used. This system has a mass of about 450 g.

Impacting a static specimen by a sabot driven projectile with sufficient high velocity will cause elasto-plastic wave processes in the specimen (a slower plastic and a faster elastic wave). If the elastic wave is reaching the rear side of the specimen, this side is accelerated; this acceleration can be observed by a VISAR [12–14]. It is assumed that the acceleration process causes a load of the specimen‘s material so that it reaches the yield point. Therefore, by measuring and evaluating the free surface velocity time signal of a specimen under impact, dynamic material properties can be derived. Typically, the acceleration is observed as a sequence of several velocity steps (Fig. 1).

1.3. Dynamic material properties derived from MTT investigations

It has been discussed elsewhere which kind of dynamic material properties can be derived from free surface velocity time curves [12–14]. Therefore, only the formulas are summarized here. The yield stress Y can be calculated by

$$Y = 0.5 * \rho * c_0 * \Delta u_{fs} \tag{1}$$

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[a] Corresponding author: `frank.bagusat@emi.fraunhofer.de`

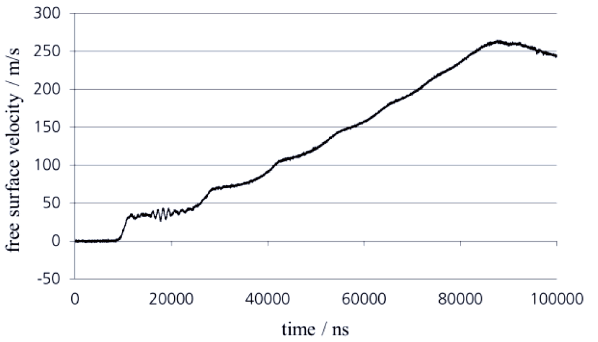

Figure 1. VISAR free surface velocity time curve, steel 11SMn30+C, rod size: 6 mm diameter, 60 mm length.

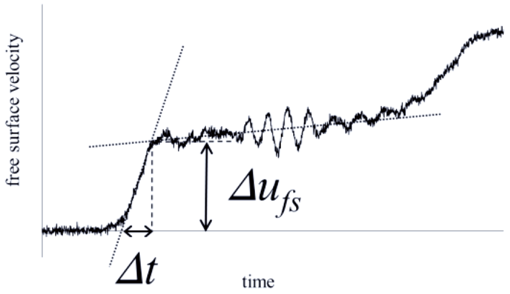

Figure 2. Principle of determination of the velocity jump Δu_{fs} and time interval Δt.

where ρ is the density of the specimen‘s material, c_0 denotes its longitudinal velocity of sound and Δu_{fs} is the height of the *first* velocity step visible in the free surface velocity time curve (Fig. 2). The strain εat the yield point can be estimated by

$$\varepsilon = \Delta u_{fs}/(2 * c_0). \tag{2}$$

The corresponding strain rate is therefore

$$d\varepsilon/dt = \varepsilon/\Delta t, \tag{3}$$

where Δt is the time interval needed for the velocity step Δu_{fs}. The determination of Δu_{fs} and Δt can be executed by a mathematical analysis or, much simpler, graphically depending on the needed accuracy (Fig. 2).

These material parameters are experimentally characterized by elastic wave processes in the specimen. Therefore, for a more accurate designation of strain and strain rate values, both are elastic values. Furthermore, due to their dependence to a velocity or time interval, these values are averaged properties.

2. Examples of MTT investigations

2.1. MTTs as one element for a strain rate dependent yield stress characterization

MTT specimen made of a high strength steel with a size of 6 mm diameter and 60 mm length were used in an extended investigation collecting yield stress data determined by various testing methods [12,14]. One result of this measurement program was a yield stress-strain rate dependency depicted in Fig. 3. MTT results here delivered last points of a linear relationship of the yield stress strain rate behavior if the strain rate is scaled logarithmically. The yield stress is strongly increasing in the strain rate region of planar plate impact investigations. It is clear that the exact inflection point of the material behavior is only determined by two methods (MTT and planar plate impact measurements), but due to the strain rate dependency of the material tested by planar plate impact technique, the indicated linear fit seems not a bad choice. It is interesting that yield stress data of the second material presented in Fig. 3, a tungsten sinter alloy (WSA), show a linear relationship (with a logarithmic strain rate scaling) over all experimentally determined data points [15]. WSA specimens had a diameter of 5 mm and a length of 50 mm.

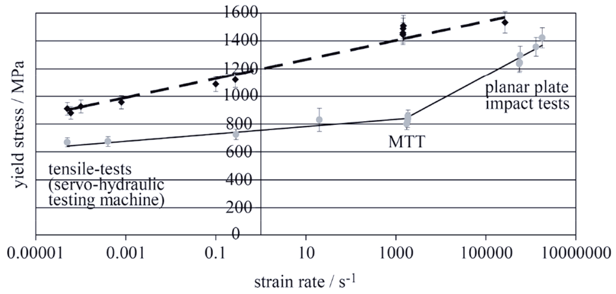

Figure 3. Yield stress as a function of strain rate for two materials: high strength steel (gray points; solid line [12,14]) and tungsten sinter alloy (WSA, black points; dashed line [15]).

These results are a very impressive illustration for the need of methods which cover different strain rate regions for material characterization.

For the investigated materials, the yield stress dependence from increasing strain rate was not clear. Some high strength steels show almost no further increase of the yield stress with strongly increasing strain rate. One would assume that the yield stress of WSA is higher than that of steel because its physical or mechanical properties are mainly given by its content of tungsten. Tungsten is considerably superior over steel in respect to mechanical properties like hardness or elastic modulus. If one had not used (in comparison to quasistatic methods) laborious MTT and planar plate impact investigations, qualitative differences between the high strength steel and WSA would not have become visible. On the other hand, if the MTT investigation had been left out, the inflection point of the yield stress would probably shift to lower strain rates.

MTT and planar plate impact investigations can be seen as necessary and useful methods of material characterization. With a lack of one or two of these methods, a strain rate dependent modelling would miss essential material characteristics.

2.2. MTTs for modelling dynamic material properties

Classical Taylor tests deliver material related data only by an analysis of the deformed specimen after the test.

MTT tests of materials like tungsten sinter alloy (WSA) can show a damage of the rod on its impacted side. This can emerge to an almost complete failure, if the impact velocity is sufficiently high. A ‘post impact’ analysis is not possible in this case.

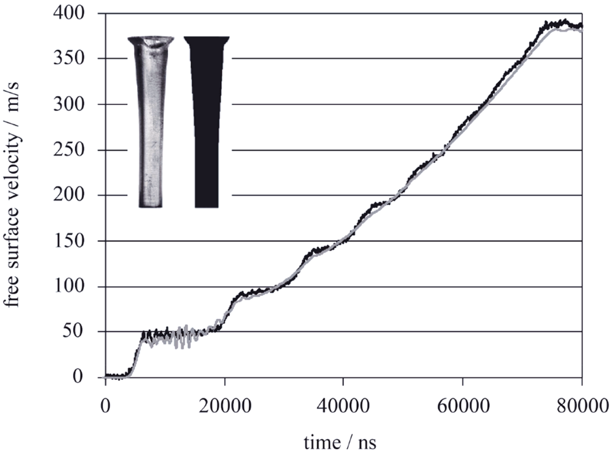

Figure 4. VISAR free surface velocity time curve [12–14] of a high strength steel and a simulation (gray curve) of the signal. Impact velocity 361 m/s. Material was the same as in experiments with results shown in Fig. 3. Experimental and simulated (black) shapes of the specimen are also shown.

A material data recording (based on wave propagation processes) during the deformation is only executable with strain gauges or with interferometric techniques as in case of the MTT. If the deformation itself is a main point of interest in a study, high speed photography might also be used in addition [17, 18].

For a validation of a chosen material model, the MTT free surface velocity time curve itself can be used. Modelling of a VISAR signal with several velocity steps (Fig. 4) representing elastic wave reflections in the material has been found to be much more sensitive than trying to simulate only the final diameter of the impacted side of the specimen correctly.

For the high strength steel used for experiments utilized in Fig. 3/Fig. 4, a phenomenological material model with a strength model and an equation of state has been developed [12, 14]. The agreement of simulated results including the VISAR curves and cross sections of deformed specimen with experimental findings has been found to be quite well, showing only differences of a few percent or less.

The Taylor rod deformation or failure with defined specimen geometry is always a highly dynamical process. It is essential that the modelling process incorporates implicitly the plastic deformation behavior which reaches (plastic) strain rates in the order of 10^5 1/s. The advantages of VISAR based MTT experiments are a continuous measurement (covering the whole acceleration process of the specimen), a very high time resolution (down to a few ns), a high absolute velocity measurement accuracy of the VISAR signals (typically ± 1–2% [9]) and an operation which is free of mechanical contact to the specimen. These properties are not given by camera or strain gauge measurements alone. Nevertheless, the experimenter is free to combine all these methods for data acquisition.

MTT investigations can therefore be a very interesting, powerful and accurate method by supplying Hopkinson and planar plate impact techniques in the intermediate strain rate regime especially for simulation purposes.

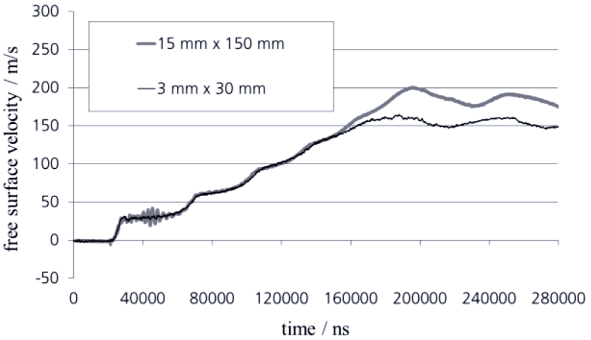

Figure 5. VISAR curves of MTT experiments with steel 11SMn30+C of different rod dimensions. The signal of the 15 mm × 150 mm specimen is shown with the original time scale, the time scale of the smaller rod was multiplied by a factor of 5 (in order to compensate a shorter travelling time of the elastic wave in the smaller rod, the scaling factor is given by the length ratio of the rods). Signal curves are smoothed.

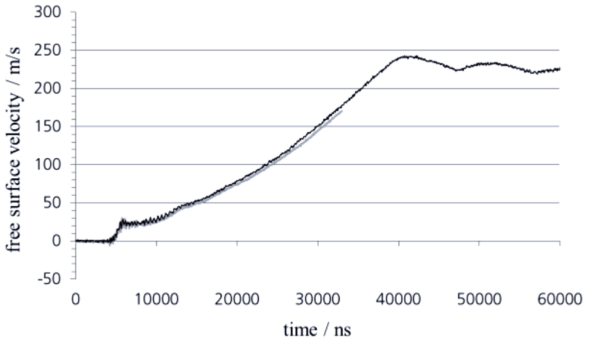

Figure 6. VISAR curves of MTT experiments with rods of pure, annealed Niobium (Nb), rod size 2 mm × 20 mm. Data of the experiment depicted in gray are cut due to signal overshoot.

3. MTT experiments with specimens of small dimensions

3.1. Considerations about the specimen size

EMI's modified Taylor tests are normally conducted with Taylor rods of 6 mm diameter and 60 mm length. Several reasons exist for reducing the geometric size of the specimens. Firstly, new materials which were very expensive and difficult to produce should be dynamically tested. Secondly, materials which are typically only available in the form of sheet material should be investigated. Thirdly, material properties of construction elements should be determined at locally different positions. This can be done much easier and with better local sensitivity by using smaller specimens.

It was an open question whether a size reduction would not have disturbing effects onto the VISAR signals, but tests with heavily varying rod sizes (Fig. 5) demonstrated a very good overlap of signal curves after adaption of the individual time scales according to the ratio of the specimen's lengths.

Rod sizes beyond the 3 mm × 30 mm dimension were tested with different materials and found to be quite easy to conduct. Figure 6 shows results of experiments with pure annealed Niobium rods of the dimension 2 mm × 20 mm.

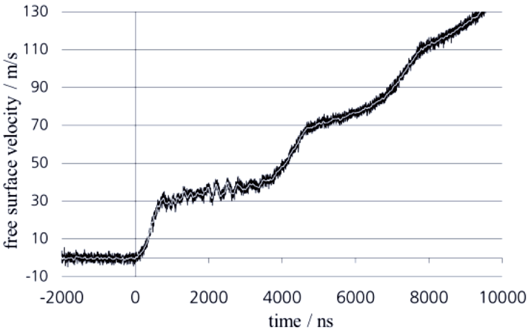

Figure 7. Effect of data smoothing on MTT VISAR curves. C45 steel rod of size 1.5 mm × 15 mm. Original data are shown in black, the smoothed curve is indicated by the fine white line. Data smoothing was applied before data reduction was executed.

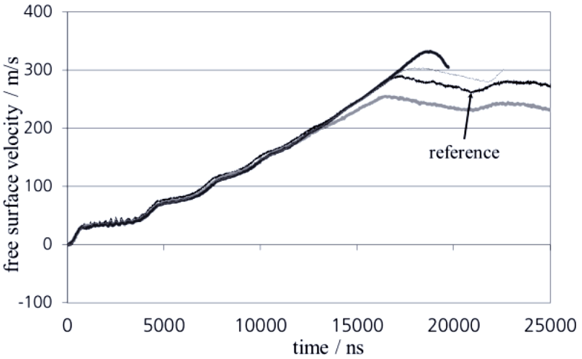

Figure 8. Signal curves (smoothed) of MTT experiments with C45 rods of dimension 1.5 mm × 15 mm. Data of an experiment with C45 steel (6 mm × 60 mm, time axis scaled) serves as reference and was not smoothed [16].

After the first elastic step, only tiny indications of more steps are observed in the acceleration process.

A further important point when working with smaller rod sizes is the signal quality. It is easy to imagine that a smaller sample could theoretically give less intense scattering signals due to the quality of adjustment of the VISAR focus on the backside of the rod or due to the obtainable quality of the polishing of smaller rods. This would result presumably in a reduced signal to noise (S/N) ratio of the measurements. In case of MTT investigations, there is a very simple way to compensate this by applying data smoothing as shown in Fig. 7. MTT signals do generally have no fast signal changes (as can be seen in planar plate impact experiments, where signal variations within a few nanoseconds occur). The typical time scale of MTT experiments falls in a range between several μs (Figs. 1, 6–9) and more than 160 μs in case of very large rods (Fig. 5). Data smoothing will therefore not eliminate essential data structures, but will improve the shape of the curve even in case of small rod sizes.

Figure 8 shows a series of experiments executed with C45 steel with rods of the dimension 1.5 mm × 15 mm. In addition, a curve of an experiment with a 6 mm × 60 mm rod is plotted. The time axis of this data set has been reduced according to the smaller samples. The figure illustrates a good reproducibility of the signal even with this rod size and also a good agreement of the signal with the 6 mm × 60 mm results.

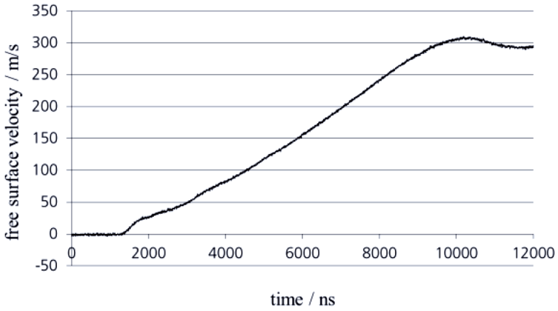

Figure 9. Free surface velocity time curve of a MTT experiment with specimen size of 0.7 mm diameter and 7 mm length (steel 115CrV3, material number 1.2210).

Investigations with rod sizes of 1.5 mm × 15 mm showed in some cases a very poor S/N-ratio (2:1 to 1:1, normally 5:1 to 10:1 or even better is observed), but with data smoothing before data reduction, even these signals were usable at the end [16].

3.2. Effects limiting the miniaturization of MTT specimens

For a valid registration of a free surface velocity time curve, several conditions of the experimental setup should be fulfilled:

1) The illuminating laser focus should cover a sufficient amount of grains, so that averaging of the back scattered signal can take place. This is necessary in order to obtain reproducible free surface velocity time curves. That means that the grain size should be much smaller than the laser focus.

   The focus diameter is typically around 0.5 mm.
2) The specimen holder system has to be stable enough so that the illuminating focus will stay on the specimen for the duration of the whole experiment. Failing this, signal loss will occur.

   Otherwise, the holder system of the specimen should have no disturbing effect on the wave propagation within the specimen.
3) The orientation of the focus point relative to the specimen should be adjustable in very small steps in order to fulfill point 2).
4) In case of small specimen sizes, the mass of the specimens also is strongly reduced. This can lead to a heating of the specimens by the illuminating laser. Therefore, laser power and illumination time have to be reduced (or the specimens have to be cooled).

It was found that a free beam VISAR setup (the classical variant of a VISAR) could be used with our laboratory setup with a minimum specimen size of 1.5 mm × 15 mm [16]. In case of smaller specimens, loss of signal was predominantly observed, so that almost no signal or only a first step of the MTT signal was recorded.

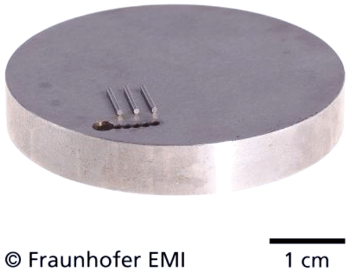

Figure 10. Specimen of C45 steel (50 mm diameter, 8 mm thickness) produced for a planar plate impact experiment and three Taylor rods with a size of 0.8 mm × 8 mm cut out of the outer border area by wire spark erosion technique. The load direction of both specimen types is identical.

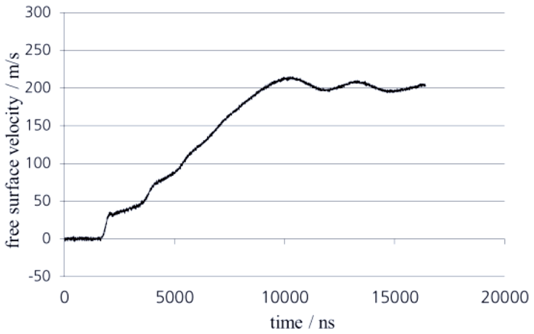

Figure 11. Free surface velocity time curve of a MTT experiment with specimen size of 0.8 mm diameter and 8 mm length (specimen taken from planar plate impact test geometry, Fig. 10).

As an alternative to a free beam VISAR, a fiber optic based VISAR (VALYN-VISAR [10]) with a focus length of 30 mm was tested. With this setup, even smaller specimens (1 mm × 10 mm and 0.7 mm × 7 mm) could be investigated successfully (Fig. 9).

These small specimen sizes enable the production of Taylor rods directly from thin plates like planar plate impact specimens (Fig. 10, experimental VISAR signal Fig. 11). The advantages of using Taylor rods manufactured from the planar plate impact test specimen can be summarized as follows. The load direction of test specimens is the same, the material is identical and the difficult polishing of small rods can be done during the preparation process of the planar plate impact test specimens so that they have perpendicular end surfaces. Furthermore, a series from MTT experiments can be produced from the outer region of each individual planar plate impact test specimen by wire spark erosion technique. This makes it possible to conduct a series of Taylor-tests of planar plate impact test specimens and can be used to control dynamic material data.

Of course, small specimen sizes offer a general benefit for the purpose of the determination of locally dynamic material properties of real construction elements.

All experimental examples shown in this article were tested with the impact facility at the EMI used for "normal size" MTT/planar plate impact test experiments.

4. Summary and conclusions

MTT experiments can deliver very accurate dynamic material properties like strain, strain rate and yield stress.

Regarding the strain rate, the method falls between split Hopkinson bar and planar plate test conditions and therefore gives additional information about the material behavior at high strain rates, which is especially helpful for purposes of material modelling and simulation of highly dynamic processes.

Results of MTT experiments with specimen sizes beyond the typical geometry of 6 mm by 60 mm show that measurements are possible with enhanced efforts concerning the specimen holder system. Minimal rod sizes of 0.7 mm × 7 mm can only be investigated with application of a VISAR system with a short observation range (fiber optic system with short focus length). That means all laboratories operating VISARS of the VALYN type can in principle execute MTT experiments with very small specimen sizes. With a VALYN-VISAR, MTT-experiments with small specimens (e.g. smaller than 2.5 mm × 25 mm) are easier to conduct than with larger specimens due to restrictions of the effective depth of field of the fiber optic probes.

Plate material with a thickness beyond 10 mm can now be investigated by planar plate impact test *and* MTT experiments executed with the same load direction due to the small possible size of the MTT specimen.

In case of specimens with sufficient small average grain size, experiments with even further reduced specimen size (e.g. 0.4 mm × 4 mm) seem to be possible, if a focus diameter optimized observation system is applied and great care is taken with laser power, so that heating up of the specimen can be neglected.

Working with small specimens offers the possibility to use also small accelerators, so that cost and time consuming handling of the specimens in larger impact facilities can be avoided.

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