EVALUATION OF DYNAMIC FORCES ESTABLISHED DURING THE TAYLOR ANVIL TEST

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This paper deals with innovation possibilities in the measurement of dynamic forces that act on the specimen during the Taylor anvil test. The goal of this work is to decrease the influence of unwanted noises in the pulse record. The Quartz Force Link piezoelectric sensor by Kistler was used to compare the waveform of shock loading with signals recorded by foil resistance strain gauges by Hottinger. The impact loading was produced by impact of specimen on the measuring rod.

Keywords
Taylor Anvil Test, high strain rate, impact loading, strain gauges

1. Introduction

Modern bulk-forming technologies demand accurate constitutive modelling at strain rates exceeding 10^4 s^{-1}.Strain rates together with temperature are one of the main factors that significantly affect the process of plastic deformation of metals. The Taylor anvil test (TAT) is a useful experiment for estimating material behaviour at high strain rates of 10^4 s^{-1}. The impact velocities of test specimens are relatively low. An advantage of TAT is the evaluation of dynamic yield stress based on empirical equation and specimen geometry. [Meyers 1994, Woodward 1994, Jones 1998]

Further computer simulation of physical experiment allows obtaining parameters for constitutive equations like the Johnson-Cook equation. [Forejt 2000, Forejt 2002]

2. Experimental Techniques

Before the Second World War G. I. Taylor had been thinking of a method for estimating the dynamic strength of materials. In 1948 he introduced his method consisting of firing a solid cylinder against a massive and rigid target. This technique is very often used, including the reverse test when a rigid wall is accelerated against the specimen. This configuration eliminates the problem with temperature stability during testing at elevated temperatures. [Field 2004]

The TAT consists in impacting a cylinder specimen on a hard surface. The cylindrical specimen of 25 mm in length and 5 mm in diameter is placed into a sabot and accelerated by expanding air in a gas gun towards the catch tank. The specimen is separated from the sabot just before its impact on the measuring bar (see Fig. 4). We do not assume any plastic deformation in the measuring bar, which is made of high-strength (quenched and tempered) steel and instrumented with strain gauges. Today the sabot is made of polystyrene.

The resulting impact on the measuring bar produces an elastic compressive pulse that is recorded by resistance strain gauges glued onto the measuring bar and connected in full Wheatstone bridge. The output voltage is conveyed via an amplifier to a data storage oscilloscope. Data are further processed in a computer. The measurement itself in the oscilloscope is triggered by a bistable trigger circuit, which is activated by the passage of the specimen between two photo diodes placed in the catch tank. The schematic illustration of TAT is shown in Fig. 1.

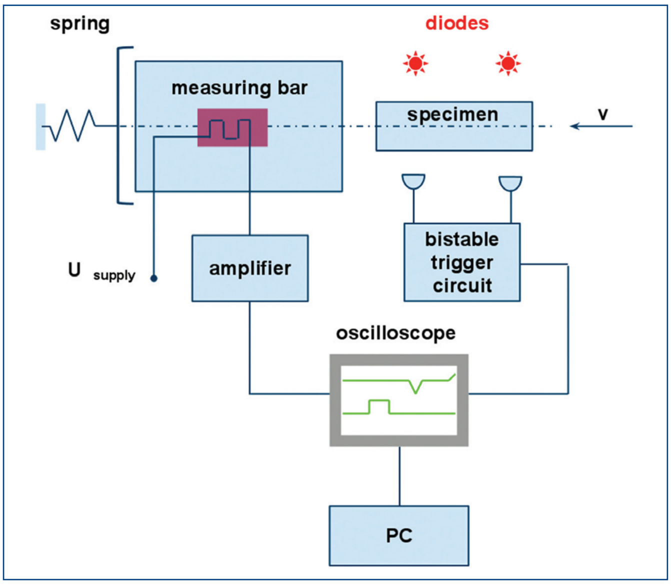

Figure 1. *Illustration of TAT*

2.1 Evaluation of Experiment

In comparison with the typical TAT, where the specimen impacts on a rigid wall, in this case the impact area is the front of the measuring bar of 20 mm in diameter and 800 mm in length. Four HBM 3/120 LY11 resistance strain gauges are glued in the middle of the bar (two lengthwise and two crosswise) and connected in full Wheatstone bridge. The incident pulse created by specimen impact is recorded via an amplifier to a Tektronix TDS oscilloscope. A record (wave 1) influenced by wave dispersion, high-frequency noise and static electrical discharge is shown in Fig. 2. [Forejt 2007]

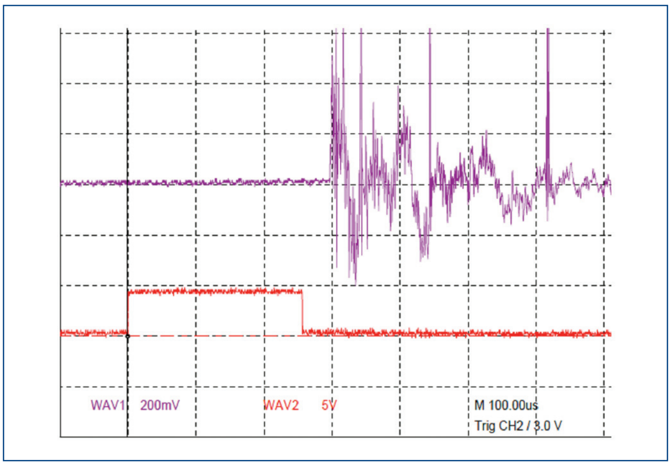

Figure 2. *Influence of static electrical discharge*

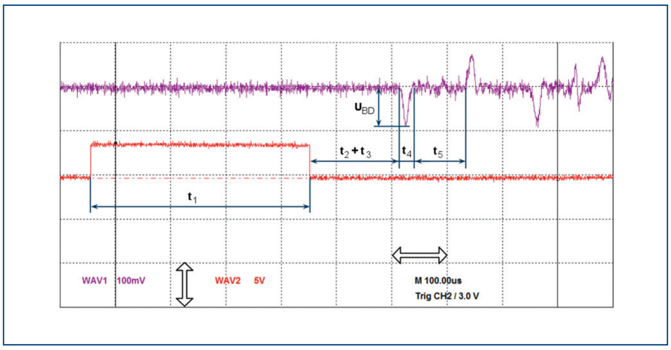

Figure 3. *Typical record without static electrical discharge*

A typical record without static electrical discharge is shown in Fig. 3. Wave 2 represents the course of transit time of specimen between photo diodes. While passing the first diode the voltage pulse starts to be measured. An advantage of this setting is the elimination of disturbing electromagnetic influences.

Time t_1 corresponds to the time when the specimen is passing between two photo diodes spaced 25 mm from each other; time t_2 corresponds to the time of the passage towards the front of measuring bar (the distance between the second photo diode and the measuring bar is 5 mm); t_3 corresponds to the time of wave propagation by velocity of sound in metals to resistance strain gauges; t_4 corresponds to the time of incident pulse duration; finally, t_5 corresponds to the time, when incident pulse reaches the end of the measuring bar and is reflected back with opposite amplitude towards the strain gauges (the second pulse in wave 1 record).

The record of voltage increment is converted to strain by using equations (1) and (2). The maximum force acting on the specimen during the deformation process is calculated as a result of the Hook law (3) and the law of action-reaction (4).

$$\varepsilon_m = \frac{U_{BD}}{U_N} \cdot \frac{2}{K} \cdot \frac{1}{z} \cdot \frac{1}{1+\mu} \text{ [-]} \quad (1)$$

$$\varepsilon_1 = \frac{1}{2}\varepsilon_m \text{ [-]} \quad (2)$$

$$\sigma_1 = \varepsilon_1 \cdot E \text{ [MPa]} \quad (3)$$

$$F_1 = F_D = \sigma_1 \cdot S_{bar} \text{ [kN]} \quad (4)$$

where U_{BD} is the increment in the measuring voltage, U_N is the supply voltage, K is the strain gauge constant, z is the amplification, μ is the Poisson number, e_m is the measured strain, ε_1 is the real strain of measuring bar, E is the Young modulus of measuring bar, and S_{bar} is the cross-sectional area of the bar.

After the impact of the specimen on the front of the bar a faster elastic wave and a slower plastic wave start to propagate from the front of specimen. At the end of specimen, the elastic compressive wave reflects back as tension wave and interacts with the plastic compression wave. This means the end of the deformation process because stress decreases to zero. [Meyers 1994]

3. Results and discussion

This part of the paper deals with the procedures and arrangements of the TAT system that reduce the noise level and high-voltage disturbances in the measuring voltage record. The polystyrene sabot rubs against the inner wall of the barrel during acceleration. Thereby a static charge appears on the sabot surface. This charge is further propagated onto the measuring bar after the impact of the specimen.

A typical record affected by static charge is shown in Fig. 2. [Forejt 2007] Such a record is hard to evaluate. It is impossible to pinpoint where the primary record with the maximum U_{BD} output voltage is 0. The measuring bar has to be perfectly insulated from the surroundings.

The transfer of electric charge from the sabot onto the catch tank and then onto the measuring bar is prevented by the application of insulating pads (see Fig. 4). Antistatic treatment is applied to the specimen and the sabot prior to the experiment. The maximum deformation force that acts on the specimen is one of the important experiment outputs. The record from the oscilloscope after the modifications discussed in the preceding paragraph is shown in Fig. 3. The maximum U_{BD} output voltage is equal to 91.3 mV; using relations (1) – (4) the deformation force can be obtained.

$$\varepsilon_m = \frac{U_{BD}}{U_N} \cdot \frac{2}{K} \cdot \frac{1}{z} \cdot \frac{1}{1+\mu} = \frac{91.3 \cdot 10^{-3}}{1.72} \cdot \frac{2}{1.99} \cdot \frac{1}{100} \cdot \frac{1}{1+0.3} = 4.10 \cdot 10^{-4} \quad (5)$$

$$\varepsilon_1 = \frac{1}{2}\varepsilon_m = \frac{1}{2} 5.18 \cdot 10^{-4} = 2.05 \cdot 10^{-4} \quad (6)$$

$$\sigma_1 = \varepsilon_1 \cdot E = 2.59 \cdot 10^{-4} \cdot 2.1 \cdot 10^5 = 43.09 \text{ MPa} \quad (7)$$

$$F_1 = F_D = \sigma_1 \cdot S_{bar} = 54.38 \cdot \frac{\pi \cdot 20^2}{4} = 13.54 \text{ kN} \quad (8)$$

The deformation force (8) is logically greater than the force (9) calculated from the calibration diagram of the measuring bar. This diagram was obtained under static loading conditions. The maximum deformation stress in the contact area of the specimen is calculated from the deformation force (8).

$$F = 28.153\varepsilon_m \left[\frac{\mu m}{m}\right] - 47.627 = 11\,495 N \approx 11.50 \text{ kN} \quad (9)$$

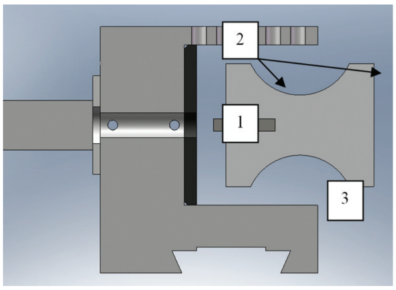

Figure 4. Detail of specimen impact area (1 – measuring bar, 2 – insulating pads, 3 – impact chamber with holes for photodiodes (sensors), 4 – sabot with specimen)

The methodology of measuring using resistance strain gauges is very often used in these days. Nevertheless, resistance strain gauges are very sensitive to surrounding electromagnetic field. As can be seen from the record in Fig. 3 there is a marked influence of noise level acting on incident pulses. High-frequency disturbances need to be removed by mathematical filtering before evaluation. It is necessary to avoid the subjective view of evaluator, who can influence the result validity inappropriately by a wrong set-up of filter parameters. The influence of high-frequency disturbances can be suppressed using semiconductor strain gauges.

Another set-up of the TAT device is described below. A piezoelectric sensor by Kistler [Kistler 2010] was placed next to the measuring bar. The sensor was connected to its own control terminal, amplifier and storage oscilloscope. This connection allowed a comparison with the record of resistance strain gauges.

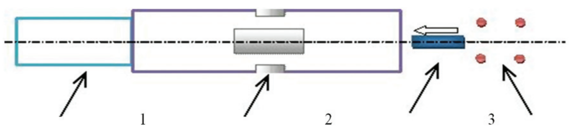

Figure 5. Illustration of TAT with piezoelectric device (1 – piezoelectric sensor, 2 – measuring bar, 3 – specimen, 4 – diodes)

The piezoelectric sensor ensures recording without the influence of noise and high-frequency disturbances. So there is no need for mathematical filtering. The control terminal is another advantage, which evaluates maximal loading force automatically in real time.

Specimen	L_0 [mm]	D_0 [mm]	L_f [mm]	D_{max} [mm]	v [m/s]	F_{max} strain gauges/piezoelectric sensor [kN]
Ti 1	25.05	5.01	24.78	5.12	96.26	8.07/7.68
Ti 2	24.95	5.00	24.03	5.50	182.75	without record/12.9
Ti 3	25.05	5.05	24.03	5.56	182.88	8.44/13.55

Table 1. *Results of preliminary measurement of dynamic forces for each specimen*

The results of preliminary measurement using the above methods are shown in Table 1. Specimens made of Ti-6Al-4V titanium alloy were accelerated to speeds of 100 to 200 m/s. The speed range was chosen because of the high yield stress of titanium alloy. After a comparison of the experimental results we can arrive at these conclusions:

- the piezoelectric sensor provides a good-quality signal without noise
- the dynamic force measured by resistance strain gauges conforms to the force recorded by the piezoelectric sensor

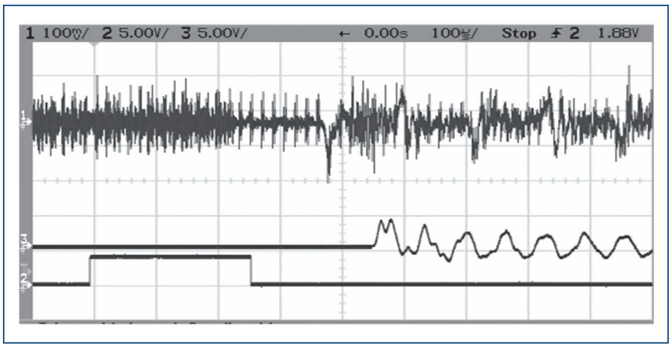

Figure 6. *Record of incident pulse of TAT for Ti–1 specimen recorded by 4-channel oscilloscope HP (Channel 1 – resistance strain gauges, Channel 2 – trigger circuit, Channel 3 – piezoelectric sensor, time base is 100 µs)*

5. Conclusions

The Taylor anvil test is typically used to determine the dynamic behaviour of materials. To analyze properly the maximum deformation force acting on the specimen it is necessary to acquire a record of output voltage without any noise and high-frequency components. These undesirable components could be eliminated by a consequent insulation of the measuring bar, earthing and implementation of the amplifier as close to the measuring bar as possible. The lengths of the measuring bar are limited by the superposition of the incident and the reflected pulses. The replacement of the resistance strain gauges is another option. Semiconductor strain gauges have a many times higher K factor. Possible adoption of capacitance detectors offers a good solution to problems with noise and high-frequency components, which could also be filtered out mathematically.

As follows from preliminary tests, the dynamic force measured by resistance strain gauges conforms to the force recorded by piezoelectric sensor. The piezoelectric sensor is more suitable because it is able to record the maximum value of dynamic force without the influence of dispersion.

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