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The Use of a Rotary Impact Testing Machine in Tests of Materials under Dynamic Strain Conditions

Abstract: The article presents characteristics of an upgraded rotary impact testing machine featuring a new measurement system based on strain gauges and enabling the recording of short signals. A dedicated test rig enabled the performance of dynamic tensile and bend tests within a linear velocity of a forcing element (striker/claw) restricted within the range of 5 m/s to 40 m/s. Tests involved TRIP and DP steels as well as alloys of non-ferrous metals PA4 and AZ31. Dynamic tensile tests were performed in relation to a striker linear velocity of 5 m/s, 15 m/s and 30 m/s. The results obtained in the above-named tests were compared with those obtained in static tensile tests. The dynamic tensile tests and structural examinations made it possible to identify correlations between strain rates, mechanical properties of the materials and the morphology of fractures. The testing methodology discussed in the article could constitute an effective tool enabling the assessment of properties of structural materials under dynamic strain conditions. The research-related test results could be used when designing the structure of energy-consuming elements of vehicles and load-bearing elements of aircraft exposed to dynamic loads.

Keywords: dynamic strain condition, rotary impact testing machine, dynamic tensile

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Introduction

Presently limited possibilities related to the investigation and determination of material characteristics at high strain rates result from the limited availability of testing equipment, the ambiguity of applied computational methods and procedures as well as the complexity of phenomena accompanying deformations. As a result, design engineers and technologists are in possession of limited information concerning the behaviour of materials under high strain rate conditions. The need for the above-named information results from the growing applicability of new materials characterised by previously unavailable mechanical and functional properties and designed to meet increasingly strict requirements concerning means of transport and rigorous conditions of acceptance tests pertaining to structural materials and elements [1–4].

The automotive industry relies on commonly applied crash tests, whereas the aviation industry has developed advanced procedures governing the acceptance of new technical solutions.

The primacy of passengers' safety imposes (on design engineers and technologists) increasingly many challenges concerning mechanical and functional properties of structural materials, whereas acceptance tests of new structural materials and elements become increasingly demanding.

Most common methods used to assess the plasticity of materials are tensile tests, compressive tests, bend tests, torsion tests, impact tests as well as model upsetting and rolling tests. Standard testing machines enable the performance of tensile tests at a strain rate of up to 0.1 s^{-1}. In turn, torsion plastometers used in torsion tests enable the obtainment of strain rates restricted within the range of 10 s^{-1} to 35 s^{-1}. A Gleeble testing system, commonly used in tests of materials, enables the

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performance of tests at strain rates restricted within the range of 0.0001 s^{-1} to 100 s^{-1} [5]. The range of strain rate, referred to as the dynamic deformation of material, is very wide. For this reason, it is impossible to perform tests within the entire range using only one device and one type of measurement equipment. Some of the aforesaid devices constitute standard laboratory equipment, where tests performed using them are standardised. For instance, impact bend tests performed using the Charpy pendulum machine are commonly known and applied also under industrial conditions. In terms of modified Hopkinson bar systems, enabling the performance of tests at strain rates restricted within the range of 500 s^{-1} to10^5 s^{-1}, primary issues are concerned with the availability of testing machines and the complexity of procedures related to analyses of results [6–8]. Machines which enable the testing of materials at rates restricted within the range of 10^2 to 10^4 s^{-1} are rotary impact testing machines. The aforesaid machines are characterised by compact design and uncomplicated testing methods. Their additional advantage includes the possibility of testing specimens made of bars, coating materials, sheets/plates and strips. The above-presented testing versatility combined with the wide range of strain rates and the relatively low cost of pre-test sample preparation have inspired search for the applicability of rotary impact testing machines in tests of materials [9–13].

The problem of dynamic deformation, also the one involving rotary impact testing machines, involves curves of force characteristics and their interpretation. Professor Janusz Klepaczko, who dedicated his entire scientific life to issues concerning the plastic deformation of materials under dynamic load conditions and accompanying phenomena, stated that the “identification of plastic properties of metals undergoing deformation at a strain rate of $5 \cdot 10^2$ s^{-1} and higher, constitutes a significant experimental issue”. Serious doubts are concerned with the correctness of analysis results, particularly at the initial stage of deformation. Therefore, it is necessary to ask whether varied curves of force characteristics observed during tests result from the specific design and operation of dynamic testing machines, the design of clamps, the shape of a given specimen or the ability to identify and filtrate disturbances [14].

Answering only some of the questions asked above will make it possible to validate results of dynamic strain tests as well as to use material characteristics in simulation software programmes and when designing materials and new structures for the automotive and aviation industries.

The article presents an upgraded testing station (provided with an advanced measurement system) used for dynamic tests and discusses results of strain and microfractographic tests involving selected metallic materials used the transport industry.

Test rig

Dynamic strain tests were performed using an RSO-type rotary impact testing machine presented in Fig. 1. The machine enables the performance of tensile and bend tests at a linear impact rate restricted within the range of 5 m/s do 40 m/s, which

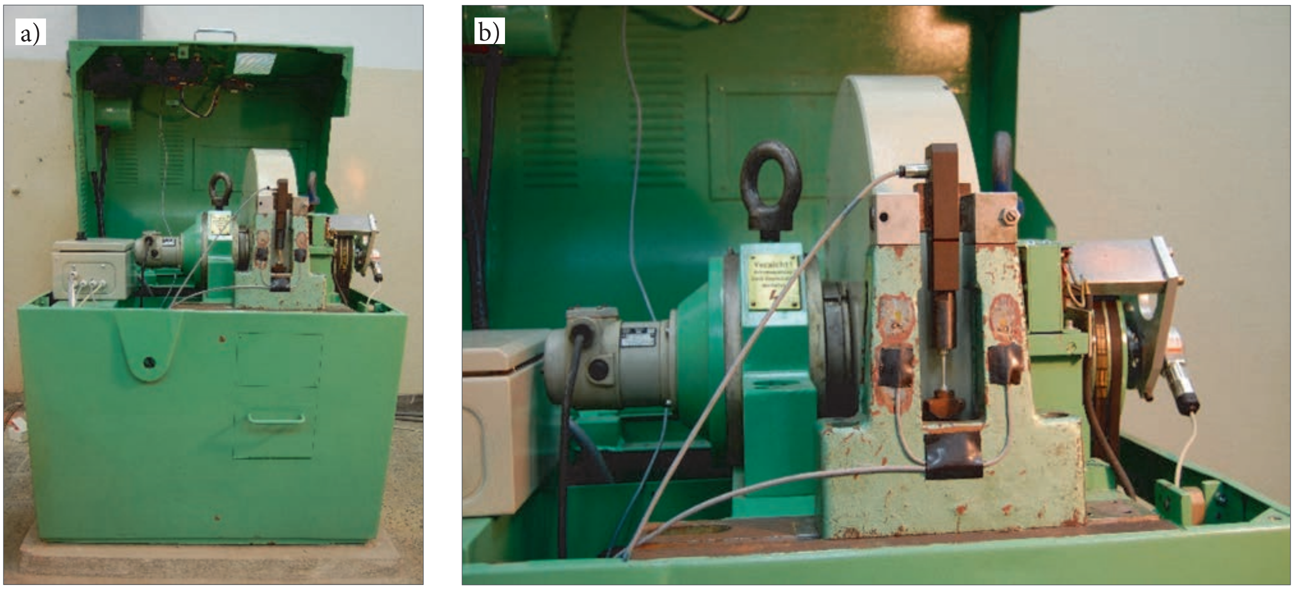

Fig. 1. Dynamic test rig (a), workspace prepared for dynamic tensile tests (b)

corresponds to a strain rate restricted within the range of 10^2 to 10^4 s^{-1}. During dynamic tensile tests, the specimen is fixed to the upper clamp and is subjected to deformation as the striker (claw) hits the anvil of the lower clamp. In turn, during impact bend tests, the specimen is fractured on the anvil by means of the striker (claw). The replaceable claw is fixed on a flywheel characterised by a very high moment of inertia. Measurements of forces exerted during tensile or bend tests are performed using an extensometric pressure sensor (25 kN), the design of which has been adapted for mounting in the elements of the stand or anvil (depending on a test being carried out). The linear velocity of the striker in the measurement system is identified by measuring the rotation rate of the testing machine flywheel. The measurement is performed using an encoder fixed on the tip of the shaft neck. During tests discussed in the article, signals were conditioned using a PCI-BASE 1000 DAQ device having a sampling frequency of 500 kHz and enabling the synchronous reading of both signals every 2 μs. The system and signal recording were controlled using a Next View 4.2 software programme (BMC).

Testing methodology

Dynamic strain tests were performed within the scope of tensile tests. Test specimens were made of metallic materials including TRIP steel, DP steel, magnesium alloy AZ31 and aluminium alloy PA4. In order to obtain the homogenous initial structure, the above-named materials were subjected to heat treatment procedures.

The tests involved the use of specimens in the form of smooth cylinders (double-sidedly threaded in the gripping part) having a diameter of 4 mm and a length (of the measurement part) of 20 mm (Fig. 2).

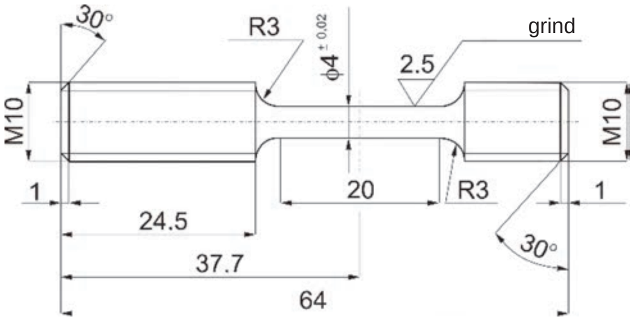

Fig. 2. Smooth cylindrical specimen used in the dynamic tensile test

The dynamic strain tests involving the use of the rotary impact testing machine were performed at striker linear velocity restricted within the range of 5 m/s to 30 m/s, which corresponded to strain rates restricted within the range of $3{\cdot}10^2$ to $6.5{\cdot}10^3$ s^{-1}. The tests involved the recording of tensile force curves in time and in relation to the linear velocity of the striker placed on the flywheel. Force characteristics and dimensions of specimen geometry before and after deformation were used to determine the strain rate, tensile strength, ultimate strain and toughness.

Ultimate strain was determined using the following dependence:

$$\varepsilon_g = 2\ln\frac{d_0}{d_1} \tag{1}$$

where

ε_g – ultimate strain,

d_0 – initial diameter of the specimen [mm],

d_1 – minimum diameter of the specimen after rupture [mm].

Strain rates corresponding to the preset linear velocity of the striker were calculated using the proportion of ultimate strain ε_g to test time t:

$$\dot{\varepsilon} = \frac{\varepsilon_g}{t} \tag{2}$$

where

$\dot{\varepsilon}$ – strain rate [s^{-1}],

ε_g – ultimate strain,

t – time [s].

Toughness was identified using the following dependence:

$$U = \frac{L_u}{A} \tag{3}$$

where

U – toughness [J/cm^2],

L_u – strain energy at rupture [J],

A – initial cross-section of the specimen [cm^2].

In addition to dynamic strain tests, the authors also performed static tensile tests. The form of fractures was identified using an S-3400 N scanning microscope (Hitachi).

Test results

The strain tests involved the recording of force curves in time. The recording time of the measurement signal amounted to 10 s (Fig. 3).

The dependence of the tensile strength of TRIP steel and DP steel on the strain rate is presented in Fig. 4a. The materials which proved particularly sensitive to the strain rate were the steels. An

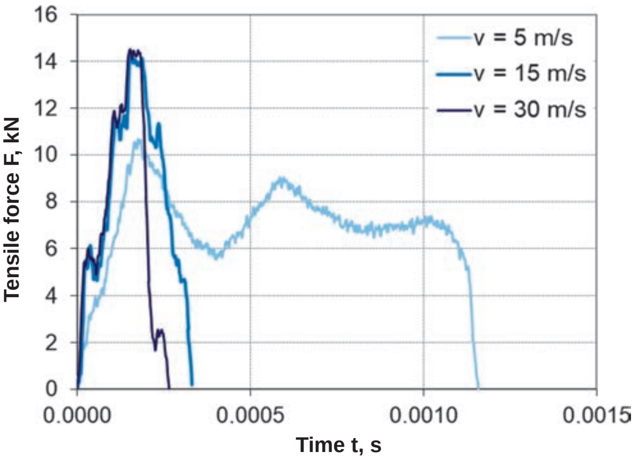

Fig. 3. Changes of tensile force in time in relation to TRIP steel and striker linear velocity v = 5 m/s, v = 15 m/s and v = 30 m/s

increase in tensile strength, if compared with tensile strength determined under static conditions, was significant.

The TRIP steel subjected to the tests obtained a tensile strength of approximately 1150 MPa in relation to striker linear velocity v = 15 m/s and 30 m/s. In turn, in relation to striker linear velocity v = 15 m/s and 30 m/s, the DP steel obtained a tensile strength of 1200 MPa and 1277 MPa respectively. The maximum tensile strength values of the steels obtained under dynamic strain conditions were significantly higher than those obtained in the static tensile tests.

In spite of hardening (tensile strength), the ultimate strain of the TRIP and DP steels was characterised by growing tendency (particularly visible in terms of the DP steel) (Fig. 4b).

The dependence of the tensile strength of alloys PA4 and AZ31 on the strain rate is presented in Fig. 5a. The tests revealed the high sensitivity of aluminium alloy PA4 to the strain rate. The alloy was characterised by increased hardening (tensile strength) within the entire range of striker linear velocity. The tensile strength of magnesium alloy AZ31 was relatively constant. The material was not characterised by increased hardening.

A significant and proportional increase in the ultimate strain was observed in aluminium alloy PA4 (Fig. 5a). The ultimate strain of the

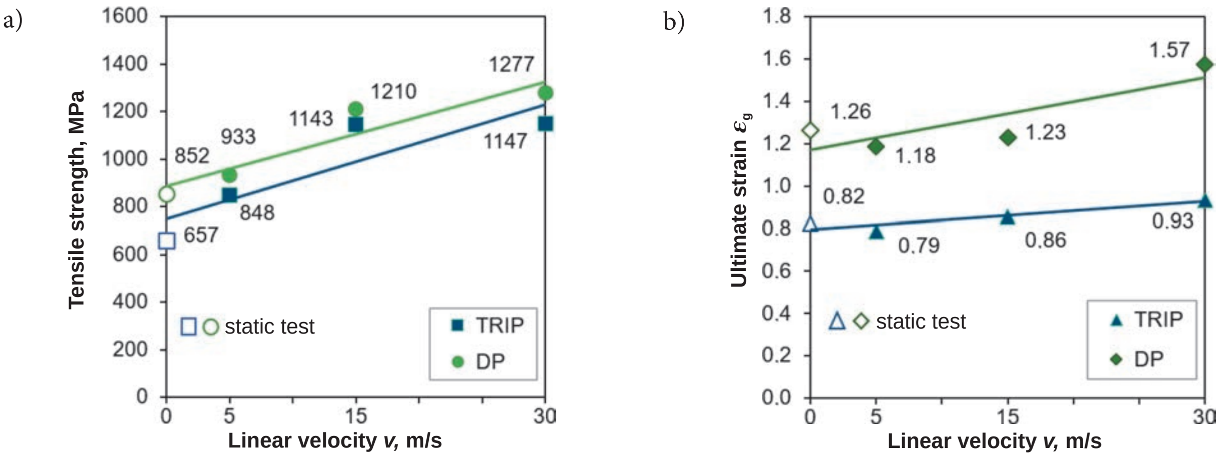

Fig. 4. Tensile strength (a) and the ultimate strain of (b) TRIP steel and DP steel in relation to the linear velocity of the striker

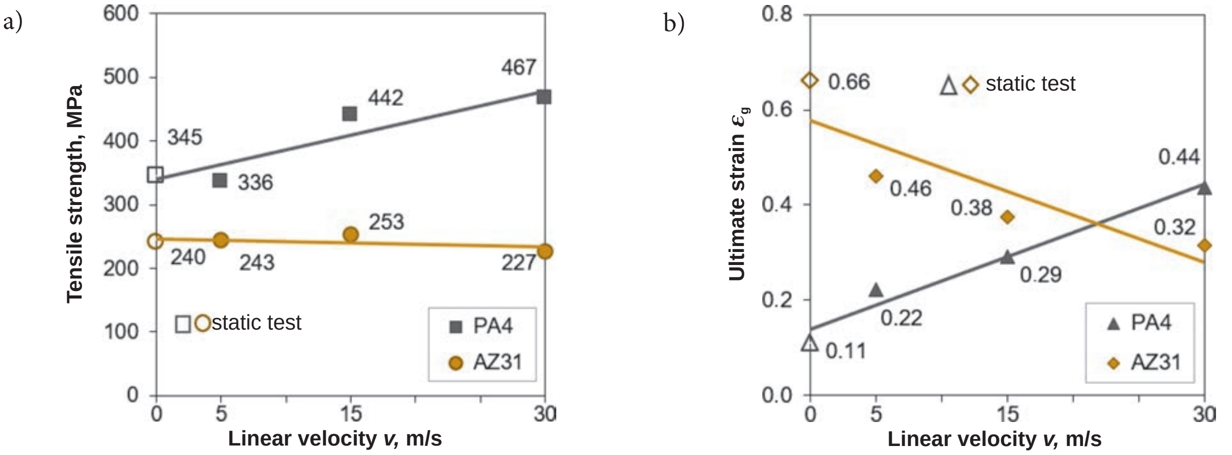

Fig. 5. Tensile strength (a) and the ultimate strain of (b) alloys PA4 and AZ31in relation to the linear velocity of the striker

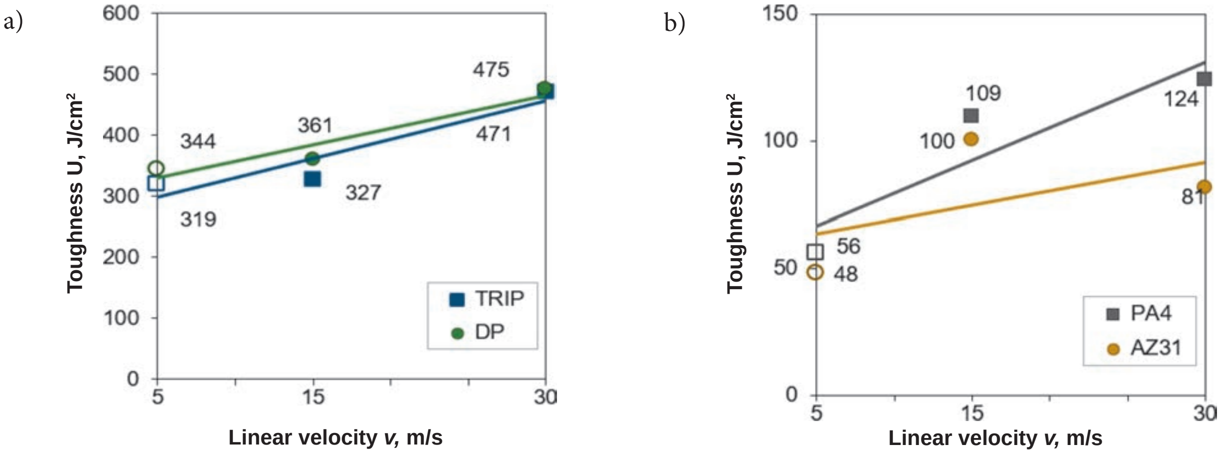

Fig. 6. Toughness results obtained in the tensile tests of the TRIP and DP steel as well as of aluminium alloy PA4 and magnesium alloy AZ31 in relation to the linear velocity of the striker

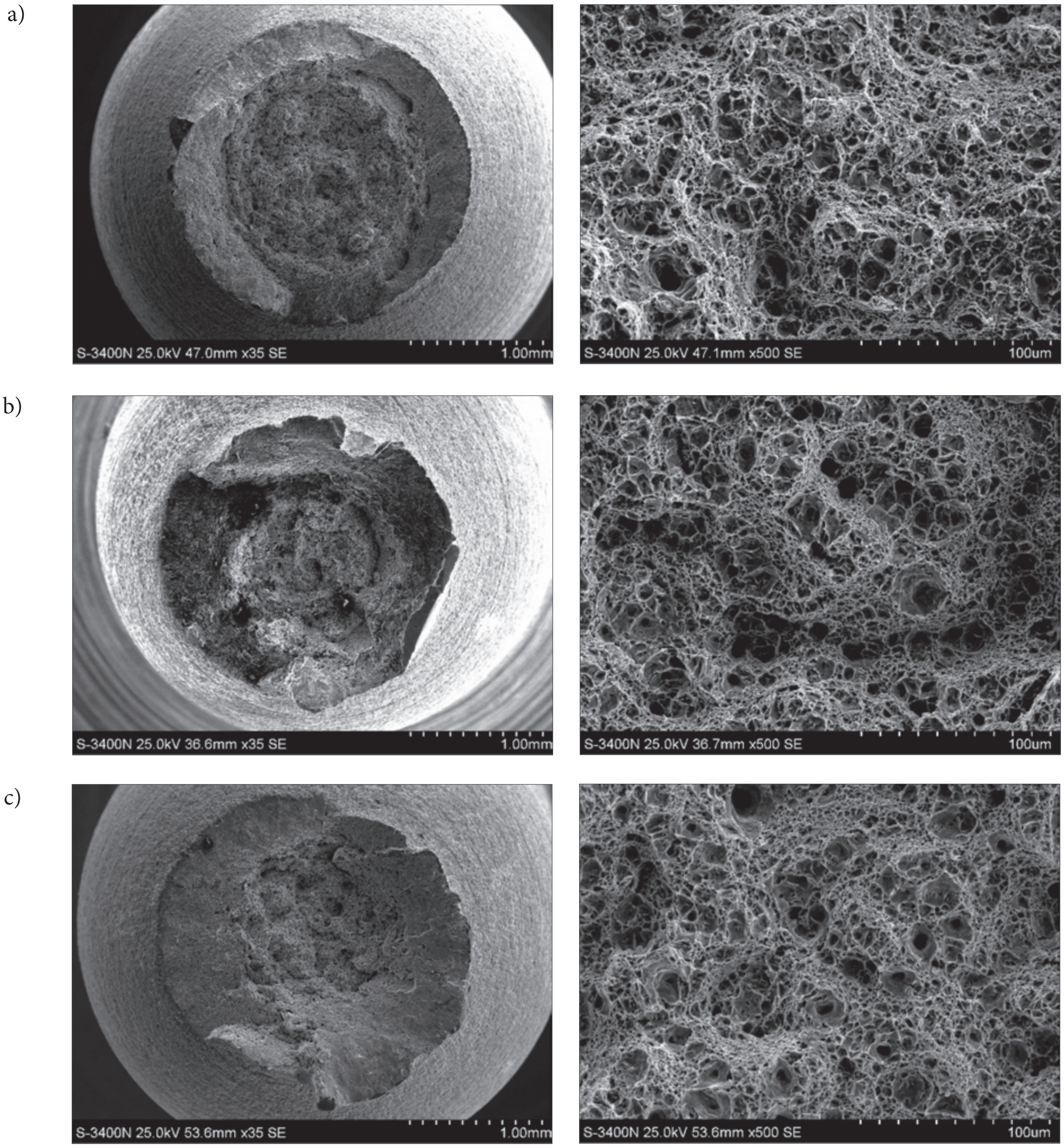

Fig. 7. Fracture surfaces in the DP steel specimens after the static (a) and dynamic tensile tests in relation to striker linear velocity v = 5 m/s and 30 m/s (b, c)

above-named alloy was nearly 3-fold higher than that identified under static conditions. In turn, the behaviour of the magnesium alloy was entirely different (Fig. 5b). The ultimate strain of magnesium alloy AZ31 decreased sharply along with an increase in the strain rate. In relation to $v = 30$ m/s, the ultimate strain of the alloy amounted to $\varepsilon_g = 0.32$ and was by half lower than that obtained under static conditions ($\varepsilon_g = 0.66$). An increase in the strain rate (striker linear velocity) was accompanied by the decreasing plastic deformability of magnesium alloy AZ31; the margin of plasticity was gradually exhausted.

The results of toughness tests (performed within the scope of dynamic tensile tests) revealed the growing toughness of the TRIP and DP steel (Fig. 6a). The toughness curves of both steels were similar, where slightly higher toughness values were obtained in relation to the DP steel. The aluminium and magnesium alloys were characterised by an increase in toughness within the entire strain rate range (Fig. 6b).

The microfractographic tests of the TRIP steel and DP steel revealed the ductile form of fractures in the specimens subjected to static tensile tests and dynamic strains, irrespective of the linear velocity of the striker. The morphology of the

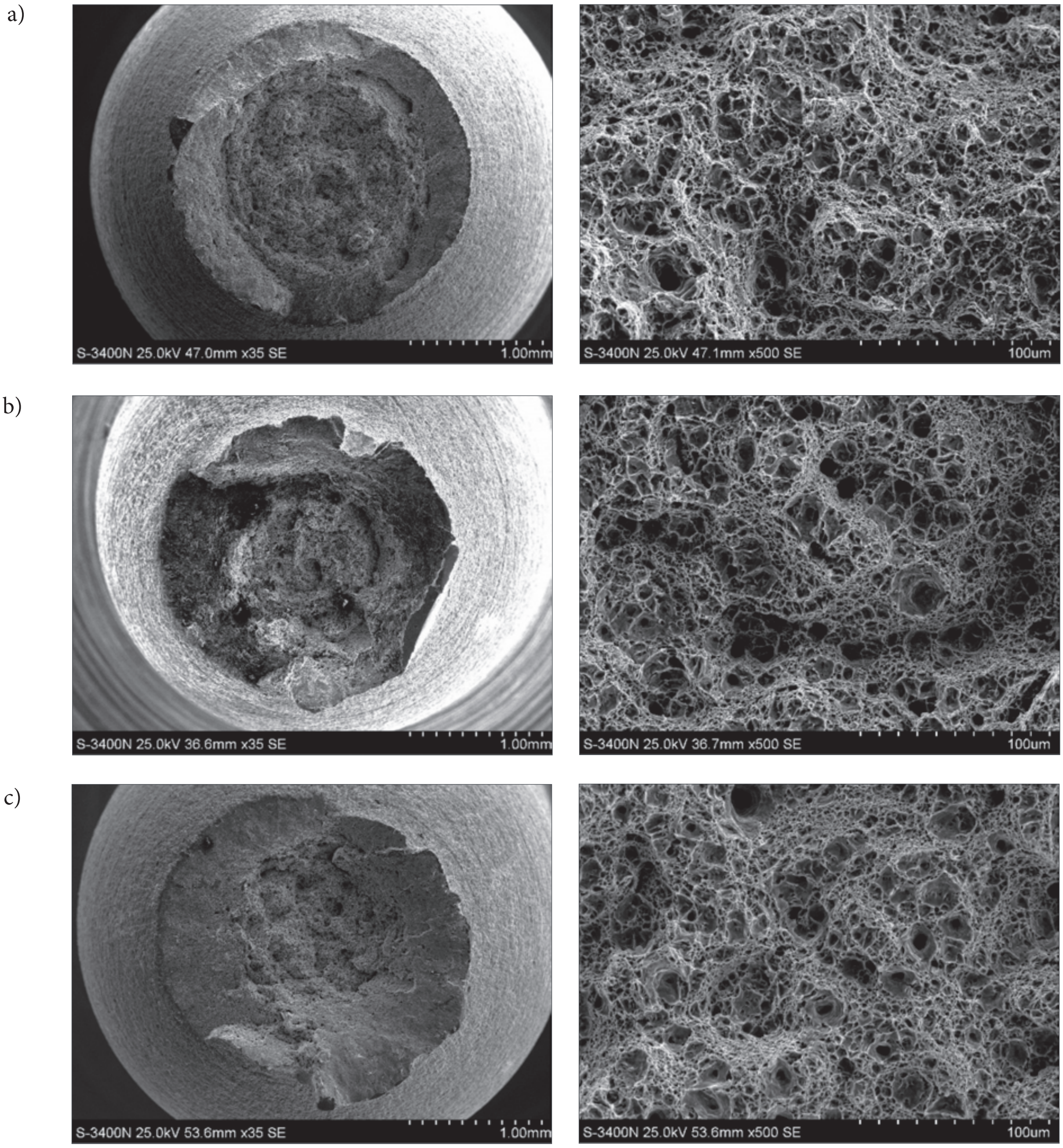

Fig. 8. Fracture surfaces in the specimens of alloy PA4 after the static (a) and dynamic tensile tests in relation to striker linear velocity $v = 5$ m/s and 30 m/s (b, c)

fractures contained "pits" characteristic of ductile cracking as well as cracks across grains on cleavage planes (Fig. 7). In addition, the DP steel contained the significant number of carbide precipitates. The fractures were more diversified in the specimens made of non-ferrous metal alloys (PA4, AZ31). The fractures observed in aluminium alloy PA4 were mixed in relation to all strain rates (Fig. 8); it was also possible to observe brittle fracture areas. Similarly, magnesium alloy AZ31 contained ductile fractures with some brittle fracture areas.

Summary

The above-presented measurement system of the rotary impact testing machine satisfied requirements concerning the recording of fast and short signals of the force and linear velocity of the forcing element (striker). The system enabled the simultaneous recording of both signals, tensile force and time within the entire linear velocity range of the striker. The versatile testing methodology applied during the tests can be used in relation to a large group of materials, ranging from strongly hardening advanced structural steels (used in the automotive industry) to alloys of non-ferrous metals (used in aviation structures).

The above-presented tests of structural materials revealed significant changes of mechanical properties along with increasing strain rates (in comparison with those obtained under quasi-static conditions).

The application potential of new structural materials in the automotive and aviation industries increasingly often depends on resistance to impact loads, which, in turn, necessitates the development of new methods enabling the testing of materials under dynamic strain conditions and the continuous improvement of measurement techniques. It is also necessary to perform further tests aimed to develop a unified procedure enabling the explicit assessment of results obtained during dynamic strain tests, under various kinematic conditions accompanying the performance of research experiments.

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