Ultrasonic detection of spall damage induced by low-velocity repeated impact

Research Article

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Abstract: This paper address the examination of spall damage in medium carbon steel subjected to a repeated impact testing. The experiments were performed well below the threshold spall-stress of 2.6 GPa and the damage introduced in the subsurface volume was investigated using the low frequency scanning acoustic microscopy. Based on B- and C-scan images (the images taken along and perpendicular to the impact surface) we made a qualitative and semi-quantitative evaluation of the damage type (voids in a ductile material or cracks in a brittle one) and its distribution. We found the spall damage development dependent on the amplitude and the duration of the stress pulses. In particular, we proved that the high, long stress pulses induce damage that resembles tensile failure of material, in which voids or cracks nucleate along the spall plane to form macro-cracks. This explains why spall-damage is not seen when the first impact is below the characteristic threshold spall-stress. However, when the tests consist of more than four impacts the spall damage is produced already under stress below the threshold-value.

Keywords: Spall damage • Repeated impact • Low-velocity plate impact test • Ultrasonic detection • Nondestructive inspection
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1. Introduction

Intense tensile stress pulses induced during high velocity impacts, cause spall damage in metals, *i.e.*, microvoids or microcracks are nucleated in the body of solid. These imperfections, although sizable, are hardly to detect and

measure since they are formed mainly in subsurface region of the tested material. Therefore, the traditional way to examine spall damage is to analyze the micrographs of polished surfaces obtained through a sequence of sections across the damage region [1–3]. This is obviously tedious, destructive, expensive, and approximate method to examine this interesting phenomenon. Indeed, the destructive technique can hardly be used in a case of structural parts. Similar concerns apply to the investigation of the spall damage growth under repeated impacts on a set of virtu-

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Table 1. Material parameters of the investigated materials.

Material	Density ρ [kg/m ³]	Poisson's ratio ν	Young's modulus E [GPa]	Bulk modulus K [GPa]	Shear modulus G [GPa]	Bulk wave velocity C [m/s]
Carbon steel	7790	0.29	209	164	81	5920

ally identical' samples. The alternative is nondestructive examination of spall-damage effect as the proper approach to this technologically and scientifically important problem – the subject that we bring to light by the present article.

Here we advocate the usage of the ultrasonic measurements as the most convenient, precise and highly efficient technique capable to resolve the so nowadays needed evaluation of spall damage in technologically significant metals and alloys (for review see Ref. [4]). Suffice it to mention that this method provides the required information concerning size, distribution and precise location of the microflaws created in aluminum and medium carbon steel during consecutive impacts [4], and therefore we presently advocate versatility of the technique and its suitability for quantitative sub-surface damage evaluation.

This paper contrasts the previously published results and it focuses on the evaluation of the spall-damage produced exclusively during low stress/low-velocity repeated impacting of medium carbon steel. This goal is accomplished by means of ultrasonic technique. To be more specific, although it is commonly admitted that in order to initiate the spall damage the first impact stress should be exceeded the particular value of threshold spall-stress [1, 2], we examine here the defects produced in the impact that is below the characteristic threshold level. It somewhat resembles the interesting effects observed during nanocompression of silicon nanoparticles [5] and in macroscale this is close to fatigue phenomenon [6].

2. Spallation induced during plate impact experiment

Microvoids or microcracks that constitute spall damage are produced by tri-axial tensile stress pulse, generated during the plate impact experiment. When a flyer plate collides with the target material, compressive stress waves generated in both plates travel toward their free surfaces, where they are reflected with the reversed phase. Hence, the original tensile waves interfere. The superposition of these 'rarefaction waves' within the target plate is a source of a tensile stress pulse, which amplitude and duration considerably affects a development of spall damage [1, 2].

Figure 1. Location of the target, flyer and the 'velocity measurement unit' denoted in the schematic of the experimental setup. The exact dimensions used in our experiments are indicated in the figure.

In the case when the impact stress is higher than the threshold spall stress and duration is long enough to create tensile failure of material, the spall damage is nucleated in the narrow range called the 'spall plane'. The latter gives origin to further formation of macro-cracks.

3. Experimental methods

3.1. Plate impact experiments

The medium carbon steel (0.45% carbon) target was impacted repeatedly by flyer plate of the same material (the detailed characteristics are given in Table 1). The detailed listing of the conditions of the experiments carried out on different specimens is provided in Table 2. The dimensions of the used materials and schematic of the experimental setup is illustrated in Figure 1. The parallel orientation of the target and flyer plates was secured within our experiments (the deviation should not exceed 1mrad as stated in Ref. [7]).

The flyer plate bonded to the polymer sabot was accelerated by a single stage gas gun, while the target plate was also bonded to the stage that was itself fastened to the target holder and to the velocity measurement unit (details in Figure 1). The flyer impact speed was measured by the optical fiber switches located 20 and 30 mm away of

Table 2. The detailed listing of the test conditions carried out on medium carbon steel specimens and the occurrence of spall damage after the each impact detected by SLFAM-technique. The symbols ○ and × stand for distinguished and non-identified spall damage, respectively.

Specimen No.		Number of Impact				
		1 st	2 nd	3 rd	4 th	5 th
R2	Impact velocity V [m/s]	58	73	66	56	55
	Impact stress σ [GPa]	1.3	1.7	1.5	1.3	1.3
	Spall Damage	×	×	×	○	○
R6	Impact velocity V [m/s]	52	60	47	65	64
	Impact stress σ [GPa]	1.2	1.4	1.1	1.5	1.5
	Spall Damage	×	×	×	×	○
R7	Impact velocity V [m/s]	56	51	52	64	75
	Impact stress σ [GPa]	1.3	1.2	1.2	1.5	1.7
	Spall Damage	×	×	×	×	○

the target plate. The special recovery chamber has been constructed to recover the target plate for further tests [4]. The front and rear surfaces of the target plate were polished with a grinder or the #1500 emery paper after each impact test. Repeated impacts were given to the identical target plate with different low impact velocities (see Table 2).

When the target and flyer are made of the same material, the compressive stress σ induced right after the collision can be obtained from the relationship [4, 8, 9]:

$$\sigma = \frac{1}{2} \rho C V, \quad C = \sqrt{\frac{1}{\rho} \left(K + \frac{4}{3} G \right)}, \quad (1)$$

where ρ , C , V , K and G are the density, the bulk (elastic) wave velocity, the velocity of the flyer, the bulk elastic modulus and the shear elastic modulus of an investigated material, respectively.

3.2. C- and B- scan Imaging

In order to detect whether the spall-damage had been induced in the target plate, we used, the scanning low frequency acoustic microscopy (SLFAM, Olympus UH Pulse-100 – the schematic given in Figure 2, see also Refs. [11–13]. UH microscope employed the frequency range, gate width and memory size of 5–200 MHz, 20 ns–1 μ s and 640 × 512 (8 bit), respectively. The spall damage was examined by ultrasonic C- or B-scan images to visualize void/crack distributions, *i.e.*, C-scan in a plane parallel to impact plane at arbitrary depth, B-scan in a plane perpendicular to impact plane. The scanning acoustic images were obtained by detection of the amplitude of the longitudinal wave reflected from the elemental area of the specific defects such as inclusions, voids or cracks. The

Figure 2. The clarification of our acoustic microscopy provided in a graphical form. To suppress the ringing of the reflected wave, an external attenuator was added to the measuring circuit, while the additional oscilloscope was used to detect the acoustic wave reflected from the damaged zone.

signal intensity registered at each point was mapped as a set of spots of variable brightness (*e.g.*, Figure 4 in the Results chapter). The necessary parameters that include: the central frequency of 30 MHz, beam diameter at focus equal 0.28 mm and focal length (in water) of 25.4 mm [14] were achieved with the PolyVinylidene DiFluoride (PVDF) point-focus transducer, similarly as we earlier described in our previous paper [4]. In the former publication we also provided a detailed account concerning the proper selection of the gate width and the gate position and overall advantage of usage of the PVDF transducer to obtain clear images of voids or cracks at arbitrary depth, the method that was successfully used also in the present study (see Ref. [4]).

Specimens were inspected by SLFAM before the initial impact in order to confirm the absence of pre-existing voids or cracks. C-scan images were acquired at the 2.0, 2.5 and 3.0 to 4.0 mm depth in the 0.1 mm interval from the impact surface, while B-scan images were taken at the central cross section of the target plate. The gate width was fixed at 30 ns which correspond to approximately 90 μ m thickness in the particular steel we investigate.

3.3. Quantitative evaluation of spall damage

The spall damage evolution was determined from the wave intensity backscattered at defects, using parameters (time-of-flight, longitudinal wave velocity, backwall echo height of target plates) that are sufficiently defined in Figure 3. The digital ultrasonic system we used [15] had been composed of ultrasonic pulser/receiver, A/D converter board and personal computer. The longitudinal wave transducer (frequency of 10 MHz, diameter 6.4 mm) made it possible

Figure 3. The typical waveform recorded using the ultrasonic measurement. The obtained data spanning from surface echo to second backwall echo (B2) were used for analyzing the ultrasonic variables.

to record the backscattering echoes at different locations, namely in the center and 10 mm both sides away of it. The measurements were performed before and right after the impact test.

The registered waveforms depicted in Figure 3 (see also Ref. [4]) provide the data concerning ultrasonic velocity and attenuation as amplitude ratio of B2 to B1 echo. The backscattering intensity, characterized by the non-dimensional frequency-dependent value N reads [4]:

$$N = \int_{f_1}^{f_2} B(f)df / \int_{f_1}^{f_2} U(f)df, \quad (2)$$

where $B(f)$ defines the amplitude spectrum of the backscattering wave, $U(f)$ denotes the surface echo, f_1 and f_2 are the lower and upper limit of the frequency f (3 and 14 MHz). The target plates were examined after the consecutive impact tests. We measured ultrasonic velocity, attenuation and backscattering intensity as well as C- and B-scan imaging.

4. Results and discussion

4.1. Detection of spall damage

The present authors evaluated the threshold stress that causes spall damage in the investigated metals [4]. It was found that for the medium carbon steel requires the damage starts from 2.6 GPa. The detailed test conditions and the stage when defects were detected are listed in Table 2. The evaluation of the impact stress was accomplished using the equation (Equation 1) with the proper materials' parameters (Table 1) and flyer's velocities (Table 2). It is worth noting that in the present research the impact stress was always below the threshold spall-stress.

The acoustic microscopy revealed, the spall damage in most cases after the fifth impact (see Figure 4 – spec.

Figure 4. The spall damage in medium carbon steel generated after the fifth impact during low-velocity repeated impact tests. The exposed particular data (C-scan image at the 3.3 mm depth) were registered for the sample No. R6.

Figure 5. The spall damage in medium carbon steel generated after the fourth (a) and fifth (b) impact during low-velocity repeated impact tests. The exposed particular data (C-scan image at the 3.5 mm depth) were registered for the sample No. R2. The spall damage nucleated by the fourth impact was increased by the fifth impact.

No. R6 where the white spots caused by reflected signal indicates the defects). Interestingly, in a single case the spall damage detected after the fourth impact developed during the subsequent fifth test (refer to Figure 5 – spec. No. R2). We always examined virtually the same region

Figure 6. Changes of ultrasonic velocity, amplitude ratio and backscattering intensity during the low-velocity repeated impact test. The data correspond to C-scan images displayed in the Figure 4.

of target plate for each of our specimens, which enabled us to conclude that the repeated impact induces spall damage despite the test is carried out below the threshold spall-stress, while the nucleation of the defects depends on the impact testing history. This is properly illustrated in Figure 4 and Figure 5 where the history of impact stress reads: Sequence 1 – 1.2 GPa (first), 1.4 GPa (second), 1.2 GPa (third), 1.5 GPa (fourth) and 1.5 GPa (fifth) and Sequence 2 – 1.3 GPa (first), 1.7 GPa (second), 1.5 GPa (third), 1.3 GPa (fourth) and 1.3 GPa (fifth), respectively.

4.2. Ultrasonic velocities, attenuation and backscattering intensity

Our previous investigations [4] already confirmed that wave velocity in metals with a large number of voids or cracks is lower than this measured for defect-free materials. This results from the ultrasonic wave scattering at voids or cracks, while the presence of defects enhances attenuation and the backscattering intensity [4, 10]. Certainly, this prompted us to use the measurements of ultrasonic wave velocity, attenuation (amplitude ratio, B2/B1) and backscattering intensity to estimate the spall damage.

We measured ultrasonic characteristics after to low-velocity repeated impacts (*e.g.*, for the specimen No. R6 – Figure 4)

and found the velocity to decreases with the increase in the impact number (refer to Figure 6). Despite we have to admit certain difficulties in quantitative evaluation of ultrasonic variables for some part of the tests (below 20%), the confirmation of our main thesis is obtained. The above mentioned impediment prompts us to look in future for accurate quantitative answer with a help of complimentary measurements by the nonlinear ultrasonic method [16]. This does not undermine, however, the validity of the presented results, while we mark here a possibility of further development in this interesting field.

5. Conclusions

Spall damage generated in medium carbon steel (0.45%C) by low-velocity repeated impact test was evaluated by means of the nondestructive, ultrasonic method (the ultrasonic C-scan images as well as the ultrasonic velocity, the attenuation and the backscattering intensity measurements). We found the defects are created relatively late, *i.e.*, after the fifth impact. Based on the C-scan image observations, we confirmed the generation of the defects despite the applied impact stress (1.1–1.7 GPa) did not exceed the threshold spall-stress. Furthermore, the nucleation phenomenon and increase of spall damage was recognized as to be dependent on the history of the impact testing.

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