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Low-Cycle Impact Fatigue Testing Based on an Automatized Split Hopkinson Bar Device

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Abstract. Preventing fatigue damage and failure in components subjected to repeated impact loading is of great interest in many engineering applications. Quite often, material response during high-rate loading differs from quasi-static response due to the material's strain rate sensitivity and adiabatic heating effects. Hence, experimental materials testing at realistic loading rates is important in many cases of impact fatigue. Impact loading tests involve an inherent challenge: since force equilibrium does not exist, the dynamic response of the whole load train must be properly accounted for in order to impose the desired loading on the specimen and to measure the specimen response. In the field of monotonic high strain rate materials testing, the Split Hopkinson Bar (SHB) technique has established itself due to its simplicity in terms of structural dynamics. However, traditional SHB setups require a long time to be reset/rearmed after the impact, and therefore they are ill-suited for cyclic impact loading studies. In this contribution, we present a modified SHB technique with fully automatized rapid resetting/rearming of the setup, which allows for controlled cyclic impact loading at a rate of 0.5 Hz. The applicability of the method is demonstrated in this paper with test results for a tempered steel.

INTRODUCTION

Many engineering applications involve cases where structures or components are subjected to repeated high velocity loadings, thus making them susceptible to fatigue damage and even failure. In some cases, cyclic impact loading is part of the designed functionality of the component, whereas in other cases repeated impacts are caused by malfunctions of the system or other abnormal situations. In any case, understanding the effects of repeating impact loading on the component material is vital for a reliable and safe design. From materials science point of view, impact loading involves certain characteristic features that must be accounted for. For example, it is well known that the mechanical response, such as strength, of most materials is dependent on the imposed strain rate and that plastic deformation occurring at a high strain rate involves heat generation in adiabatic conditions, which in turn can affect the material response. Hence, cyclic impact loading involves both mechanical aspects, such as structural vibration induced loadings, as well as effects related to the strain rate and temperature sensitivity of the material behavior.

From the testing point of view, impact loading involves an inherent challenge: even in a very simple test setup the dynamic response of the whole load train, i.e., the specimen and the components used to impose loads on it, has to be properly accounted for in order to impose the designed loading on the specimen and to measure the specimen material response.

In this paper, we present a low-cycle impact fatigue testing method based on the Split Hopkinson Bar (SHB) technique [1]. The SHB was selected since this technique enables good control of the loading imposed on the specimen and facilitates accurate measurement of the specimen response. For these reasons, the SHB technique is a well-established means for measuring the high strain rate monotonic mechanical response of nearly all types of materials. The main benefit of the SHB technique is its simplicity. In its classical form, the SHB technique requires only three slender linear-elastic bars: two long bars, the "input bar" and the "output bar", between which the specimen is

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sandwiched, and a short "striker", which is used to generate the impact loading by propelling it against the input bar. The input and output bars are used both to impose the loading on the specimen and to determine its mechanical response based on the measurement of the elastic waves traveling in the bars during the experiment.

The main drawback of the SHB technique in terms of cyclic loading is the relatively long time required for the resetting/rearming of the setup between the individual impacts. In most setups, resetting of the specimen and reloading of the striker involves manual or semi-manual work, which is inherently time-consuming. This challenge has been previously addressed in the literature by a variety of means, such as by using a mechanical crank shaft assembly or a hydraulic system to propel the striker and reload it [2], or by using a mechanical spring to propel the striker with electromagnet-based reloading of the spring [3]. Some works have described the use of two strikers in sequence in order to generate two consecutive impact loadings on the specimen with little idle time between the impacts [4, 5], or to utilize the residual waves in the bars for reloading the (low strength) specimen [6]. These latter techniques, however, do not solve the challenge of generating hundreds or thousands of loadings within the limits of practical resources. It should also be noted that all the above-mentioned techniques are not strictly speaking *Split* Hopkinson Bar techniques, since in some of the described setups the output bar is not used [2, 3] but the specimen is fixed on a rigid support. This approach simplifies the resetting of the specimen, thus allowing for a high impact frequency but limiting the measurement of the specimen response (in the SHB technique the output bar is usually the most reliable means of measuring the load imposed on the specimen).

In the current contribution, we present an approach where an existing conventional SHB setup is modified for cyclic impact loading experiments by incorporating an automatized resetting system of the specimen and rapid reloading of the striker into the basic SHB device. With the modified setup, well-controlled impact loading pulses can be imposed on the specimen at a frequency of 0.5 Hz with simultaneous measurement of the loading pulse shape and the specimen response. Moreover, the presented approach is relatively simple and can be easily incorporated into SHB setups based on pneumatic propelling of the striker. The applicability of the method is demonstrated in this paper with test results for a tempered steel.

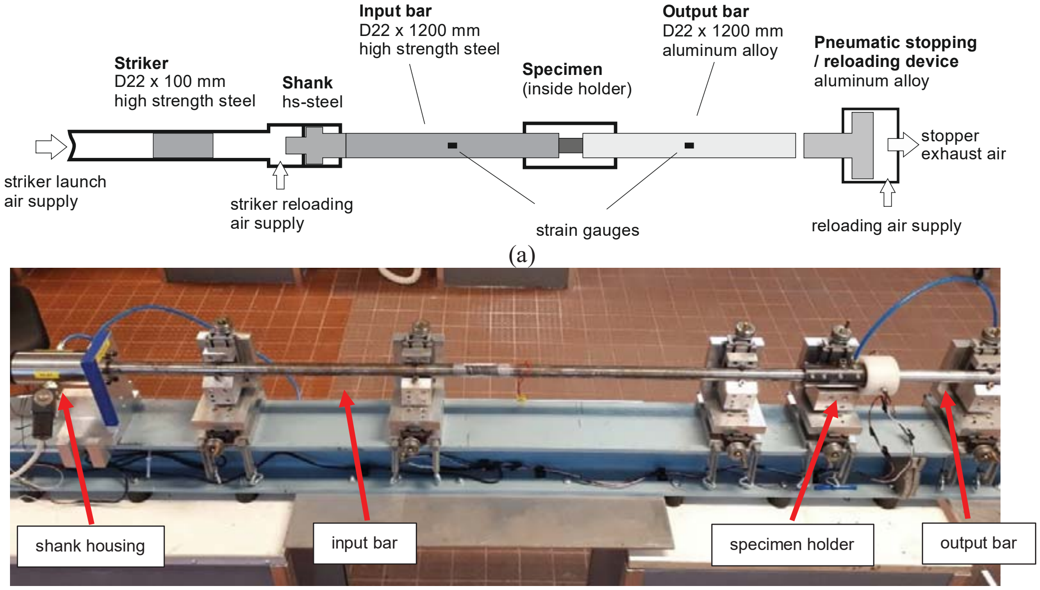
DEVELOPMENT OF THE TEST SETUP

Figure 1 illustrates the main components of the developed fully automatized rapid-reloading SHB setup. One of the key design goals was to maintain the most beneficial characteristics of the SHB technique also in the cyclic loading setup, i.e., to maintain the good control of the loading amplitude (determined by the striker speed) and loading duration (determined by the striker length), as well as to have the capability to accurately measure both the imposed loading as well as the specimen response (facilitated by the input and output bars of the setup). For these reasons, it was decided that the classical SHB configuration, especially the generation of the impact loading via a free-flying uniform cross-section striker, should be changed as little as possible. This, however, introduced challenges in terms of reaching a high enough impact frequency, since in the SHB technique the impact chain "floats", i.e., there is no static support in the axial direction but the whole impact test is governed by the dynamic response of the setup. Even though this feature is beneficial in terms of the analysis of the impact test, it introduces a notable drawback for cyclic tests: after each impact loading the components of the setup (striker, specimen, bars, stopping system) have to be carefully reset back to their original positions with a method that does not interfere with the dynamics of the actual loading event (in conventional SHB tests most of the resetting is carried out manually by the operator).

In the existing SHB setup at Tampere University, on which the modifications were built, the striker is loaded with a vacuum pump connected to the launch tube. This method, although being robust and offering straightforward possibilities for automatization, was considered to be too slow for the current application (with the vacuum pump, the typical loading time is in the order of 10 to 15 seconds). As Fig. 1 and Fig. 2a) illustrate, in the new setup rapid striker reloading is facilitated by placing a special shank piece at the end of the launch tube. The shank and the accompanying electronically controlled relief/reload-valves enable the launch tube to be pneumatically sealed so that compressed air can be used both to propel and reload the striker (with the use of the shank, the striker can be reloaded in less than a second). On the other hand, the shank transmits the mechanical impulse (the loading wave) generated by the striker to the input bar. As shown in Fig. 3, the shank introduces some distortion to the loading wave in the form of a stepwise "tail". The tail, which is absent when the shank is not used, is formed by the changes in the cross-sectional area within the shank, which introduce partial reflection and transmission of the elastic wave, as it passes through the shank. This "ringing" is unavoidable, since the mechanical and pneumatic design inevitably necessitates some geometrical discontinuities in the shank. However, in the current design these disturbances are rather successfully minimized. In effect, the impact loading generated by the rapid-reloading system differs only little from the loading generated by the conventional system. As can also be seen in Fig. 3a), the shape and amplitude of the loading pulse generated by the striker impact can be accurately numerically predicted based on the geometry and elastic material properties of the setup by using either simple one-dimensional linear elastic stress wave theory [1], or the linear elastic finite element method, such as the Abaqus Explicit FE solver.

The second main challenge, i.e., automatization of resetting the bars and the specimen between the consecutive impacts was solved with the pneumatic stopper/resetting-device shown in Fig. 2b). The device consists of a two-stage piston assembly connected to the end of the output bar. The piston assembly is surrounded by a cylinder, which is rigidly fixed to the support structure of the test setup. At the end of the cylinder there is a narrow exhaust channel, through which air can escape as it is being pushed by the piston assembly at the end of the impact test. The two-stage construction of the piston assembly with inner and outer pistons is designed to allow for using the same stopping device for different test setups (in the case of a larger object to be stopped, the two-stage piston assembly would be replaced by one solid piston). The exhaust channel in the cylinder is connected to ambient pressure via an orifice. In addition, the exhaust channel is connected to the high-pressure supply via an electronic valve, which allows for moving the stopper piston back to its initial position. As can be seen in Fig. 2b), the piston motion in the reloading direction is controlled by a spring-loaded flange. During reloading with compressed air, the springs are compressed allowing the piston to travel 5-10 mm beyond its zero position. As the compressed air supply is closed, the springs relax and push the piston back to its zero position. This motion is the key feature of the resetting mechanism: the stopper piston pushes the bars and the specimen back to their initial position, and then retracts to a safe distance so that the dynamic response of the test setup during the impact event is not interfered by the stopping mechanism.

The pneumatic launch system was already in the original setup fully digitally controlled with electronic pneumatic valves and a pressure gauge connected to a PC. This facilitated a rather straightforward conversion of the setup to fully automatized operation. In short, the setup operates in a simple loop, which involves 1) preparing for the striker launch by checking that the test setup components are in place (based on optical sensors) and verifying that the air reservoir is at the correct launch pressure, 2) opening and closing the striker fire valve in a rapid succession, and 3) reloading the striker and resetting the bars and the specimen, as described above. The launch air reservoir is constantly connected to an external air supply through a manual pressure regulator, so that re-pressurizing begins immediately after the fire valve is closed. In practice, the above described sequence of events can be carried out in approximately 2 seconds, thus giving an impact rate of ~0.5 Hz, as illustrated in Fig. 3b).



(a)

(b)

FIGURE 1. a) schematic illustration of the main components of the developed fully automatized rapid-reloading SHB setup (not in scale), and b) photograph of part of the test setup showing the shank-housing, the input bar, the specimen holder as well as part of the output bar.

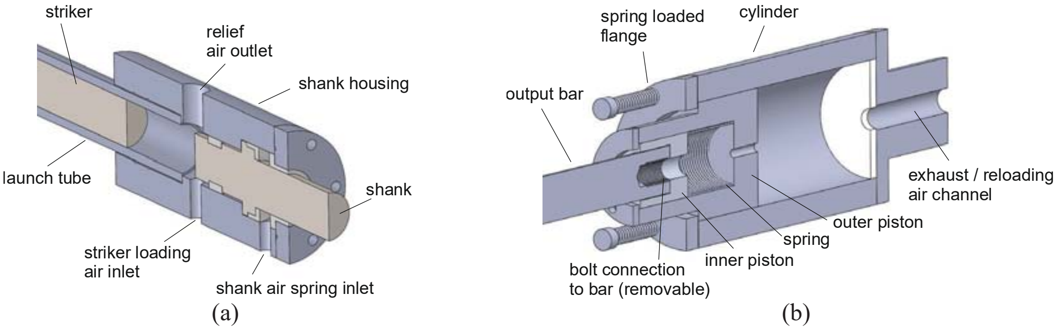


FIGURE 2. A CAD-model (cut section) of a) the shank used to pneumatically seal the launch tube end and to transmit the momentum of the striker to the input bar, and b) the pneumatic stopping/resetting-device. The specimen holder used in the test cases is shown in Fig. 4.

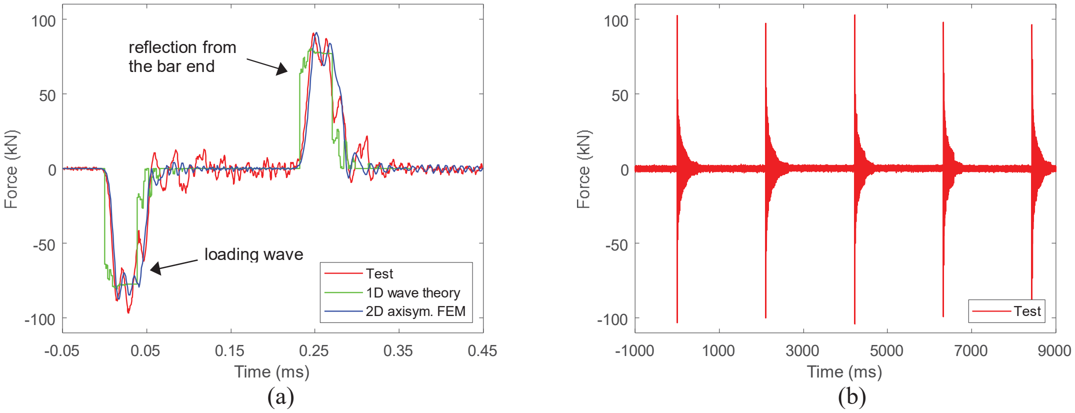


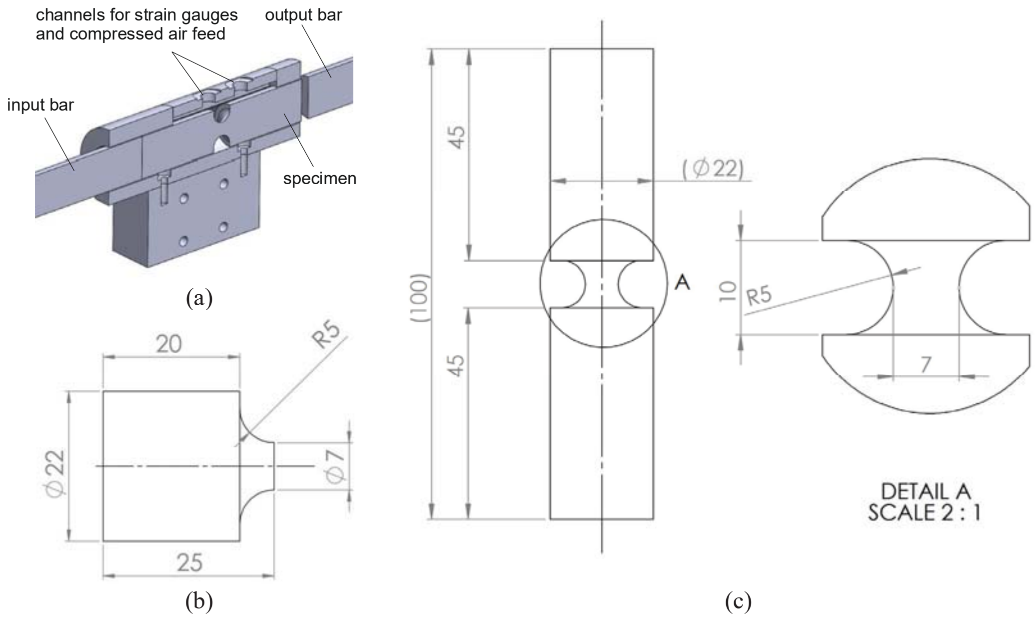
FIGURE 3. Example data for the loading characteristics of the setup (test data shown for a setup comprising only the input bar and the stopping mechanism): a) high sampling frequency record of a typical loading wave and its tensile reflection alongside with numerical predictions based on linear-elastic 1D wave theory and 2D axisymmetric finite element simulation, and b) cyclic loading at ~0.5 Hz with a striker speed of 12 m/s.

EXAMPLES OF IMPACT FATIGUE TESTS

In this section, the applicability of the above described method is demonstrated with cyclic impact loading measurements carried out on a tempered steel alloy 42CrMo4. Two different types of impact loading induced fatigue cases were considered: a) direct damage on the impact surfaces, and b) local cyclic compression/tension loading caused by the dynamic effects of macroscopic compressive loading. Fig. 4a) presents the specimen holder used in both types of tests, while Figs. 4b) and 4c) show the different specimen geometries used in the tests. Both geometries were prepared by mechanical turning from the test material supplied as a D22mm bar. The specimen geometry used in the first case study, i.e. the “contact surface fatigue”, is a cylindrical “dog-bone” specimen cut in half in the midlength. The purpose of the large diameter transition sections is to facilitate good alignment of the specimen halves, and to limit the loading of the input and output bars while providing large contact pressures on the actual test surfaces. In practice, each striker impact in this test mode is similar to a classical SHB test with a single-piece specimen of uniform cross-section sandwiched between the input and output bars, and the purpose of the specimen holder is only to provide lateral support and alignment for the specimen halves. Furthermore, in terms of the wave motion in the setup, the “contact surface fatigue” experiment is similar to a conventional SHB test, which facilitates a straightforward measurement of the contact surface pressure during the impact event, as shown in Fig 5. a). An example of the contact surface damage generated during a cyclic impact test is shown in Fig. 5b). This particular specimen was impacted 4300 times, after which a cross-sectional sample was prepared from it and inspected with a scanning electron microscope. On the impact surface, material removal by near-surface lateral cracking, microscopic plastic deformation near the cracks, and white-layer formation on the surface can be observed.

The second case, i.e. the “vibrating specimen”, differs to some extent from the conventional SHB testing. The specimen geometry used in this test is also based on the cylindrical dog-bone, but the dimensions of the transition sections are selected so that back-and-forth wave motion (“ringing”) is introduced in the gauge section after a single impact on the front end of the specimen. Also in this case the test setup consists of the input and output bars with the specimen placed between them. However, in these tests the output bar is retracted before the impact to a distance of 5 mm from the specimen. This allows the specimen to move in an oscillating manner before hitting the output bar. This “ringing” leads to a series of compression/tension-loadings of the gauge section of the specimen, as illustrated in Figs. 6a) and 6b). It should be noted that a linear elastic finite element analysis indicates that the lowest natural frequency for this specimen type, when made from steel, is around 15 kHz, i.e., 15 full cycles in a millisecond. This corresponds well with the periodic oscillations in the experimental data shown in Fig. 6b). It should also be noted that in this test mode, the effective number of fatiguing cycles is much higher than the number of impacts, as every impact produces a large number of reverberations in the gauge section of the specimen, although at reducing amplitudes due to the decay of the loading signal. The data reveals also lower frequency oscillations in the strain gauge data, which are probably due to the plastic deformation taking place in the gauge section. As can be seen in Fig. 6a), the actual loading event is followed ~15 ms later by a second loading event. This is due to the dynamic characteristics of the stopping device, which causes a rapid deceleration of the specimen and reversal of its velocity, and thus a “bounce-back” of the specimen against the input bar. This is an artifact of the experiment, which could be solved by fine-tuning the stopping device. However, in the present case, the secondary loading is similarly to the actual loading repeatable and can be included in the analysis of the loading history of the specimen.

In order to preserve the fracture surfaces in the “vibrating specimen” experiment, the following method is used to monitor the condition of the specimen between the consecutive impacts and to stop the test when the specimen is fully fractured. Compressed air is constantly fed to the specimen holder so that the volume surrounding the specimen gauge section is at a small overpressure. The overpressure is so small that it does not affect the specimen response nor its motion during the test, when the specimen is still in one piece. However, when the specimen fractures, the overpressure pushes the specimen halves away from each other. An optical sensor is monitoring the gap between the specimen and the output bar at the end of each reloading sequence. For an intact specimen, when the output bar is retracted, the specimen does not move, and an open gap is registered by the sensor and the striker is launched. In contrast, when the specimen is fractured into two pieces, the overpressure pushes the specimen piece against the output bar at the end of the reloading sequence, which is registered by the optical sensor and the test is stopped automatically. With this method the specimen can be recovered from the impact test with no ‘postmortem’ loading damage (some in-test damage of the fracture surfaces is inevitable, since only the final failure of the specimen can be detected with this method). An example of the fracture surface of a tested specimen is shown in Figs. 6c) and d). As can be seen, the fracture surface is composed of areas created by fatigue crack propagation and of the final overload failure in the center area of the specimen cross-section. It is also noteworthy that in a closer inspection, large areas of the fracture surfaces appear damaged by the two contacting surfaces hitting each other before the final fracture. As noted above, in this kind of loading mode this damage type is unavoidable.

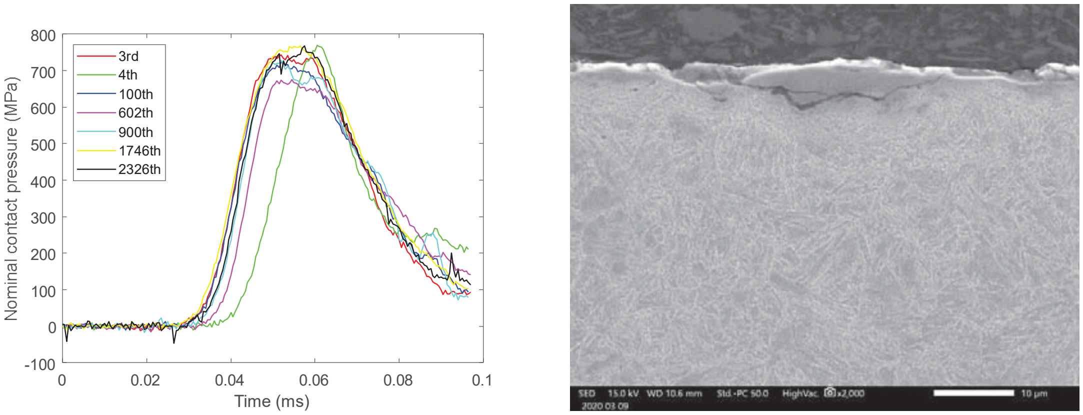


(a)

(b)

(c)

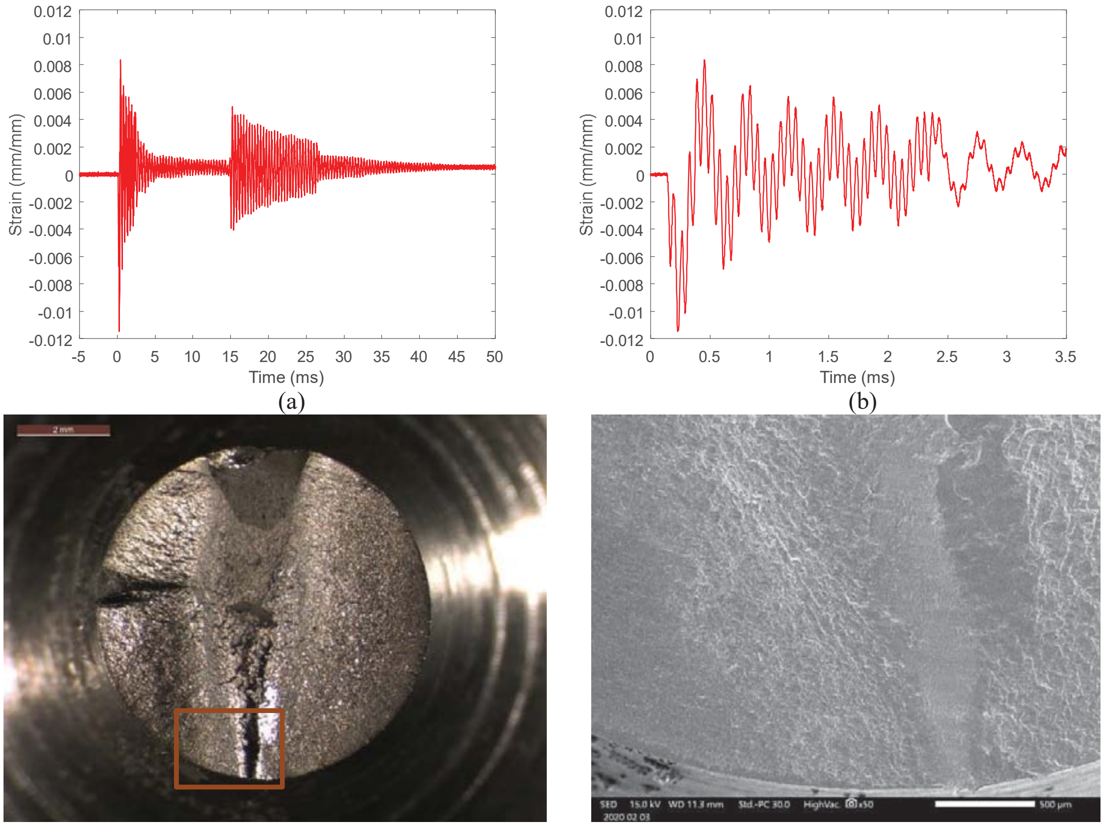
FIGURE 4. a) a CAD-model (cut section) of the specimen holder used in the experiments, b) drawing of the "contact surface fatigue" specimen composed of two symmetrical halves, and c) drawing of the "vibrating specimen" used for studying the cyclic compression/tension loading introduced by impact loading.



(a)

(b)

FIGURE 5. Impact fatigue test carried out with the "contact surface fatigue" specimen: a) examples of the time-history of the nominal contact pressure during the impact (determined from the stress wave measured from the output bar), striker speed 7 m/s, and b) scanning electron microscope image of the cross-section of the impact surface after 4300 impacts (the scale bar denotes 10 µm).



(a) (b)

(c) (d)

FIGURE 6. Impact fatigue test carried out with the "vibrating specimen": a) typical record of the signal from a strain gauge mounted on the specimen gauge section, striker speed 7 m/s, b) zoom in on the signal recorded from the early part of the loading, c) stereomicroscope image of the fracture surface (specimen failed after 313 impacts), and d) scanning electron microscope image of the area highlighted with the rectangle in c).

CONCLUSIONS

In this paper, an impact fatigue testing method based on the Split Hopkinson Bar (SHB) technique is presented. The method is based on the modification of a conventional striker based SHB setup, into which a rapid reloading and automatized specimen/bar resetting capability was built. In the current state, the device is capable of carrying out cyclic impact loading at a rate of 0.5 Hz with full control of the loading amplitude and duration, as well as accurate measurement of the specimen response. The usability of the method in low cycle impact fatigue studies is demonstrated with two test cases. The first one is related to contact surface fatigue, while the second case is related to compression/tension cyclic loading caused by impact-induced elastic wave reverberations within the specimen. Both cases show that well-controlled impact fatigue studies can be carried out with the SHB technique with rather straightforward modifications to the conventional test arrangement. For future studies, it is worthwhile to consider means of increasing the impact frequency by converting the pneumatic system used here to a hydraulic one. In addition, it is foreseen that the characteristics of the impact induced cyclic loading of the specimen (amplitude, mean load, number of cycles) can be tailored to a given case by changing the geometry of the specimen and thus controlling the reverberating wave motion in it.

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