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MECHANICAL COUPLING DEVICES TO VARIOUS TYPES OF VEHICLES UNDER CYCLIC LOADING

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ABSTRACT–The paper focuses on experimental approaches for selected mechanical coupling components to type-approval. The obtained results have enabled to present behaviour of the following tested objects: ball (with homologation certificate), transport platform, and rigid drawbars under cyclic loading. They follow details of tests to components made of typical and high strength steels as well as various kinds of aluminium alloy, such as mounting systems, parameters of loading signals, the procedure for assessing the quality of the elements after tests as well as fatigue and fracture zones, and reasons to cracks occurrence due to loading cycles performed. Moreover, they show advantages and disadvantages of the experimental approaches.

KEY WORDS : Stand test, Mechanical coupling device, Component, Fatigue, Cyclic loading, Crack, Fracture, Requirements

1. INTRODUCTION

Mechanical coupling devices (Figures 1, 2 (b), 3) are a special kind of automotive component used for connecting towing and towed vehicles. They are used in salon and estate cars, pick-up trucks, terrain vehicles, Sport Utility Vehicles (SUV) as well as tow trucks, which help to move various kinds of vehicles from roads after a car accident. During this, mechanical coupling devices are subjected to cyclic loading with various amplitude and frequency depending on the relationship between the mass of the cars coupled and road quality. It leads to different values of stress i.e. low and high in the element considered. Therefore, this kind of component is tested under cyclic loading based on the knowledge of mechanical engineering, strength materials, and regimes of the UN Regulation No. 55 (UN Regulation No. 55, 2020; Weiland, 2006; Mircea *et al.*, 2016).

The research field indicated as a first creates requirements for the mounting system, which should be designed to reflect the operational one. The welds inspection is also conducted according to the rules of mechanical engineering.

The strength of materials enables one to predict the value of stress and compare it with the mechanical parameters of materials used for the manufacturing of a tested component. This also determines the values of the number of cycles, which take of 2×10^6 and 3×10^6 for the steel and aluminum alloy, respectively. The UN Regulation No. 55 bases on conclusions of mechanical engineering and strength of materials, which are submitted in Appendix No 6 (UN Regulation No. 55). This section directly formulates a value of the amplitude of cyclic force based on technical features of a mechanical coupling device, as well as recommends the executive signal shape used to control of testing machine i.e. sinusoidal function. An amplitude value is determined

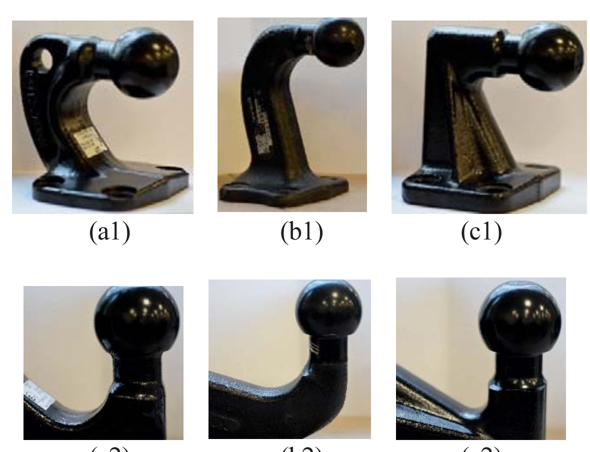

Figure 1. Types of coupling ball with different shapes of arm: (a1, a2) radial, (b1, b2) linear-radial relation shape, (c1, c2) trapezoidal-linear sections.

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(a)

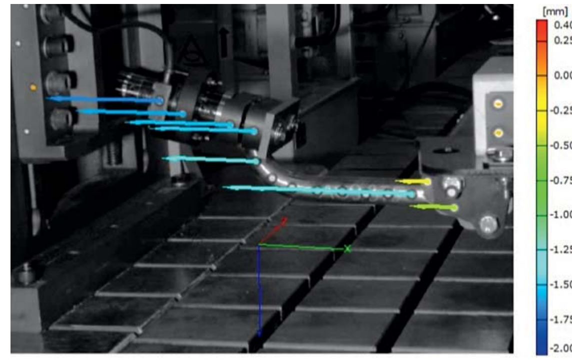
(b)

Figure 2. Swing frame with a coupling system on anti-vibration platform: (a) General view; (b) Connection of actuator with a coupling ball (Szymczak *et al*., 2019).

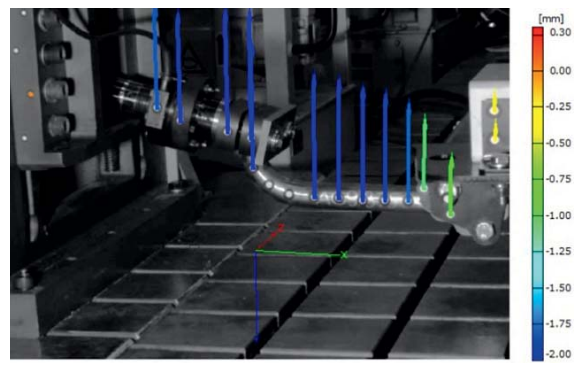
by the ratio 0.6 being the relationship between the amplitude to dynamic force D of a mechanical coupling device. A frequency value is limited by the 30 Hz. The orientation of the vector force is determined by the angle of ± 15 °.

The angle is related to the loading components i.e. horizontal and vertical forces and bending moments in both perpendicular directions, (UN Regulation No. 55, 2020; Weiland, 2006). Its sign is the resulted in the relationship between the center of a ball and the highest attachment point of a mechanical coupling device. If the ball is below the point for mounting, the angle takes the positive value, in the opposite case, the negative one assigns (UN Regulation No. 55, 2020). An incorrectly defined sign of the angle influences the bending moment.

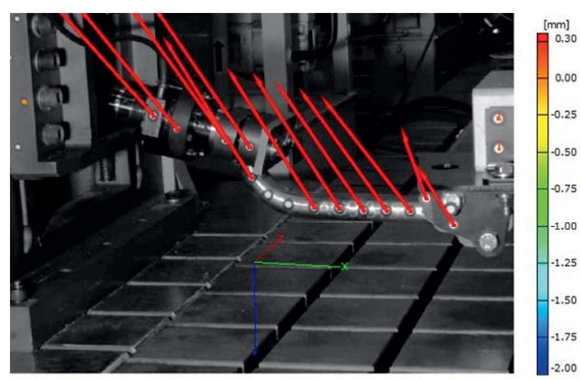
Ratio R, as the quotient of minimum to maximum value of stress/force directly follows a component behaviour under fatigue, giving a number of cycles to fracture. The UN Regulation No. 55 has defined the value on - 1, concerning the lowest value of the number of cycles to fracture in comparison to the ratio's value within the range above - 1 up to 0 at the same value of amplitude and



(a)



(b)



(c)

Figure 3. Displacement components in 3D coordinate system: (a) 0x (Brodecki *et al.*, 2018); (b) 0y; (c) 0z captured in testing a coupling ball dedicated to SUV vehicle by means of the PONTOS 5M DIC system.

frequency of cyclic force signal (GRRF Working Group ECE R55 Agri, 2014).

Research groups directly connected with the automotive industry have performed experiments on mechanical coupling devices under cyclic loading (Mircea *et al.*, 2016; Brodecki *et al.*, 2018; Szymczak *et al.*, 2019). They have used various types of stand platforms with T-slots and facilities for mounting systems (Mircea *et al.*, 2016; Szymczak *et al.*, 2019). Servomotors possess a different loading capacity and a range for orientation of the vector force. The loading signal is conducted by means of a digital controller and closed-loop feedback for comparison of the executive and reference functions.

Various types of mechanical coupling devices are tested. Among them worth noticing the following: coupling balls, (Zatočilová *et al.*, 2014; GRRF Working Group ECE R55 Agri, 2014; Szymczak *et al.*, 2019), rigid drawbars (Mircea *et al.*, 2016), and towing eyes. A number of examinations for the components is different and strongly relates to the requirements of branches of industry. In this case worth emphasising the coupling balls are usually tested for the automotive industry (GRRF Working Group ECE R55 Agri, 2014; Zatočilová *et al.*, 2014; Szymczak *et al.*, 2019). The drawbars are related to the agricultural industry and therefore this branch makes efforts for capturing data from testing of the element (Mircea *et al.*, 2016). The towing eyes are the most universal component of mechanical coupling devices and therefore their results are required by all branches of the industry, containing military ones.

Mechanical coupling ball behaviour under static loading at different levels can be captured by means of photogrammetric technique collected in the TRITOP system, while a model of the tested object can be elaborated using 3D scanner Atos III Triple Scan. This allows validating FEA results and improving the modelling process because of the very small difference between both methods can be indicated of 10 % (Zatočilová *et al.*, 2014). This stage can be supported by a wide analysis by means of advanced software for FEA, taking stress distribution in selected regions due to fatigue as well as welding and forming processes (Lee *et al.*, 2017).

The behaviour of this class component under cyclic loading can be followed by means of the PONTOS 5 M DIC system, Figure 3 (Brodecki *et al.*, 2018). These data enable to follow the component tested behaviour indicating it's the weakest and the strongest regions for elaborating the stiffness map. On the basis of these data, the component can be improved up to positive results and approval, reducing time for investigations. In this measurement stage for deformation determining the DIC method employed in VIC-3D is successfully applied (Zhan *et al.*, 2019).

In the case of road tests, an influence of technical features (with and without suspension) of a mechanical component, as well as a response in a form of the following physical quantities: spectrum of frequencies, the maximum amplitude of vertical acceleration root, mean square of the accelerations respectively are captured (Nedelcu *et al.*, 2015). At stochastic data from a lot of operational stages of vehicles, containing repair and maintenance the transition probability matrix is employed (Kozłowski *et al.*, 2020). This subject can be supported by the synthesis of maintenance vehicle driving if manufacturers estimate the lifetime of an operating component (Puchalski *et al.*, 2020).

With respect to the number of applications, the coupling balls are used very often, because they cover almost all types of cars, containing special vehicles such as tow trucks. In this case, the component is jointed to the swing frame having the fork and actuators (Szymczak *et al.*, 2019). Using this kind of element the whole object can be tested reaching the strongest and weakest regions of the frame up to fracture or a required number of loading cycles. In the case of crack occurrence, this kind of data is used for determining the reasons. It is conducted based on fractography analysis, hardness tests as well as microstructure observations by means of SEM and LM techniques.

Worth to emphasize that, the number of variants of mechanical coupling devices is not limited and they require different mounting systems as well as the selection of regions for inspection. Therefore, the aim of the paper is concentrated on discussing selected details of experiments performed on various kinds of mechanical devices for connection of vehicles and results collecting advantages and disadvantages.

2. DETAILS OF EXPERIMENTS

All tests were conducted by means of a huge anti-vibration platform with "T" slots having dimensions of 9 × 3 [m]. Stators and supports were used for mounting the tested components (Figures 4 ~ 7). They were employed at various configurations. In the case of a typical mechanical coupling device such as the coupling ball for the SUV from

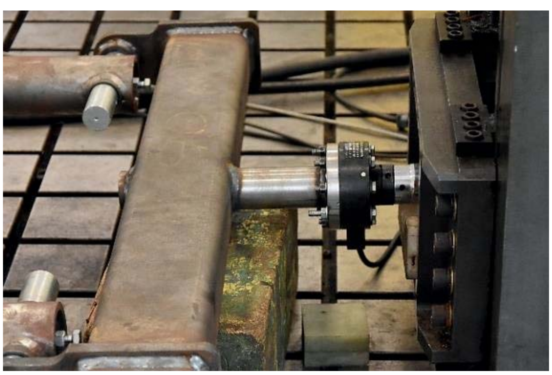
(a)

(b)

Figure 4. Coupling ball: (a) With a beam and supports to SUV from the EU; (b) On adapter to SUV from the USA.

the European Union, their outside zones were used (Figure 4 (a)). The inner regions of the elements are taken to test this kind of SUV component coming from the USA (Figure 4 (b)). Rigid drawbars were mounted by means of the same stations but their upper sections were directly used, especially if the tested element contained two subcomponents under different horizontal coordinate planes (Figure 5 (a)).

(a)



(b)

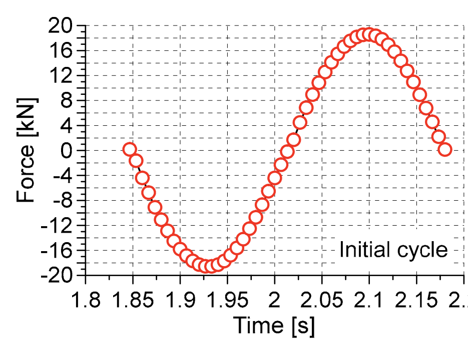
Figure 5. Rigid agricultural drawbar: (a) On a platform before test; (b) Adapter of the component for connection with a servomotor.

Figure 6. Swing frame (material: S235 steel) with a fork, actuators and A50-X class ball coupled with a testing stand station.

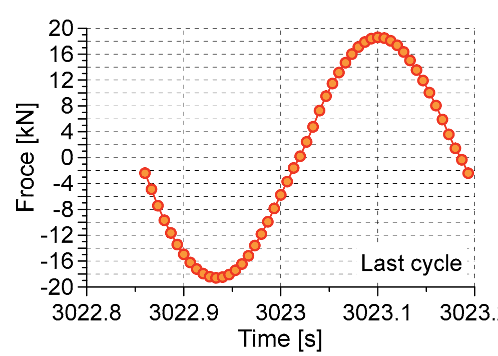
Additional, in this case, the coupling manner is different because a special beam with a flange region is required (Figure 5 (b)). This follows the operational features between the drawbar and tractor.

Swing frames (Figure 6) required more stations than in the case of a mechanical coupling device for SUV vehicles (Figure 4) and agricultural machines (Figure 5). It is the result of the vehicle's frame, which should be delivered with the component examined. This was used with respect to testing at the same conditions as they will appear during exploitation.

Figure 7. Transport platform (Material: 1050 aluminium alloy) with a coupling function of vehicles supported by stators and connected with an actuator before test.



(a)



(b)

Figure 8. Course of cyclic force at: (a), (b) initial and last cycles of test i.e. at 2×10^6, respectively.

Transport platforms were also tested using a vehicle frame, which has played the main subcomponent role to mount the tested object (Figure 7). In this case, the distance between the lowest region of the examined element and the anti-vibration platform was taken into account because the component was subjected to significant displacement under cyclic loading.

The testing procedure contained the following stages: controlling the servo-hydraulic actuator under a force signal, performing the initial test, checking the record system, and conducting the final experiment.

An amplitude of cyclic force was determined by 0.6 D, while a frequency was strongly related to the stiffness of the components tested (Figure 8, Table 1). In the case of the short and rigid element, a value of frequency was equal up to 10 Hz (Figure 8). When the behaviour of a tested object expressed movement, as an effect of its construction, then the value of the physical quantity was smaller, reaching 5 or 3 Hz, only (Table 1). The same experimental observations were captured in the case of the agricultural rigid drawbar (Figure 5, Table 1) and swing frame to tow truck (Figure 6, Table 1).

Loading parameters used for examining the different kinds of components enable to follow values of frequency as the key parameter for concluding on the stiffness of the tested object (Table 1). In the case of compact elements such as a coupling ball, mechanical coupling adapter, a value of frequency can be determined by of 5 ÷ 7 Hz, while in the opposite case the two times smaller value is required. The final stage of the tests should be focused on elements and regions for inspections. Usually, this is done taking subcomponents, welds and screws as well as mounting manner.

3. RESULTS

3.1. Cracks and Fractures

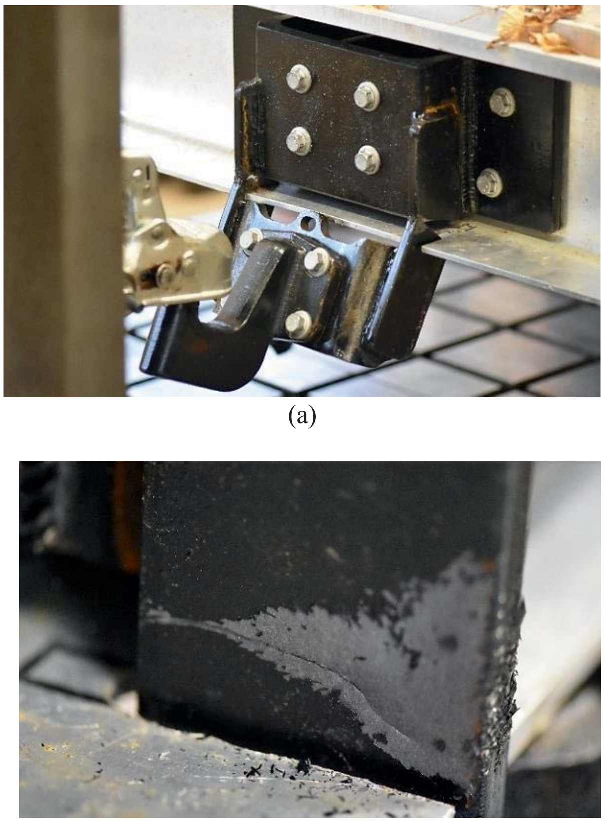
The behaviour of mechanical devices was strongly related to material type, component geometry, stiffness distribution and weld quality (Figures 9 ~ 13). This can illustrate a crack path in the steel component even the others are made of the aluminium alloy (Figure 9). Based on this data some difficulties related to the designing stage of the component are clearly evidenced. The reasons for the fracture occurrence can be avoided in the analysis of stiffness and stress distribution, taking mechanical parameters of all materials and geometry of elements used, respectively.

As it was investigated an influence of stiffness on the fracture occurrence was visible in components made of the aluminium alloy (Figure 10) because they were directly connected with another element for coupling. Therefore, this mechanical feature should be followed in details, indicating the weakest region. In the opposite case, the hair cracks (Figures 10 (a), (c), (d)), as well as the bigger ones in the horizontal and radial arrangement (Figure 10 (b)), can occur. With respect to the operational conditions of the component the mentioned cracks had a different meaning because the hair cracks were very difficult for inspection and they can appear in many exploited vehicles leading finally to the fracture. They can be revealed by means of macro-photography (Figure 10 (a)) or loading stage (Figure 10 (d)); therefore the first mentioned technique is recommended for applying in the inspection processes of a vehicle. The major cracks precede the final fracture and in opposition to the hair ones they are very easy for evidencing if the inspection is regularly conducted.

Another reason for the fracture is presented in Figure 11. In this case, the component breaking appeared although the

Table 1. Components, loading conditions and final results: D – dynamic force, S – static load, Ampl. – amplitude (symmetrical loading cycles), f – frequency, LNC – limited number of cycles in the test.

Component	Technical parameters		Cyclic force signal		LNC	Details of inspection on permanent deformation and cracks
	D [kN]	S [kg]	Ampl. [kN]	f [Hz]		
SUV mechanical coupling device / EU	10.9	90	6.54	7	2×10^6	Subcomponents, screws and welds as well as a coupling ball. Positive result.
SUV mechanical coupling device / USA	20.5	350	12.3	5	2×10^6	Rectangular tube, welds and region for bolts as well as screws. Positive result.
Agricultural drawbar	15.8	-	15.8	2	2×10^6	Elements, screws, welds. Negative result due to cracks.
Swing frame	31	375	18.6	4	2×10^6	Subcomponents, welds, screws and region for coupling, Positive result.
Transport platform	23.5	250	14.1	3	5×10^5	Coupling region, screws, welds, mounting manner and subcomponents. Negative result due to cracks.



(a)

(b)

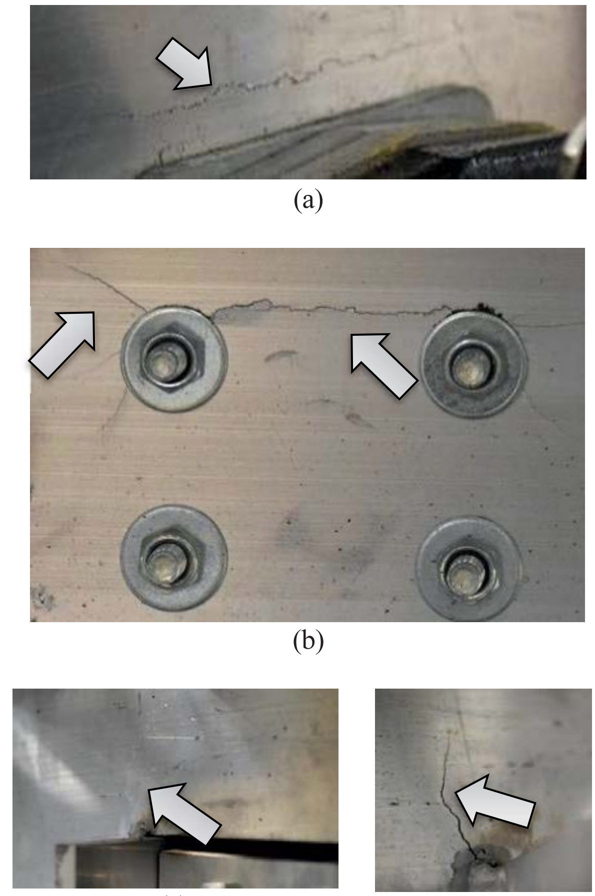
Figure 9. Fracture of the support for a coupling ball after number of 1.7 × 10^5 cycles: (a) General view; (b) Crack trajectory: Amplitude = ± 14.1 kN, Frequency = 3 Hz.

element has possessed the approval certificate. As it can be noticed the number of cycles was significantly smaller than 2 × 10^6 - required for accepting its quality under cyclic loading. This result is connected with the kinematics of the tested object (transport platform, Figure 7) influencing a stress state and its value in comparison to the mounting and loading conditions used it the approval test to the certificate.

Welds are also directly related to the fractures because the cracks began in these regions independently on the material kind (Figures 10 (c), (d); 12, 13). The reasons were connected with the quality of weld (Figures 10 and 13) or Heat Affected Zone (HAZ) (Figure 12). As it was obtained in the fatigue test of the rigid drawbar the cracks in the weld can appear if the required number of cycles i.e. 2×10^6 was reached (Figure 13). Therefore, the weld inspection should not be ignored even the number of loading cycles are satisfied.

3.2. Data to Positive Assessment

A final assessment of the technical quality of the examined components was conducted based on quantitative and qualitative data collected during testing as well as at



(a)

(b)

(c) (d)

Figure 10. Cracks in a transport platform made of aluminium alloy: 6061 (a) and (b) zone for mounting a coupling ball – number of cycles 1.1 × 10^5, (c) and (d) hair crack in 6005 at unloaded and loaded of 8 kN states – number of loading cycles 2.4 × 10^4, respectively.

inspection after the experiment, respectively. The first mentioned stage was connected with variations of the control signals and the object response in a form of displacement versus time (Figure 14).

This should be followed at a few sections of the loading process taking the initial (Figure 14 (a)) and final (Figure 14 (b)) ones. In the quality assessment, the differences in amplitude, as well as maximum and minimum values, were analysed taking technical features of the tested component such as bolts and screws for theirs loosens as an effect of the cyclic loading applied. A small difference between the initial and final courses of displacement has indicated a positive response of the tested component without any cracks or deformation (Figure 14). As it can be noticed in Figure 14, the maximum value of displacement is constant reaching - 45 mm while the smallest one is higher by 1 mm compared to the initial cycles. This difference is resulted by the exploitation of the tested component under cyclic force

(a)

(b)

(c)

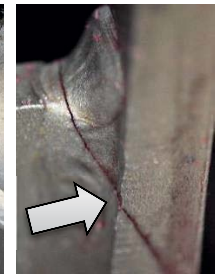
Figure 11. Fracture of the coupling ball at number of loading cycles 1.7 × 10^5: (a) General view; (b) Ball; (c) From left – fatigue region, fracture zone and tearing section, cyclic force parameters: Amplitude = ± 14.1 kN, Frequency = 3 Hz.

(a)

(b)

Figure 12. Crack in HAZ and parent material (S235 steel) of the mechanical coupling device for the SUV vehicle, cyclic force parameters: Amplitude = ± 6.54 kN, Frequency = 10 Hz.

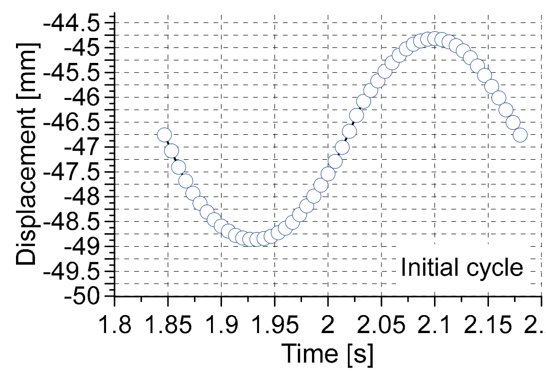
(a)



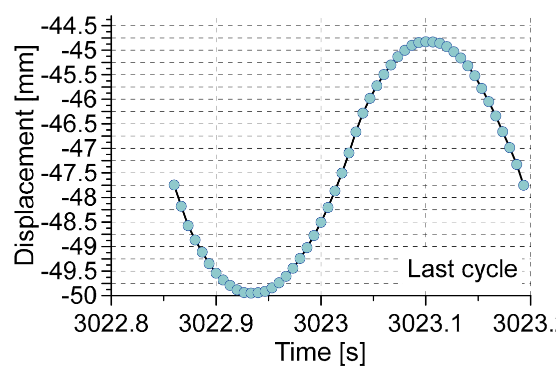
(b)

(c)

Figure 13. Cracks paths in the rigid drawbar after the following number of cycles: (a) 1 × 10^6, (b) and (c) in macrophotography and dye-penetrant techniques, respectively, 2 × 10^6, cyclic force parameters: Amplitude = ± 15.8 kN, Frequency = 3 Hz.



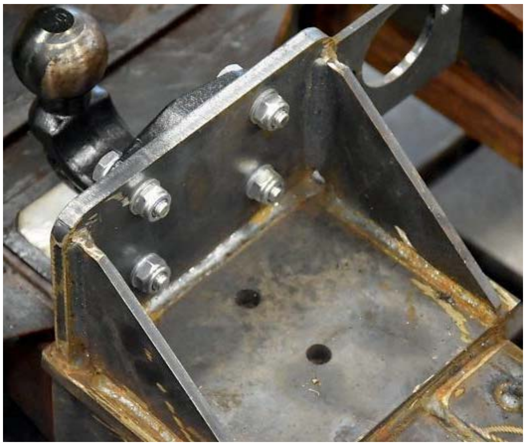
(a)



(b)

Figure 14. Courses of displacement at: (a) Initial; (b) Last cycles of test i.e. at 2 × 10^6.

signal. In the case of cracks or permanent deformation, differences between a displacement signal in the initial and final stages will be several times bigger, expressing a reduction of the stiffness of the examined element. If any significant variations between the signal shape at the beginning and final sections of the test are not indicated then this stage can be introduced to the positive results and



(a)

(b)

Figure 15. Coupling region after 2×10^6 loading cycles: (a) Box support and strength screws; (b) Coupling ball.

(a)

(b)

Figure 16. Joints with welds of a swing frame recommended to a tow truck after 2×10^6 loading cycles: (a) Multi-elements region; (b) Arms reinforced by triangle plate.

subsequently an inspection of the component should be conducted.

This stage as a quality assessment has to be focused on observation of all regions (Figures 15 and 16) of the tested objects and welds and neighbored zones (Figure 17) using the macro-photography technique (Figures 17 (a1) and (a2)) and the dye-penetrant manner (Figures 17 (b1) and (b2)). Results from observations should reflect a technical state of a coupling ball (Figure 15) if even this element is approved because in the case of various types of the swing as well as rigid frames the balls are the integrated subcomponents. Other regions represented by profiles, joint regions and reinforcement zones are also important sections of component for the qualitative approach (Figure 16). Finally, welds and their regions were subjected to inspection at magnification in macro-views (Figure 17 (a)) and dye-penetrant method (Figure 17 (b)). A lack of any cracks or permanent deformation (Figures 15 ~ 17) from the inspection conducted at both methods has enabled us to assign the high quality of the tested component.

(a1)

(a2)

(b1)

(b2)

Figure 17. Welds in the inspection stage conducted by means of: (a) Macro-photography observations (Material: S700MC high strength steel); (b) Dye-penetrant method (Material: S235 steel) after loading cycles of 2×10^6.

4. CONCLUSION

Examination of different types of the components for mechanical coupling has enabled to formulate the following sentences:

(1) Compact mechanical coupling devices can be tested under force cyclic signal with a frequency between 5 ÷ 10 Hz while in the case of other ones a value of this parameter should be reduced two times,

(2) The limited number of cycles for the mechanical coupling devices made of steel is equal to 2×10^6 cycles. In the case of components made of aluminium alloy, the 3×10^6 cycles are required for finishing the test,

(3) Dynamic force value (D), to coupling vehicles by employing a ball mounted on a swing frame of tow truck, was represented by 31 kN. In the case of SUV this value was between 11 kN and 21 kN. The aluminium alloy platform with a coupling ball was designed to towing vehicles up to force value of 24 kN. Nevertheless, this kind of component still requires more fatigue experiments due to lower fatigue resistance of alloy than steel,

(4) Mechanical coupling devices having regions with different stiffness and reflecting kinematic behaviour under cyclic loading demand the most efforts on manufacturers and research groups for capturing positive results,

(5) In the case of the tested objects containing a coupling ball with a certificate of homologation, the inspection should be conducted in all regions of the component examined and the element used for coupling with an actuator,

(6) Every crack in an approved coupling ball is the basis for replacing the used component on the same class element but in the better quality.

Taking into account features of the tests on the mounting systems, cyclic force, and inspection, advantages and disadvantages can be formulated:

(1) Advantages: (a) Force signal in closed-loop feedback control, (b) Operational mounting system, (c) Number of cycles related to taking or exceeding product lifetime, (d) Physical assessment of the quality of the component,

(2) Disadvantages: (a) Large test platform, (b) Multi-functional mounting system, (c) Low frequency of cyclic force signal, (d) Long time to final results.

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