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Original Research

THE INFLUENCE OF ADHESIVE MATERIAL PROPERTIES ON THE IMPACT STRENGTH OF ADHESIVE BLOCK JOINTS

WPŁYW WŁAŚCIWOŚCI MATERIAŁU KLEJONEGO NA UDARNOŚĆ POŁĄCZEŃ KLEJOWYCH BLOKOWYCH

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Abstract

Adhesive joints are becoming increasingly popular in the construction of aircraft and other means of transport. Today, bonding is mainly used in the construction of helicopter fuselages, wings or lifting rotors. The increased popularity of bonding is forcing designers to seek new and improve research methods as well as enhancing the existing test methods which specify the static, fatigue or impact strength of joints. A variety of tests are used to determine the strength of structures, although new ones are constantly being sought so as to be applied more quickly and without specialised equipment. Current testing standards are also being modified in order to speed up and simplify the testing process, resulting in safer structures that use adhesive joints.

The aim of the research presented in this paper was to test whether there is a relationship between the mechanical properties of adhesive materials and the impact strength of adhesive block joints with a cylindrical top element.

Construction steel S235JR, commercially marked wear-resistant steel Raex 400 and 2017A aluminium alloy were used for the manufacture of the samples. From each material, 10 samples were prepared with upper elements of different diameters, namely: 17.8 mm, 12.6 mm and 8.9 mm. A pendulum hammer was used to determine the strength of the adhesive joint against dynamic load application. For the sake of the research, the authors used a modified PN-EN ISO 9653 with a mounted hammer equal to the maximum energy of 15 J.

Lower failure energy was characteristic of samples made from material with a lower value of Young's modulus (aluminum alloy) and from steel with a lower yield strength. The joint failure energy grew with increasing the joint area, which was approximately parabolic.

Keywords: bond, adhesive joint, impact strength, block sample

Streszczenie

Połączenia klejowe są coraz bardziej popularne w konstrukcji statków powietrznych oraz innych środków transportu. Dziś klejenie stosuje się głównie przy budowie kadłubów, skrzydeł lub wirników nośnych śmigłowców. Zwiększenie popularności klejenia zmusza konstruktorów do poszukiwania nowych oraz udoskonalania istniejących metod badawczych określających wytrzymałość połączeń statyczną, zmęczeniową czy udarową. Stosuje się różnorodne badania by określić wytrzymałość konstrukcji, lecz wciąż poszukiwane są nowe, które można stosować szybciej oraz bez specjalistycznego wyposażenia. Także obecne normy badawcze są modyfikowane by przyśpieszyć oraz uprościć proces badawczy co skutkuje zwiększeniem bezpieczeństwa konstrukcji w których wykorzystano połączenia klejowe.

Celem przedstawionych w artykule badań było sprawdzenie czy istnieje zależność pomiędzy właściwościami mechanicznymi materiałów klejonych i wytrzymałością udarową połączeń klejowych blokowych z górnym elementem o kształcie cylindrycznym.

Do wykonania próbek wykorzystano stal konstrukcyjną S235JR, stal trudnościeralną o oznaczeniu handlowym Raex 400, oraz stop aluminium 2017A. Z każdego materiału przygotowano po 10 próbek z górnymi elementami o różnej średnicy, mianowicie: 17,8 mm, 12,6 mm oraz 8,9 mm. W celu określenia wytrzymałości połączenia klejowego na dynamiczne

przyłożenie obciążenia wykorzystano młot wahadłowy. Do badania wykorzystano zmodyfikowaną normę PN-EN ISO 9653 z zamontowanym młotem o maksymalnej energii wynoszącej 15 J.
Niższa energia niszczenia cechowała próbki wykonane z materiału o mniejszej wartości modułu Younga (stopu aluminium) oraz ze stali o mniejszej granicy plastyczności. Energia niszczenia połączeń rosła wraz ze wzrostem powierzchni spoin – w przybliżeniu parabolicznie.

Słowa kluczowe: klej, połączenie klejowe, udarność, próbka blokowa

1. Introduction

Joints made with bond are just as stable and durable as their counterparts made by riveting or welding (Adams et al. 1997). They are used in the production of, for example, lightweight and very strong sandwich composites, which are used, among other things, in the construction of aircraft flight controls such as ailerons, flaps and rudders. Also, wing or fuselage plating is now made using adhesive joints (Higgins, 2000).

The large-scale use of adhesive joints necessitates testing their strength, and while static property tests are well known and widely used (Naito et al., 2012; Grant et al., 2009; Ramalho et al., 2020), certain types of tests are not widespread for various reasons (Casas--Rodriguez, et al., 2007; Goglio & Rosetto, 2008). One type of such tests is the impact test of adhesive block joints performed with a pendulum hammer (Sato 2005) This test provides information about the strength of a joint (or rather an adhesive bond) against a dynamic application of load to joint elements.

The energy of the pendulum is used to destroy a sample while the testing machine software calculates the value of the joint destruction energy, taking into account the part of the kinetic energy used to reject the sample element. The manner in which the upper element is bonded to the block allows the large face of the upper element of the sample to be struck easily (Fig. 1). If the top piece is bonded properly, the hammer strikes parallel to the bonded surface and the load distribution is even across the entire impacted surface of the top piece. However, such an impact is very difficult to achieve in practice. The bonded plate is usually minimally shifted from the lower element of the sample, resulting in misalignment with the pendulum, leading to incorrect results (Adams 2005; Komorek 2018).

The use of a cylindrical top block sample in adhesive bonding impact tests is a way to make them less complicated and independent of incorrectly bonded sample pieces. In a standard test, as mentioned earlier, the main problem is to very accurately bond the upper element to the block (Godzimirski, et al. 2019; Komorek, et al. 2020; Adams & Harris 1996). The use of a cylindrical upper sample element may solve the presented problem, however the phenomenon, which is likely to occur in this type of testing, is plastic deformation of the impacted element. In a standard sample, the hammer strikes the rectangular side of the sample, i.e. the energy is transferred onto a large area and the element does not deform plastically. With a cylindrical element, the energy is transferred linearly, which can lead to plastic deformation of this sample element (Adams 2005; Komorek 2018).

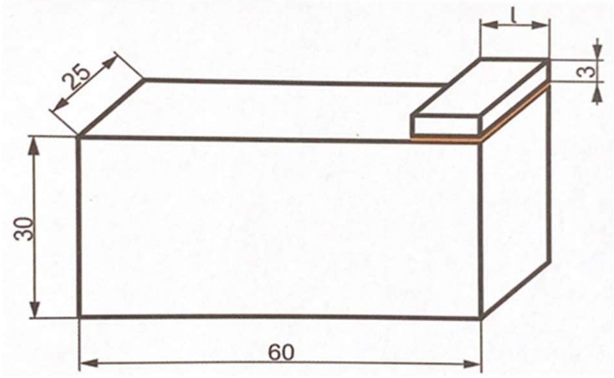

Fig. 1. Diagram of the examined object, undergoing impact testing of adhesive bonds in accordance with ISO 9653:1998

The aim of the examination was to check whether the cylindrical upper parts of the samples, to which the load is applied, deform plastically. The elements were made from different materials. Each type of material served to prepare elements of three different diameters. Each material was characterized with yield strength.

It is assumed that some of the elements will deform plastically during the examination. This deformation consumes some energy which is not subtracted from the indicated failure energy. In this way, the impact strength of the joint is overestimated. In the research, the authors want to prove that decreasing the diameter of the impacted piece and increasing the yield strength should result in the absence of plastic deformation of the impacted element, If the authors' expectations are confirmed, the use of samples with smaller upper elements will significantly increase the reliability of the obtained results, which will increase the usefulness of this research method.

2. Research methodology

In order to carry out research aimed at checking the authors' assumptions, it was decided to adopt the following research scheme: - preparation of the lower elements of the samples (using the water jet cutting method), preparation of the upper elements of the samples with three different diameters and from three different materials (laser cutting method), - preparation of the surface of the glued elements (abrasive blasting and degreasing), making glue joints, removing glue flashes, impact testing of all prepared joints, visual observation of plastic deformations of sample elements.

Cylindrical shapes were used as the upper elements of the samples to test the impact strength of block joints. The diameters were as follows: 17.8 mm, 12.6 mm and 8.9 mm. They were all 3 mm thick (Fig. 2), and they were made of three different materials - S235JR and wear-resistant steel Raex 400 as well as 2017A aluminium alloy.

Fig. 2. Upper elements of block samples with diameters of 17.8 mm and 12.6 mm

The diameters of the upper elements were selected in such a way that the area of the smallest fittings constituted 1/2 surface area of the average piece and 1/4 surface area of the largest piece (the surface area of this piece was equal to 250 mm^2). The material properties of the sample elements are given in Table 1.

Table 1. Material properties of bonded pieces

	Yield stress $R_{p0,2}$, (MPa)	**Tensile strength, (MPa)**
Raex 400	1,000	1,250
S235JR	235	410
2017A	240-260	350-390

Each of the upper parts of the samples was blasted in a sandblasting chamber. Dried quartz sand (Airpress, Poland) (quartz content above 97%) with a grain size of 0.1-0.5 mm was used as the abrasive medium. This treatment was intended to mattify and create a uniform surface for gluing.After cleaning by abrasive blasting, the sample elements were immersed in 99% isopropyl alcohol (Archem, Poland) for 5 minutes and then washed with a brush to remove dirt and degrease from the adherends' surfaces. After washing, the sample elements were placed in a laboratory drying chamber at a temperature of 40°C for 2 minutes to evaporate the isopropyl alcohol.

The lower elements to which the cylindrical elements were bonded were cuboidal in shape, measuring 60x25x30 mm. They were made of steel and aluminium alloy, depending on the exploited upper sample element. The bottom elements were prepared for gluing using the same method as the upper elements.

Loctite Hysol EA9464 adhesive was used as the adhesive material. Loctite Hysol EA 9464 is manufactured by Henkel Corporation, USA. Loctite Hysol 9464 formula ensures short setting and hardening times. Parts can be moved after curing for 3-4 hours at 22 0C. Maximum strength properties are achieved after curing for 3 days at room temperature. The shear strength (adhesive hardened for 7 days at 22°C) of connections between shot-blasted structural steel elements is 22 MPa, and of connections between aluminum elements, ground with sandpaper (P400A grain) - 18.2 MPa. The peel strength when bonding elements made of structural steel is 10.5 N/mm, and when bonding etched aluminum elements it is 7 N/mm (Technical sheet of Loctite 2003).

The samples were bonded in batches of 10 under identical conditions. EA 9464 adhesive is a two-component adhesive, and the ingredients are contained in a double cartridge. A special gun for this type of cartridge is used to squeeze the glue ingredients from the cartridges. The gun allows you to simultaneously squeeze out equal amounts of both ingredients from both cartridges, so that they can be mixed together in a 1:1 ratio. The glue was squeezed onto a clean sheet of paper through a special mixing nozzle attached to the cartridge. Then the thin layer of adhesive mixture was applied with a spatula to the joining elements. The authors assembled the samples by placing the upper element in the middle of the lower element, at its very edge. When assembling the sample elements, auxiliary marks on the lower element and a magnifying glass were used to determine the correct positioning of the elements. (Fig. 3).

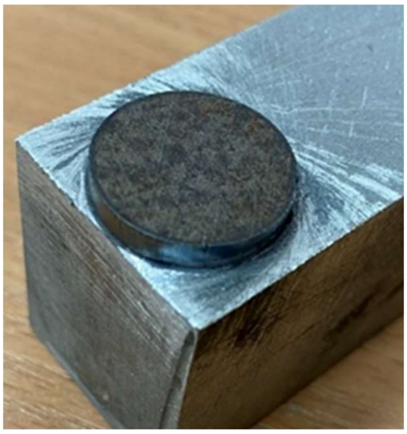

Fig. 3. Test sample

After an assembly, the samples were subjected to a load that produced a joint thickness of approximately 0.10 mm in each piece. The joints were hardened at room temperature for 7 days, applying constant pressure on the glued batches of samples (10 pieces) during the hardening period using a 10 kg weight.

The aim of the test was to check the strength of the adhesive bond against impact loads applied to the upper part of the sample. The test stand used for the tests was the "Julietta" pendulum hammer for testing lap and block joints (Fig. 4).

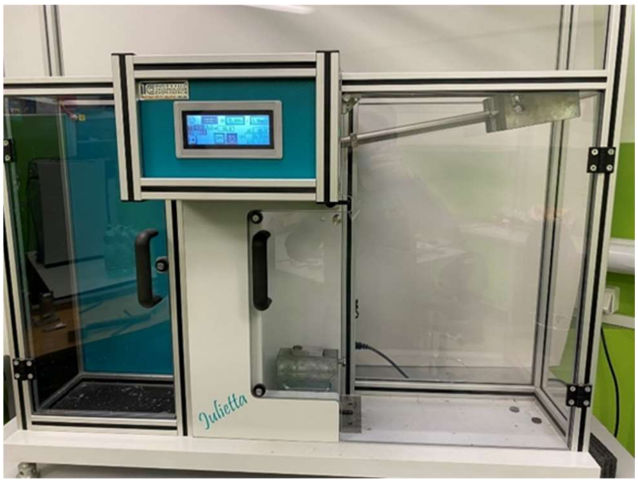

Fig. 4. "Julietta" device for testing impact strength of adhesive joints

The samples were placed in a special test machine handle (Fig. 5) prior to testing in order to stabilise them and ensure that the load was applied perpendicularly to the sample face. The examination was conducted in accordance with PN-EN ISO 9653 with a mounted hammer whose maximum energy was equal to 15 J and whose velocity was equal to 2,96 m/s.

Fig. 5. Sample mounted in the handle of the testing device

Fig. 6. Hammer prior to sample impact

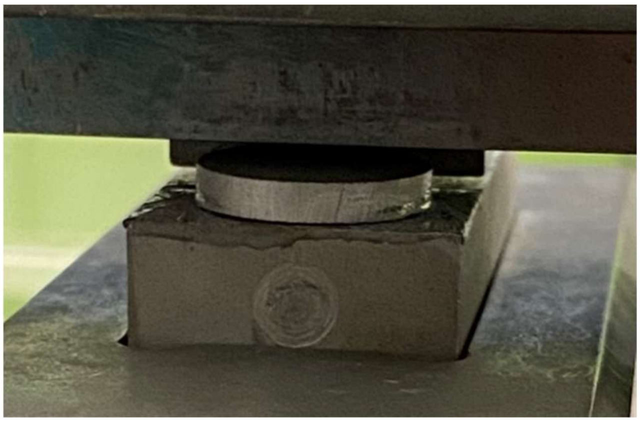

Fig. 7. View of sample during a hammer is striking

3. Research findings and their analysis

First, the authors examined the samples in which the upper element was made of PA6 aluminium alloy and whose diameter was 17.8 mm, which corresponds to the surface area of a standard adhesive bonding impact test sample in accordance with the norm PN-EN ISO 9653 equal to 250 mm^2. Most of the damage was cohesive in its nature, however some samples were damaged in an adhesive or mixed manner (Fig. 8).

Fig. 8. Method of failure of samples whose upper elements were made of 2017A alloy with a diameter of 17.8 mm

Next, samples with a diameter of 12.6 mm and a surface area of 125 mm^2 were examined. The last samples made from 2017A material had diameters of upper elements equal to 8.9 mm, which corresponded to a surface area of 62.5 mm^2. In the last group, slightly larger areas of adhesive damage were observed than in the two previous studies, involving PA6 material (Fig. 9).

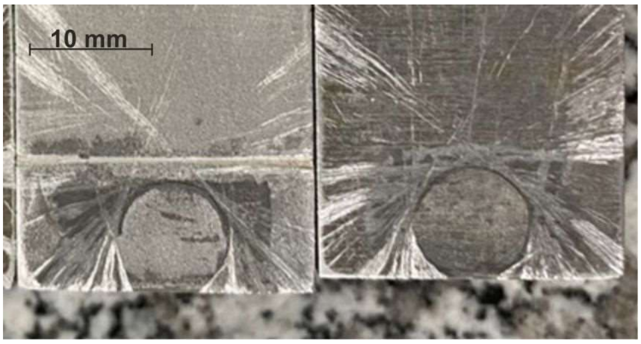

Fig. 9. Manner of destruction of the 2017A sample with a diameter equal to 8.9 mm

Most of the damage was cohesive in its nature with a small proportion of adhesive damage in each batch.

As expected, larger surface areas of adhesive joints corresponded to higher destruction energies (Fig. 10).

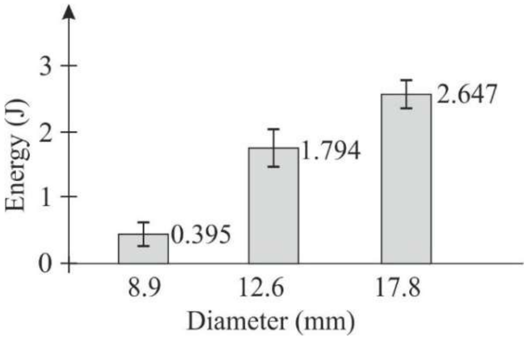

Fig. 10. Average destruction energy of all examined 2017A samples

In subsequent tests, samples made of Raex 400 material with a diameter of 17.8 mm were tested. The destruction observed in this batch was cohesive in its nature with little adhesion damage (Fig. 11).

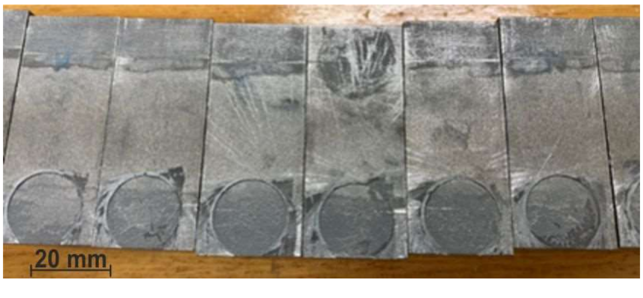

Fig. 11. Destruction of Raex 400 samples

In the next step, the authors examined ten samples of the same material with a diameter of 12.6 mm. Similarly to the samples which are 17.8 mm in diameter, mainly cohesive damage was observed in this batch (Fig. 12).

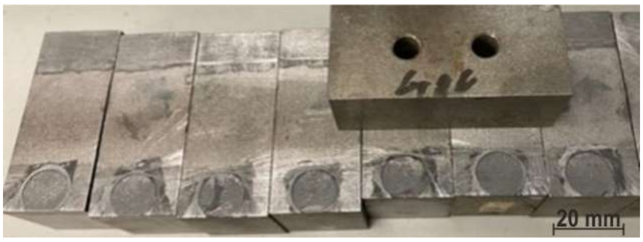

Fig. 12. Cohesive destruction of Raex 400 material samples with a diameter of 12.6 mm

In a batch made up of 8.9-mm-diameter samples, adhesive damage with a small amount of mixed damage was mainly observed (Fig. 13).

Fig. 13. Adhesive destruction of samples made up of Raex 400 material, 8.9 mm in diameter

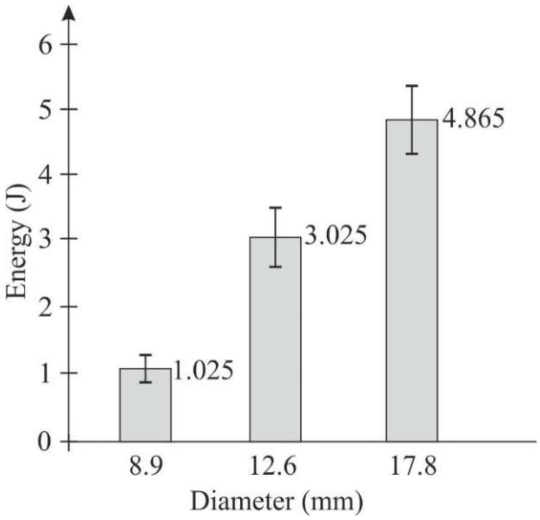

Fig. 14. Average destruction energy of all examined Raex 400 samples

The relationship between the energy of destruction and the surface area of the adhesive joint of elements made of Raex400 steel (Fig. 14) was similar to that in the joint of elements made of 2017A.

In the first two batches, it is possible to observe mostly cohesive damage with a small share of adhesive damage. In the last test batches, 8.9 mm in diameter, it was possible to observe mainly adhesive damage.

Finally, a series of samples was tested with the upper elements made up of S235JR steel. Firstly, the authors examined samples with a diameter of 17.8 mm. In this case, mainly cohesive damage was observed. Adhesive damage was identified on a small area of three samples (Fig. 15).

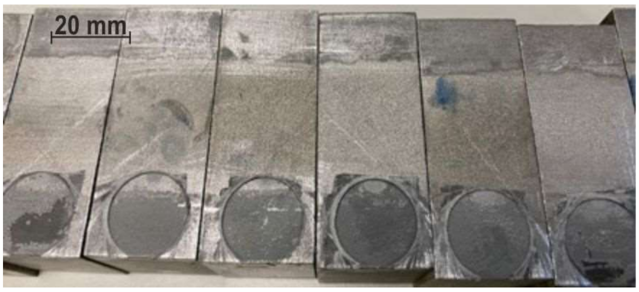

Fig. 15. Adhesive destruction of samples made up of S235JR material, 17.8 mm in diameter

The S325JR steel specimens with a 12.6 mm upper element also demonstrated mostly cohesive damage. Mixed damage appeared on several samples (Fig. 16).

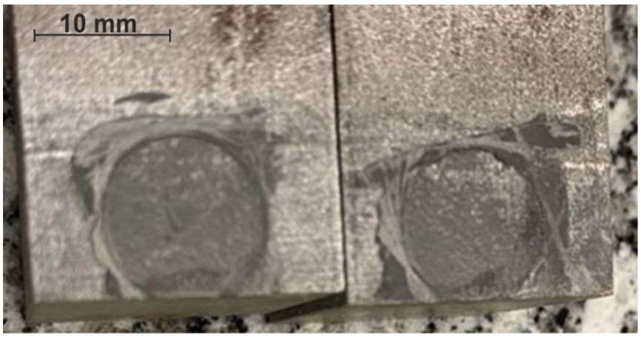

Fig. 16. Cohesive and mixed destruction on samples made up of S235JR material, 12.6 mm in diameter

In the case of S235JR steel samples with the top element of 8.9 mm in diameter, the damage to the samples was mostly cohesive in nature with small areas of adhesion damage and one sample adhesively damaged (Fig. 17).

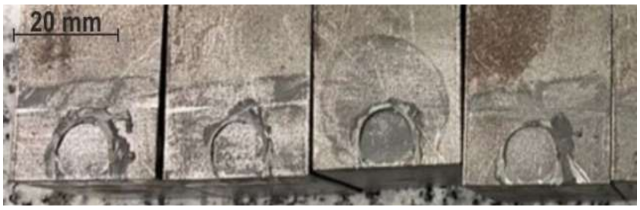

Fig. 17. Adhesive destruction of samples made up of S235JR material, 8.9 mm in diameter

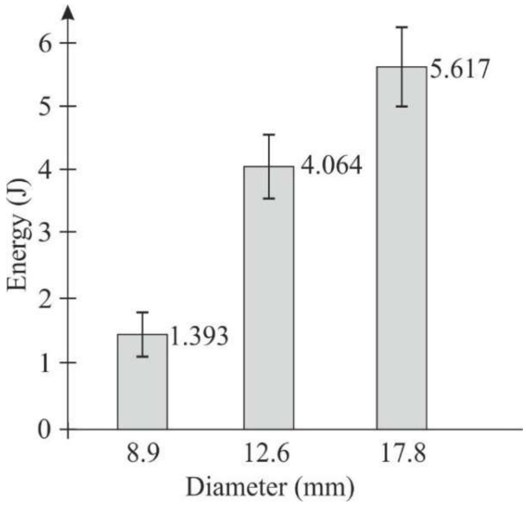

Fig. 18. Average destruction energy of all examined S235JR samples

In the samples, 8.9 mm in diameter, it was mainly possible to observe adhesion damage, while the remaining batches showed cohesive damage.

The destruction energy of the examined joints increased disproportionately along with increasing the joint area, which was approximately parabolic (Fig. 18).

Impact strength of samples made of different materials

The impact strength was defined as the quotient of the energy of joint destruction to its surface area.

The results of the conducted examination for samples, 17.8 mm in diameter, have been presented in Fig. 19.

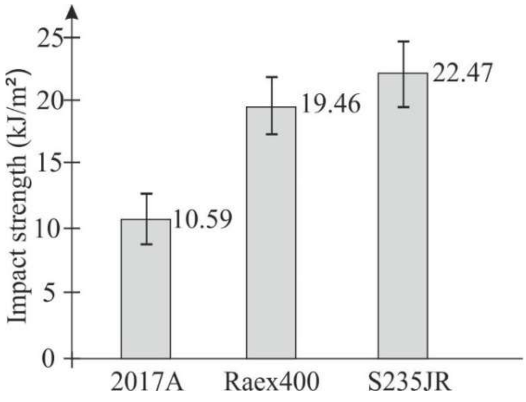

Fig. 19. Average impact strength of samples which are 17.8 mm in diameter

Samples made from S235JR steel had the highest impact strength (Fig. 19). Their impact strength was 112% higher than that of the aluminium alloy samples and 15% higher than that of the test series made from Raex 400 steel.

The average values of impact strength of the samples, 12.6 mm in diameter, of all the materials have been presented in Fig. 20.

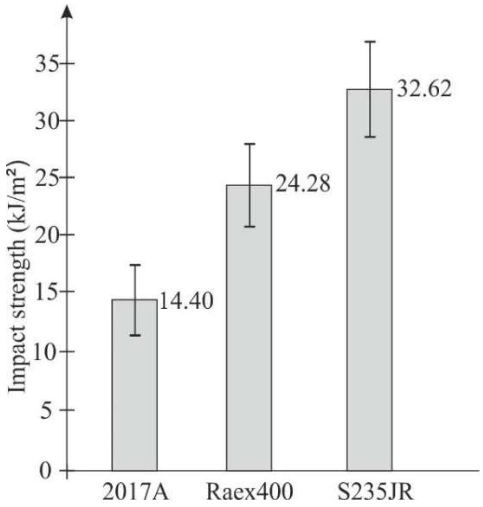

Fig. 20. Average impact strength of samples which were 12.6 mm in diameter

While analysing the results of samples whose upper element equalled 12.6 mm in diameter, a significant difference can be seen between samples made of steel. The impact strength of the S235JR steel samples is 35% higher than that of the Raex 400 steel samples. The impact strength of aluminium alloy samples is 56 % lower than the impact strength in samples made from S235JR steel.

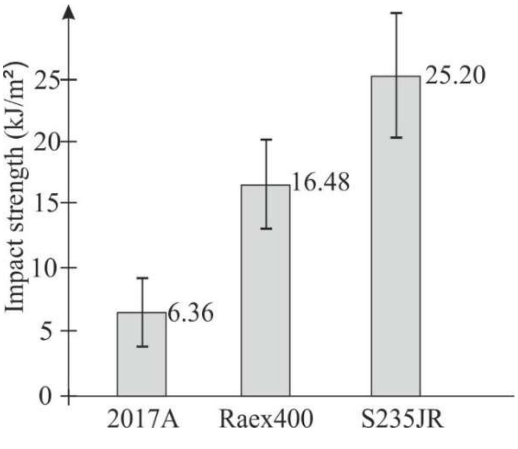

Fig. 21. Average impact strength of samples which are 8.9 mm in diameter

Fig. 21 shows the average impact strength of the samples whose upper elements are equal to 8.9 mm in diameter. Similarly to samples which are 12.6 mm in diameter, there is a clear difference in impact strength between the steel samples. S235JR steel samples have an impact strength which is 35% higher than that of Raex 400 and 75% higher than that of 2017A alloy. Aluminium alloy samples have a significantly lower impact strength than steel samples.

Plastic deformation

After a visual inspection of all the damaged samples, plastic deformation was found on two materials with the lowest yield strength, namely S235JR steel and 2017A aluminium alloy, respectively.

The deformation of S235JR steel components was observed with samples of 17.8 mm (Fig. 22) and 12.6 mm (Fig. 23) in diameter. At 8.9 mm in diameter, no distortion was observed.

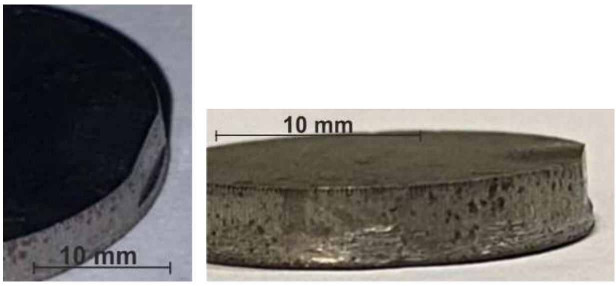

Fig. 22. Plastic deformation of a sample element, 17.8 mm in diameter, made of S235JR steel

Fig. 23. Plastic deformation of a sample element, 12.6 mm in diameter, made of S235JR steel

The deformation of the 2017A aluminium alloy samples was also observed in pieces whose diameter equalled 17.8 mm (Fig. 24) and 12.6 mm (Fig. 25). No plastic deformation was observed with the smallest diameter.

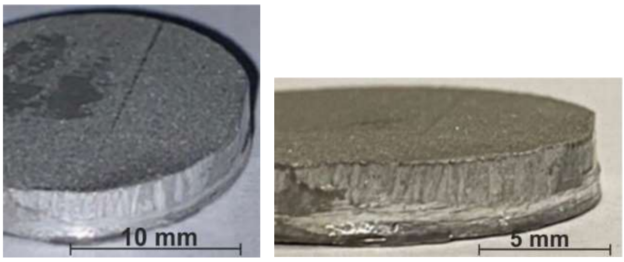

Fig. 24. Plastic deformation of a piece, 17.8 mm in diameter, made of 2017A alloy

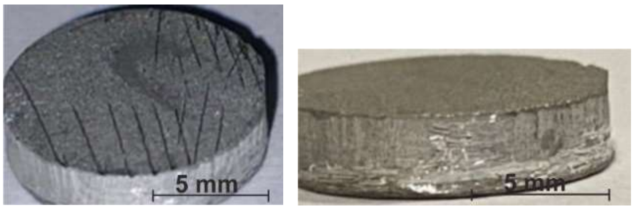

Fig. 25. Plastic deformation of a sample piece whose diameter equalled 12.6 mm, made of 2017A alloy

No plastic deformation was found in samples made from Raex 400 steel with any diameter (Fig. 26).

Fig. 26. Non-plastically deformed sample pieces, 17.8 mm in diameter, made up of Raex 400 steel

4. Conclusions

Based on the obtained results, the following conclusions were drawn:

1. by making the upper cylindrical parts of the block samples from a high yield strength material, plastic deformation of these parts can be avoided, thereby increasing the reliability of the impact test results obtained by this method;
2. plastic deformation of the upper parts of the samples made of low yield strength materials only occurred at diameters of 17.8 mm and 12.6 mm. No deformation was observed in the upper 8.9 mm diameter elements;
3. the upper parts of the samples made of Raex 400, which had the highest yield strength of the tested materials, did not deform at any of the diameters of the upper parts;
4. the joints failure energy increased with increasing the joint area, which was approximately parabolic. This shows that the stresses in the loaded joints are not distributed uniformly and the destruction of the joint starts at the point of contact between the dropping tool and the cylindrical element;
5. the lowest failure energy of aluminium alloy samples is due to the low value of the Young's modulus of this material. The same load force corresponds to almost three-fold elastic deformation of the aluminium alloy element than of the steel element. Greater deformation of the bonded component corresponds to greater deformation of the joint and its faster destruction;
6. higher destruction energy of S235JR steel samples compared to Raex 400 steel is due to low yield strength of S235JR steel. The plastic deformation of the loaded components made of this steel requires providing energy, which adds up to the fracture energy of the joint.

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