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DETERMINATION OF THE TENSILE PROPERTIES OF SPECIMENS WITH SMALL DIMENSIONS

MERJENJE TRDNOSTNIH LASTNOSTI S PREIZKU[ANCI MALIH DIMENZIJ

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In prac tice it hap pens that not enough ma te rial is avail able in or der to ex tract stan dar d ten sile spec i mens. This is es pe cially the case when welded joints like la ser welds or ex plo sive cladded joints have to be char ac ter ised. Sim i lar prob lems ap pear in case of fail ures of com po nents where not enough ma te rial for in ves ti ga tion is avail able. Up to now in di rect so lu tions were used. Yield strength and ten sile strength were ob tained by con ver sion cal cu la tions of mea sured ha rd ness pro files. These con ver sions con tain er rors. Fur ther more, im por tant in for ma tion con cern ing the de for ma tion be haviour is lost. In this con tri bu tion the test tech nique of mini flat ten sile spec i mens with mea sur ing area of 1 mm is dis cussed, from the extracting pro cess on up to mea sur ing the elon ga tion di rectly on the spec i men. The dis cussed test ing de vice is pro te cted by Pat ent DE 197 44 104 A1 and Patr.Reg.No.9800255 SLO.

Key words: ma te rial test ing, ten sile spec i mens, mini flat tensile spec i mens, me chan i cal prop er ties, welded joints

Zgodi se, da za merjenje trdnostnih lastnosti ni na voljo dovolj materiala za izdelavo standardnih nateznih preizku{ancev. Ta prob lem je {e posebej aktualen pri karakterizaciji varjenih spojev, narejenih z novimi tehnologija mi (lasersko varjenje, eksplozijsko varjenje itd.), kjer so posamezne cone vara zelo ozke in lah ko govorimo le bolj o liniji spajanja. S klasi~nimi nateznimi preizku{anci v tak{nem primeru seveda ne moremo izmeriti profila mehanskih lastnosti preko varjenega spoja. Podobno ve lja tudi pri ana li zi vzrokov razli~nih po{kodb strojnih delov in komponent, kjer imajo lah ko ostanki tako majhen volumen, da ne omogo~ajo izdelave dovolj velikih nateznih preizku{ancev in zato mehanskih lastnosti materiala tudi ne moremo neposredno izmeriti. Pri opisanih te`avah so si do sedaj pomagali posredno, namre~ z merjenj em profilov (mikro)trdot in prera~unavanjem izmerjenih vrednosti v napetost te~enja oziroma v trdnost materiala. Zlasti prer a~unavanje v trdnost materiala pa je lah ko povezano z znatnimi napakami, pa tudi nobenih podatkov o duktilnosti materia la (raztezek, kontrakcija) pri tem ne pridobimo. V prispevku je zato predstavljen mini natezni plo{~ati preizku{anec preseka 1mm^2, odvzemanje materiala za izdelavo in sama izdelava tak{nega preizku{anca ter na~in presku{anja, pri katerem se kljub mini aturizaciji meri raztezek neposredno na preizku{ancu. Del naprave, ki slu`i merjenju raztezka je tudi ustrezno patentno za{~i ten (DE 197 44 104 A1, P-9800255 SLO).

Klju~ne besede: preizku{anje materiala, natezni preizku{anci, miniplo{~ati natezni preizku{anci, mehanske lastnosti , zvarjeni spoji

1 INTRODUCTION

In practice the conversion of properties is popular, the most common one is the conversion of hardness values into tensile properties. Some frequently offered reasons for such conversions are "not enough material", "no suitable testing device available" or "to save money". If tensile properties are needed, these reasons are not acceptable, because in this case "mini"- or "microtensile" specimens may be used[1,2,3,4]. The tensile properties can not be reduced simply to the terms: yield strength, tensile strength and Young's modulus, because only the entire stress-strain curve adequately depicts the complete tensile behaviour. Such information is required for engineering defect assessment procedures and FE-calculations.

2 THE PROB LEMS WITH CON VERTED HARD NESS VAL UES AS SUB STI TUTE FOR REAL TEN SILE PROP ER TIES

By converting hardness values into tensile properties only rather qualitative tensile properties can be obtained. The tabulations given in older standards were defined explicitly as "tabulations for comparison". Comparison within the same testing method is generally accepted and makes sense, e.g. the comparison of hardness HB with HV or HRC. But conversion of hardness values into tensile strength, or even worse into yield strength, is incorrect and not allowed because within these two testing methods physically different damage processes occur.

It is quite simple to establish a mathematical correlation between hardness values and tensile strength if only a few material conditions or only steels belonging to the same grade are tested, which in practice is usually the case. Up to now, a systematic approach has been lacking because conversion and comparison with "real" tensile properties was usually only performed for those materials which were of concern to the corresponding authors. It is obscure to conclude generalising results from such comparisons and to declare them as a substitute for tensile testing. A literature survey showed that in particular for welded joints, which are a favourite area for such conversions because of one of the above mentioned reasons, i.e. "not enough material", the performed comparison is based on only a few hardness indentations and on a few weld metal specimens (which - in the case of a small weld metal - may even contain HAZ or base metal).

An additional aspect that is often neglected is the fact that in contrast to real tensile tests, converted hardness values provide no information about the dependency of direction, e.g. the tensile strength longitudinal or transverse to the rolling or welding direction.

When converting one type of hardness value into another one, like e.g. converting HB to HRC, limitations and possible problems have to be considered[5]. Some time ago it became fashionable to obtain properties which have to be determined in "expensive" experiments by converting the results obtained from "cheaper" experiments.

For example, in[6] it is claimed that not enough of the weld metal is available in order to extract standard specimens, therefore hardness values are converted into yield strengths. The conversion used from[7], which is actually only valid for special conditions, is used while the conditions demanded are not given. The results obtained from this conversion provide an input parameter for a defect assessment procedure, which actually demands stress-strain properties in terms of yield strength, tensile strength, Young’s modulus and strain hardening coefficient.

Another example can be seen in[8], where the fracture toughness K_{Ic} is determined by the conversion of hardness values.

According to testing standards, for a correct determination of hardness in a pure base material with an uncertainty less than e.g. +/- 5 %, 18 indentations have to be performed and evaluated if the testing load equals 1 N or higher [5]. If the testing load is smaller, more indentations are demanded. In order to obtain a statistically sound "tensile strength" from a hardness conversion, even more hardness indentations would be necessary.

Actually, in the surveyed literature, in not every case were the required number of indentations for the base material provided. In[6] a "tensile strength" and even a "yield strength" are derived from a handful of hardness indentations.

It is understood that for in-service structures, materials for specimens cannot always be extracted and that not for all structures spare material is reserved, especially if they have been built years ago. But one has to consider that the results of conversions may produce significant errors, e.g. about 20% in[10]. The question is, whether FE-calculations or defect assessments based on such conversions are sufficient and can be trusted, and who will take the responsibility for the predicted life of a structure, which is assessed with converted hardness values. Finding mathematical correlations between hardness values and "real" tensile strength is no prob lem, but generalising those results is dangerous, especially if evidence is scarce.

Present standards like ASTM, for certain reasons, do not provide conversion tabulations from hardness into tensile strength.

Hardness, tensile and impact testing were among the first methods used in order to characterise the failure behaviour of a structure. As a result of failures, which could not be explained by these methods, fracture mechanical investigations taking into account an existing crack have been developed.

Today some conversions from notch impact toughness into fracture toughness, J-Integral or COD have been established. They are usually performed in cases when fracture toughness testing is accompanied by problems.

Well-established institutions exist, which invest considerable time and effort in verifying these conversions. They would have spared these efforts if "quick-and-easy-to-do" hardness measurements were sufficient.

As long as verification is not sufficient, the data base is quite small and the laboratory does not have its own tests for comparison and verification, one should stick to the "real" experiments as suggested in[11].

3 MANUFACTURING OF MINI FLAT TENSILE SPECIMENS

Typical areas for the determination of tensile properties with mini flat tensile specimens are given in the following[1,12]:

- Determination of gradients in properties, e.g. for HAZ or segregation;
- Testing of semi-finished products with small cross section;
- Determination of material properties if only small amounts of material are available, e.g. failure analysis;
- Determination of material properties in the case of small weld geometry, e.g. a laser weldment;
- Testing of radiated material with the aim of keeping the amount of irradiated material as small as possible;
- Mechanical behaviour of microstructure in micro-components.

The common type of mini flat tensile specimen, shown in **Fig. 1**, was developed by[12,13]. The dimensions are: specimen width 2 mm, thickness 0.5 mm, gauge length Lo - depending on the testing device - 9 or $5{,}65*\sqrt{So}$ mm (So = cross section area). In **Fig. 1** a modification, with the specimen width being 1 mm, is shown too. By extracting these specimens with spark erosion cutting a sectioning distance of 0.6 mm can be achieved. This is a great advantage, in comparison with extraction by machining, especially when gradients in mechanical properties have to be determined.

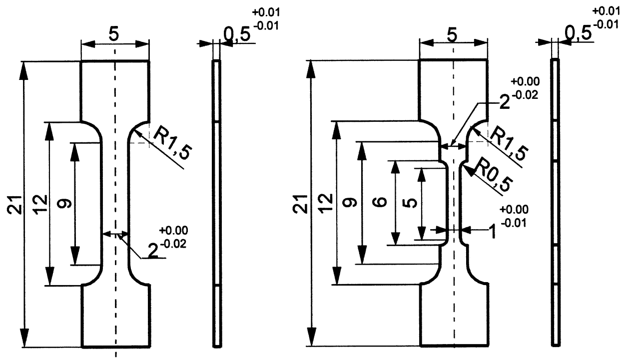


Figure 1: Mini flat tensile specimens
Slika 1: Mini natezni plo{~ati preizku{anci

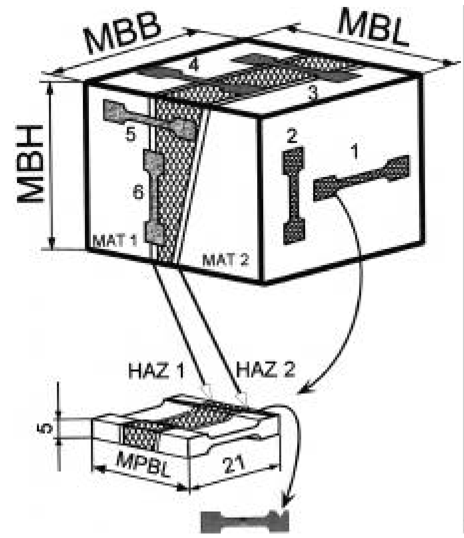


Figure 3: Various extraction positions for mini specimen bars
Slika 3: Razli~ne mo`nosti izrezov mini blokov

For the characterisation of welded joints, specific information is necessary, as shown in **Fig. 2**. A welded joint consists of a single or two different types of base material (MAT1 and MAT2) and heat affected zones (HAZ1 and HAZ 2) and of the weld metal (WM). Depending on the welding process the weld metal width and the width of the HAZ located between weld metal and uninfluenced base metal is narrow or wide. Before extracting a "bar" from a welded joint (e.g. by spark erosion cutting) the exact position in the welded joint has to be determined as well as its length (MBL), height (MBH) and width (MBB), **Fig. 2**. The height may enclose the thickness of the base metal plate.

By etching the surface of the bar, the locations of weld metal and the heat affected zone(s) are determined, which helps to decide where to extract "mini specimen bars". In **Fig. 3** various extraction positions for mini specimen bars are given. The selection is carried out in accordance with the position significant for the following assessments. In **Fig. 3** an identification marking for the separate specimens is also depicted: A notch, diagonal to the specimens length, is machined into the specimen’s head. Thus the exact position of every single specimen can be determined after the specimens have been extracted, even after testing them. The sectioning of a mini specimen bar is shown in **Fig. 4**: the first spark erosive cut is performed at a significant place, e.g. a fusion line or the HAZ. In the following the neighbouring specimens are sliced off along the entire gradient. With a known diameter of the wire used for spark erosion (it should be as thin as possible) the specimen position can be traced which is important for determining a gradient in mechanical properties. Keeping the heat input as low as possible, and sufficient cooling, are necessary in order to keep the influence resulting from heat input as low as possible.

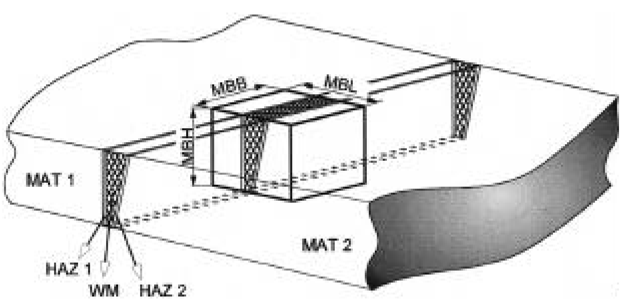


Figure 2: Welded joint consisting of base materials 1 and 2, HAZ 1 and 2, and weld metal; Extraction of bar
Slika 2: Izrez bloka iz zvarjenca

4 TESTING OF MINI FLAT TENSILE SPECIMEN

For correct testing it is necessary to have an appropriate holding and testing device. Holding and

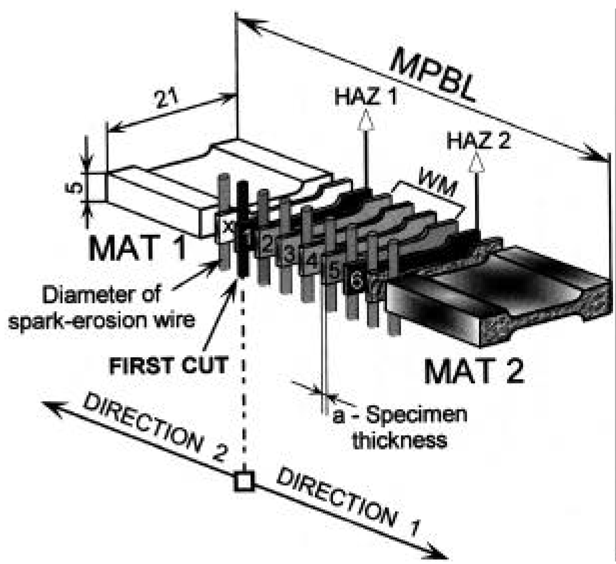


Figure 4: Sectioning of mini specimen bar
Slika 4: Razrez mini bloka

testing devices have been developed for various specimen geometries. For several testing procedures (J, COD) it is of major concern to measure the elongation, e.g. in order to obtain the stress-strain curve for a tensile test.

Measuring elongation on small specimens like mini flat tensile specimen is associated with a specific problem: the space where a measuring device could be mounted is quite small, the measuring devices commonly used for specimens with "standard" size are not applicable to the mini flat tensile specimens. Therefore, instead of measuring the real elongation of the specimen's gauge length the elongation is measured over a larger base/distance, e.g. the stroke of the cross head. Among the measuring devices available, especially for small gauge lengths, no type is capable of measuring strains up to e.g. 80%.

A further problem is an appropriate holding device for such small specimens. Of the commonly used holding devices several are time-consuming, clumsy or may even lead to results containing errors as it was comprehensively discussed in[1]. The most serviceable method is to hold the specimen by round pins at its shoulders. In[1], three different methods to measure elongation were applied while using the holding device designed with round pins. The comparison proved that the closer the measuring base was placed to the real specimens gauge length, the more accurate were the results. The main results obtained from the different methods, **Fig. 5**, are given in **Fig. 6**.

4.1 Stroke of cross head:

The stroke of the crosshead is measured, e.g. with a linear variable transducer mounted on the frame of the machine, method "A" in **Fig. 5**. In this case the measured elongation encloses everything between the specimen and the crosshead.

4.2 Measurement at the distance of the specimens shoulders

Measuring method according to "B" is to be preferred to "A" because the elongation is measured closer to the specimen, i.e. at the holding device. In this case a clip-on-gauge was applied. The gauge length is given by the distance between the centres of the round pins, which is identical to the radius of the specimen shoulder.

4.3 Elongation measured directly on the specimen:

With method "C" the elongation is measured directly on the specimen, **Fig. 5**. This is the only method which satisfies the requirements according to standards for testing of common (standard) specimens. A method for realising this method is given in[2]. With these method the elongation can be measured according to the standards[14] for a proportional specimen with the gauge length being defined with the initial measuring length Lo:

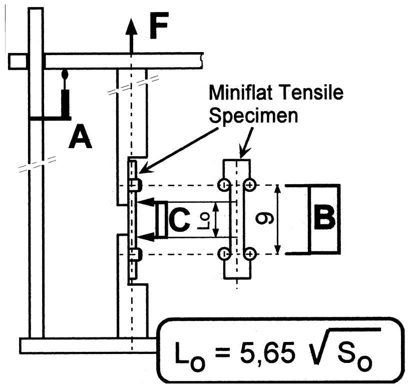


Figure 5: Different testing methods of mini flat tensile specimens
Slika 5: Razli~ne metode preizku{anja mini preizku{ancev

$$Lo = 5.65*\sqrt{So}.$$

The stress-strain curves obtained with the methods A, B and C for a spring steel are compared quantitatively in **Fig. 6**. With method C the linear-elastic regime depicts the highest slope of all three curves. Comparison with standard round tensile specimens, tested according to standards, revealed that with method C the best coincidence of the slopes obtained from the round tensile specimen and the mini flat tensile specimen can be achieved, i.e. with method C the obtained stress-strain curve is the most accurate one. The largest deviation was obtained with method A, because of the remote measuring base.

The comparison proves that for a correct stress-strain curve the elongation has to be measured directly at the specimen.

5 APPLICATION OF MINI FLAT TENSILE SPECIMENS

A suitable application of mini flat tensile specimens is a joint welded by explosive cladding, as it was performed in[15]. This weld is more of a cladding in

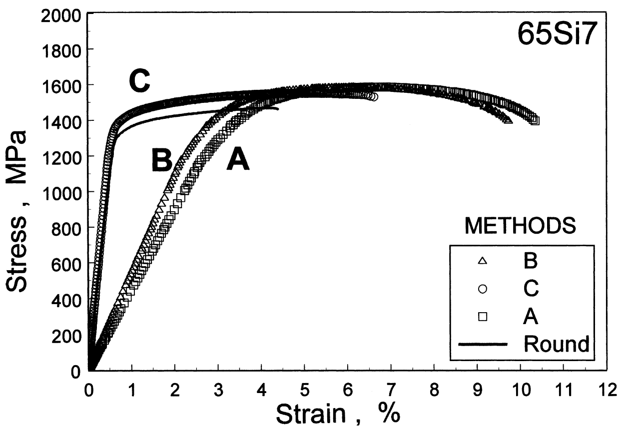
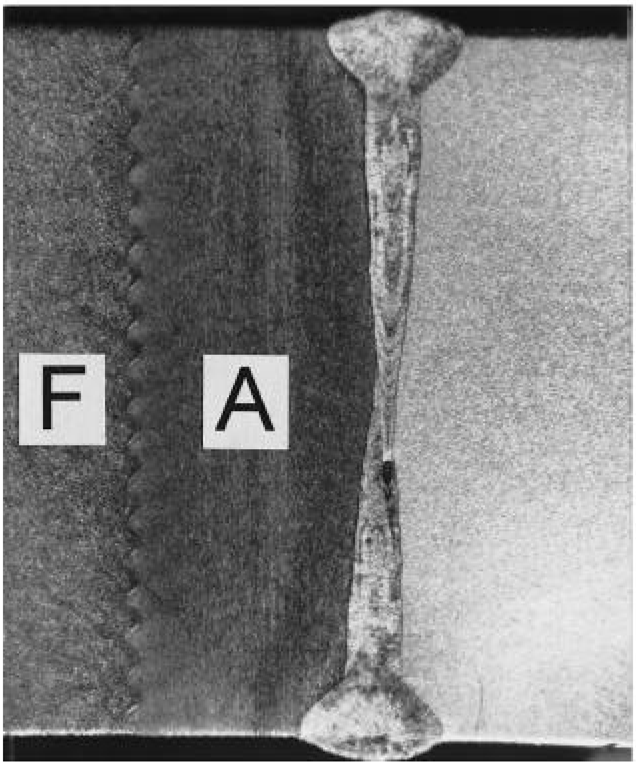


Figure 6: Comparison of stress-strain curves obtained with different testing methods
Slika 6: Primerjava razli~nih metod preizku{anj



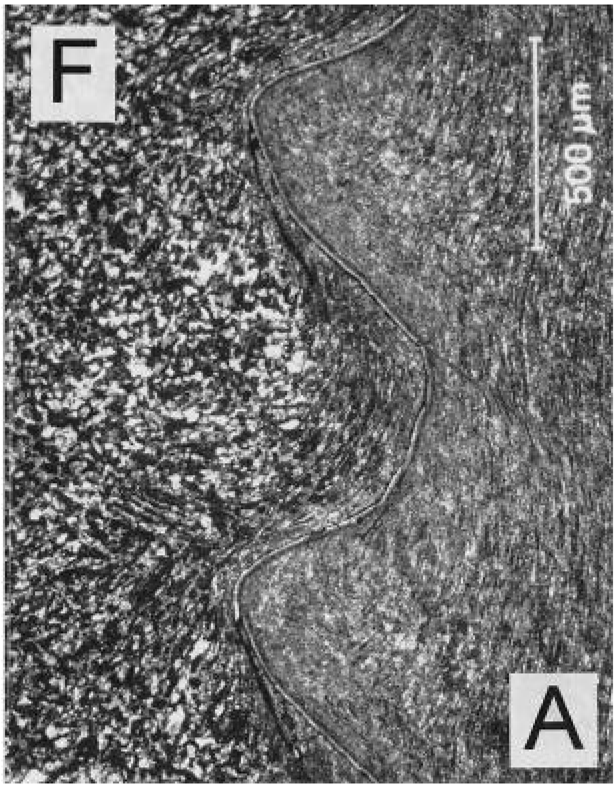


Figure 7a: Macrograph of the explosive cladded joint A-austenitic steel, F-ferritic steel
Figure 7b: Micrograph of the explosive cladded joint
Slika 7a: Makrostruktura explozijsko zvarjenega spoja A-avstenitno jeklo, F-feritno jeklo
Slika 7b: Mikrostruktura explozijsko zvarjenega spoja

comparison to other weld processes and contains actually no "visible" weld metal, only a fusion line. In this example, a cladded joint consisting of an austenitic steel of 5 mm thickness clad on a ferritic steel with 20 mm thickness was investigated. In addition, austenitic base metal was welded by laser welding to the cladded joint in order to have a larger volume (for extracting other specimen types).

From this welded joint a bar was extracted according to **Fig. 2**. Macro- and micrographs of the structure are given in **Figs. 7a and 7b**. The macrograph depicts the regular wavelike fusion line, **Fig 7a**.

Fig. 7b depicts the plastic deformation of the microstructure near the fusion line. Both materials were subjected to large plastic deformation, with the austenitic steel having the larger deformed region.

From the bar, three mini specimen bars were extracted from different joint positions ("levels") by spark erosion, **Fig. 8**. Each bar represents one test series, i.e. one level of height in the joint. From these mini specimen bars the mini flat tensile specimen themselves were sliced according to **Fig. 4**. The position of the first cut of each of the three mini specimen bars was shifted. For the first series, the first cut was performed at the fusion line. For the second series, the cut was shifted by about half the thickness of the specimen. In this way the gradient in the mechanical properties can be obtained more precisely, i.e. the local distance between the obtained properties is smaller.

The stress-strain curves obtained for the austenitic part clearly exhibit the gradient in mechanical properties, **Fig. 9**.

Towards the fusion line the obtained maximum stresses are larger and the obtained strains are smaller. The maximum stresses are 2 times higher than for the austenitic base metal. This is caused by the significant plastic deformation which leads to intense strain

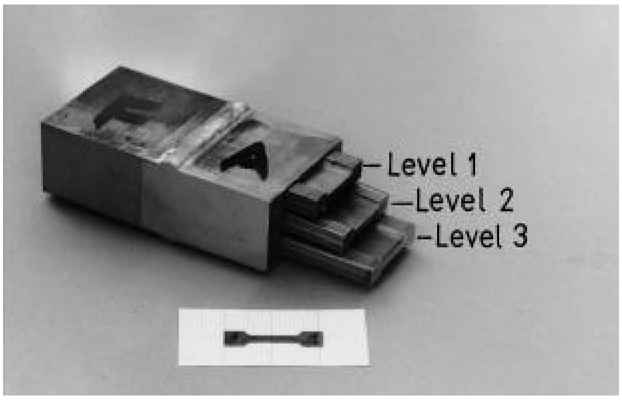


Figure 8: Three mini specimen bars extracted from different levels within the explosive cladded joint
Slika 8: Trije nivoji izrezov mini blokov iz eksplozijskega zvarjenca

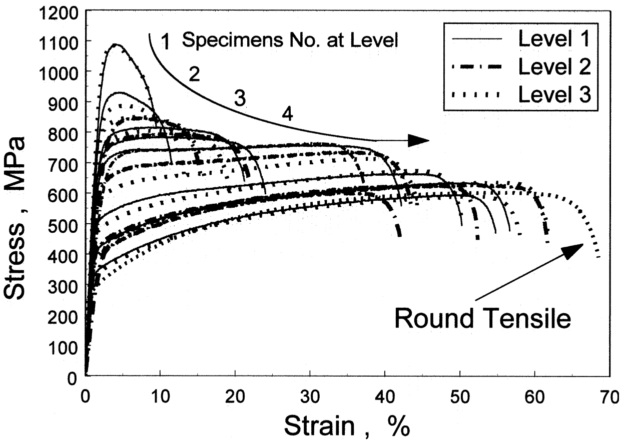


Figure 9: Stress-strain curves obtained from mini flat tensile specimens for the austenitic part
Slika 9: Krivulje napetost-deformacija za avstenitno obmo~je

hardening on the austenitic side. With increasing distance from the fusion line, the obtained stresses are lower and the strains larger. For comparison, the stress-strain curve obtained from a stan dar d round tensile specimen (testing diameter 8 mm) is plotted in **Fig. 9**, which depicts the good agreement between mini flat tensile specimens and stan dar d tensile specimens.

6 SUMMARY

In this paper problems associated with the conversion of material properties and with the testing of mini flat tensile specimens are discussed. The reasons specified for the conversions, mostly from hardness values into another material property, e.g. yield strength and tensile strength, are "saving costs and time", and / or "not enough material available for testing". These conversions are spreading like an avalanche, aided with computational help. It is understood by the authors, that cases exist where no material for testing is available, but one has to bear in mind that properties obtained by conversion are no substitute for real mechanical properties and in critical cases only orders of magnitude can be obtained. The literature survey showed that in some cases the conditions and limitations for conversions were not considered, and that quite often general results were concluded from a small number of hardness indentations, sometimes for welded joints not even one real tensile test had been conducted. One has to make an appeal not to advertise these conversions because industry might try to substitute the real experiments. A real material property like e.g. yield strength or tensile strength can be obtained only by real tensile testing. An enhanced (i.e. most accurate) defect assessment is only possible when (among other things) a complete stress-strain curve is available (which unfortunately, even today, is not usually supplied with the acceptance test of a steel). If one wants to take advantage of new steel grades and proper assessments, which will both lead to real saving, one should not reduce the initial testing which will provide valuable input parameters.

In this paper it was shown that it is possible to extract and to test small specimens in an effective and economic manner and to achieve the correct results. A new method, which allows the measuring of elongation directly at the specimen is discussed and compared with other methods. An example of an application using an explosive cladded joint, exhibiting a strong gradient in the mechanical properties, is shown.

The results show that with the new testing device, tensile properties of small regimes can be obtained with good quality.

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