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Assessment and Comparison of the Mechanical Properties of Laser Welded Joints in Docol 1200M and Strenx S700MC Steel Alloy Grades Under Impact Loads

Paweł PROCHENKA[*1,2], Jacek JANISZEWSKI[1]

[1]*Military University of Technology, Faculty of Mechatronics and Aerospace,*
2 Sylwestra Kaliskiego Str., 00-908 Warsaw, Poland
[2]*BOZAMET sp. z o.o., Ujrzanów 282A, 08-110 Ujrzanów, Poland*
[*]*Corresponding author's e-mail address and ORCID*:
pawel.prochenka@wat.edu.pl; https://orcid.org/0000-0002-8510-7485

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Abstract. The article evaluates the strength and ductility of laser butt joints made of 2 mm Docol 1200 M martensitic steel sheets based on the hardness, quasi-static and dynamic tensile tests. Technological research of laser welding process was carried out on welding cell using IPG fiber – based welding source with 6 kW maximum power. The tests were carried out for parallel and perpendicular orientation of specimens by rolling direction. In addition, the obtained results were compared with the analogous results obtained during the Strenx S700 MC steel tests. Dynamic tests were performed using the tensile split Hopkinson pressure bar technique with strain rates of 10^3 s^{-1}.

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The obtained results showed that the strength of Docol 1200 M under dynamic tensile test conditions are similar to the material strength under static tensile test conditions. However, due to the breaking of the specimens in the heat affected zone, the strength of the welded joint is much lower than in base material, which was not observed during the Strenx S700 MC steel tests.

Keywords: laser welding, split Hopkinson pressure bar, high-strength steel, energy absorber

1. INTRODUCTION

One of the challenges currently posed to land vehicle design engineers is the continuous drive towards vehicle weight reduction coupled with the optimum safety of the occupants. This is not only evident in the automotive engineering of civil vehicles, but also in military vehicle engineering. The weight reduction of light combat vehicles has been a primary engineering criterion. The low weight of light combat vehicles translates directly into the operational capabilities of military units, increased operating range, better fuel economy and minimised development costs of vehicle versions [1]. An example is the JLTV (*Joint Light Tactical Vehicle*) program announced by the Pentagon in 2005. Its objective is to combine the mobility of ATVs (*All-Terrain Vehicles*) with the ballistic protection of mine-resistant vehicles (Fig. 1).

The transport of troops, personnel and military gear is handled with land motor vehicles, which include tactical combat vehicles. Tactical combat vehicles can withstand the explosion of a land mine or IEDs (*Improvised Explosive Devices*), usually planted on the roadside. An optimum level of protection is achieved by the application of high-strength engineered materials in the chassis elements of combat vehicles which are mechanical energy absorbers, and by the application of light ballistic shielding, to name a few of the potential solutions [2].

The weight of a combat vehicle is often reduced by applying innovative design solutions, usually as a consequence of novel structural materials. An example of a novel structural material can be AHSS (*Advanced High-Strength Steels*). The high strength parameters of AHSS are determined in quasi-static and dynamic conditions and make the material a good choice for the construction of civilian and combat vehicle bodies alike. Most often, the body elements are made from low-alloy, biphasic steel, martensitic or manganese-boron steel grades which are intended for hardening during stamping.

Another method for vehicle weight reduction is TWB (*Tailored Welded Blanks*). The TWB process consists in welding a minimum of two blanks into one blank. This process is most often made with laser beam welding. Laser beam welding enables joining of sheet steel elements of different grades and thickness for specific parts of the vehicle structure which demand the highest strength parameters of materials.

TWB helps reduce the thickness of material in non-critical areas. This contributes to an overall weight reduction of parts [3].

Fig. 1. LTVs (light tactical vehicles) by make: Oshkosh (left) and Lockheed Martin (right)

Unlike conventional welding processes, laser beam welding inputs much less heat into the base metals, and it is the fastest-evolving technology of bonding of thin AHSS sheets [4]. However, any good quality weld requires tackling multiple processing challenges. Aside from the design criteria related to the transfer of static and fatigue loads, welds fabricated for the construction of combat vehicles are expected to feature high endurance and impact strength under dynamic loads caused by explosion of a mine or another explosive ordnance. Hence, the quality of welds fabricated in combat vehicle structures should be tested under dynamic conditions, provided by the test methods like SHPB (split Hopkinson pressure bar) [5].

This paper discusses NDT (*Non-Destructive Testing*) (by visual examination) and DT (*Destructive Testing*) (by micro hardness distribution testing and quasi-static and dynamic tensile tests) of welds in sheets made from Docol 1200M and Strenx S700MC steel grades.

Static tensile testing of welds is the preferred test method for the assessment of weld endurance; however, the method does not emulate the real-life conditions of loads applied to sheet steel welds used in combat vehicles. This demanded more advanced research methods that allowed the testing of sheet welds under impact loads. The research discussed here used a tensile SHPB method which allowed the determination and plotting of tensile strength curves at strain rates above 10^3 s^{-1} [6].

The paper features three main parts: part one is a characterisation of the strength parameters of AHSS grades selected for the tests and a discussion of the processing aspects of laser beam welding of AHSS sheets. Part two describes the test methodology, classified into NDT and DT. Part three is a summary and discussion of the test results.

2. CHARACTERISTICS OF THE MATERIALS AND LASER BEAM WELDING

AHSS are a group of complex and advanced structural materials with carefully selected chemical components and multiphase structures developed in precisely controlled heating and cooling processes. There are various strain hardening procedures applied in the manufacturing of AHSS and intended to produce specified ranges of mechanical strength, ductility and fatigue life [7]. The AHSS grades were sourced in the form of sheets from SSAB, a Swedish manufacturer of high-strength steel alloys. Both AHSS grades were delivered in sheets complete with quality certificates.

Strenx S700MC is a low-alloy AHSS grade with a minimum yield stress above 700 MPa and 12% of elongation. Strenx S700MC is made in heat treatment and mechanical working processes and sold in coils, sheets and blanks. Components can be fabricated from Strenx S700MC in most plastic forming processes; in the automotive industry, press-stamping is used with progressive (follow-on-die) tooling. Figure 2 shows Strenx S700MC classified as conventional HSLA steel. The chemical composition is shown in Table 1.

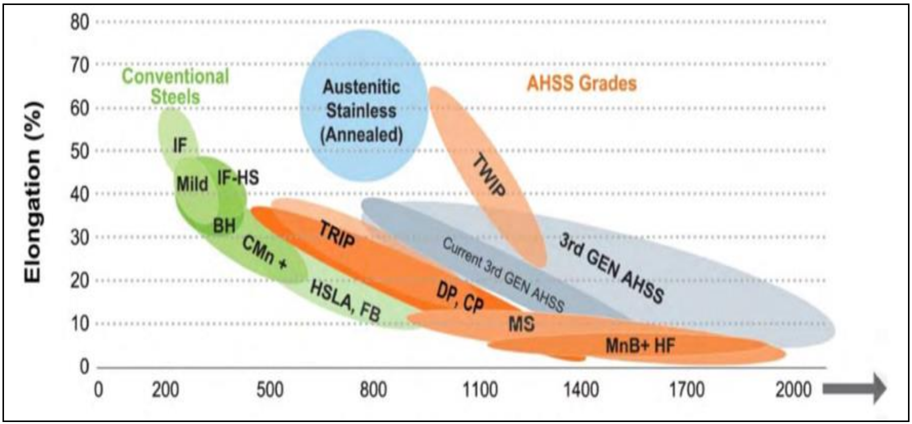

Fig. 2. Steel grade classification [3]

Table 1. Chemical composition of Strenx S700MC and Docol 1200M

	C max [%]	**Si max [%]**	**Mn max [%]**	**P max [%]**	**S max [%]**	**Al $_{tot}$ min [%]**	**Nb max [%]**	**V max [%]**	**Ti max [%]**
Strenx S700MC	0.12	0.21	2.10	0.020	0.010	0.015	0.09	0.20	0.15
Docol 1200M	0.14	0.40	2.00	0.020	0.010	0.015	0.10	-	-

Docol 1200M is a martensitic AHSS grade (the group MS in Fig. 2) with a minimum yield stress above 1200 MPa and 3% of elongation. Given its low ductility, Docol 1200M is formed mainly by cold roll forming, although many automotive products are made from this steel grade by press stamping. Depending on customer specifications, Docol 1200M is available mechanically worked, or heat treated and mechanically worked. It is available in coils, sheets and blanks. The test specimens were made from mechanically worked AHSS grade blanks, given their more common use in the automotive industry.

Joining of two AHSS sheets by welding is a great processing challenge; AHSS steel grades readily undergo phase transition because of the energy input during welding. A consequence is altered mechanical properties of the base material and a reduced endurance of welds. Critical to the production of high-strength welds in AHSS weldments is to minimise the energy input from the welding process. Hence, parts made from AHSS are most often joined by laser beam welding, which seems to be one of the most promising joining technologies for thin AHSS sheets. To fabricate a weld with a sufficient strength, the laser beam welding process parameters must be fine-tuned and closely controlled in the actual process.

The specimens from the selected AHSS grades were laser welded with a welding machine at Bozamet Sp. z o.o. company (Poland). The welding machine cell featured an IPG fibre laser source rated at 6 kW, an ABB welding robot and an IPG welding head connected to the welding laser source with an optical cable providing a laser focal spot with a diameter of 0.6 mm. An overview of the welding cell is shown in Fig. 3.

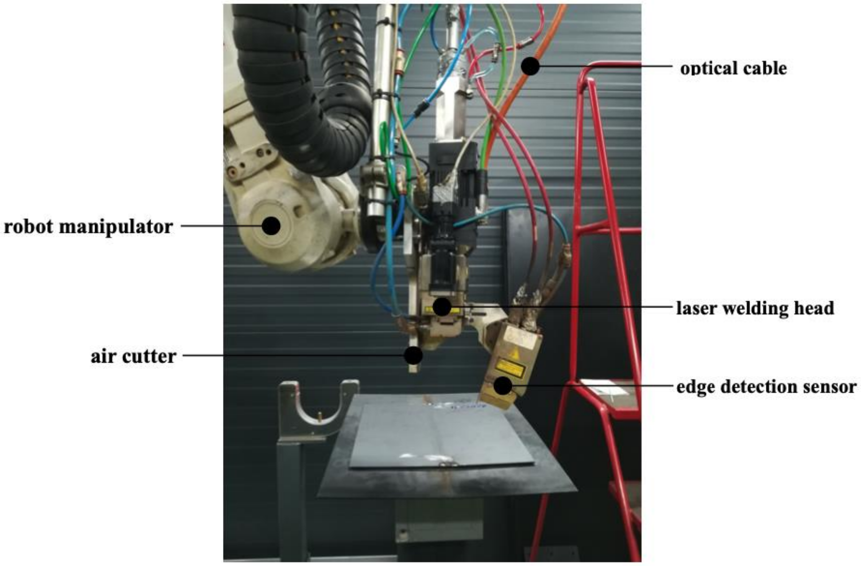

Fig. 3. Overview of the interior of the welding machine cell: the IPG welding head is ready for the welding of the semi-finished specimens from a Docol 1200M sheet

The AHSS sheets were joined by laser beam welding without any materials other than the base metals. The semi-finished strength test specimens were laser-cut in prior from a 2 mm AHSS sheet. Laser cutting of the sheet was chosen by the authors due to the extremely high quality of the cut edges, unlike in mechanical working-based cutting processes.

The parameters of the laser beam welding process were chosen from processing tests with the baseline being the laser welding parameters applied to Strenx S700MC, as discussed in [8].

However, the first several pilot tests revealed no root fusion. The next step was to incrementally increase the laser beam welding power until root fusion was achieved. This occurred at the laser beam output of 4200 W (Fig. 4).

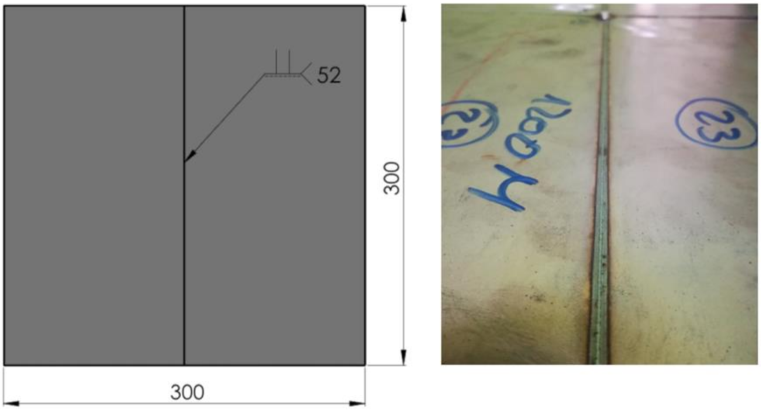

Fig. 4. View of a butt weld between Docol 1200M sheets

The final laser beam welding parameters for Docol 1200M are listed in Table 2 and collated with the laser beam welding parameters applied to Strenx S700MC.

Table 2. Laser beam welding parameters for Strenx S700MC [8] and Docol 1200M

Parameter	**Strenx S700MC**	**Docol 1200M**
Laser beam trajectory	Linear	Linear
Output power [W]	3100	4200
Welding speed [mm/s]	70	70
Spot diameter [mm]	0.6	0.6
Linear energy output [J/mm]	44	59
Welded sheet thickness [mm]	2	2
Joint type	Butt	Butt

3. TEST METHODOLOGY

The mechanical strength and ductility of laser welds were assessed with the following test methods: The Vickers hardness distribution test, a quasi-static tensile test, and an SHPB (split Hopkinson pressure bar) test.

The static tensile test was performed with the method from PN-EN ISO 6892-1:2010, on an MTS Criterion C45 machine. The specimens (Fig. 7) were prepared by laser cutting from prior semi-finished sheets. Each specimen cut was sized 320 x 300 mm and in two orientations of the sheet, i.e. in parallel and perpendicular to the direction of sheet rolling. The strength tests were performed with a strain rate of 0.001 s^{-1}. The dynamic tensile strength SHPB tests were performed with a strain rate of 1000 s^{-1}.

The tests were performed on an SHPB test rig, comprising a propulsion system, an array of Hopkins pressure bars, and a strain gauge measurement system. A schematic diagram of the SHPB test rig is shown in Fig. 5.

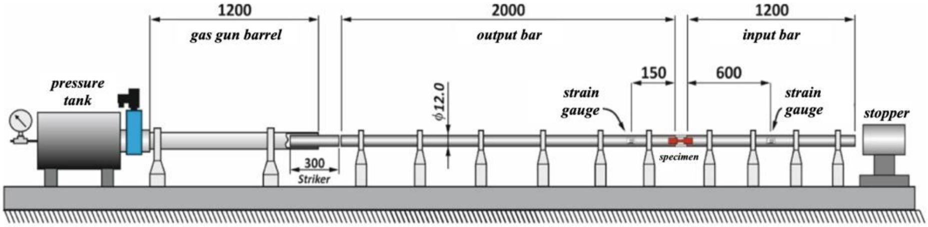

Fig. 5. Schematic diagram of the SHPB test rig in the tensile strength test configuration [8]

To convert the existing SHPB test rig to tensile strength testing, a specimen fixture system was designed with a relay sleeve. It is shown in Fig. 6.

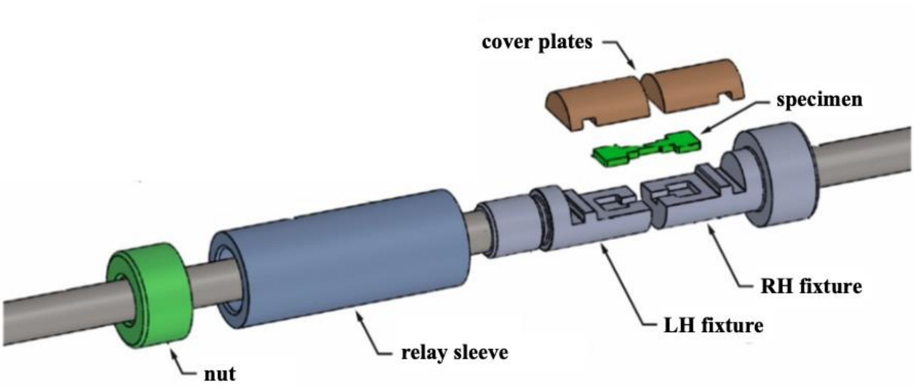

Fig. 6. Fixtures holding the specimen between the bars [8]

The process of specimen loading had the following order: when the striker hit the receiver bar, an elastic wave was generated in the latter, which propagated toward the specimen, while passing through the relay sleeve and the fixtures, followed by the input bar. Next, the elastic wave was rebound from the end of the input bar, which reversed the sense of the wave and converting the wave into a tensioning wave which, when it reached the specimen, caused the specimen to be elastically and plastically tensioned. Figure 9 shows an overview of a specimen held in the fixtures following the SHPB test.

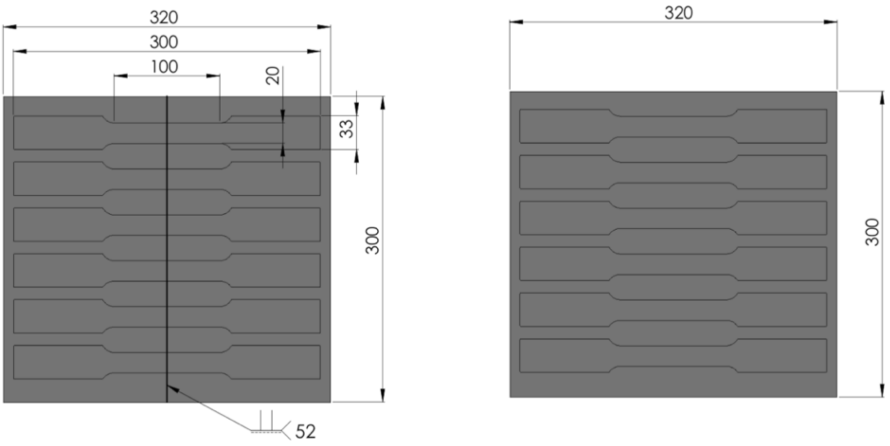

Fig. 7. Overview of the semi-finished sheets with the orientation of the specimens during laser cutting

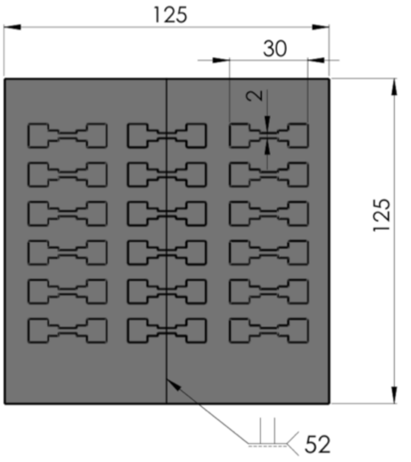

Fig. 8. Orientation of the specimens for SHPB testing on semi-finished sheet metal

The specimens with the geometry shown in Fig. 8 were cut by electromachining from the semi-finished sheets.

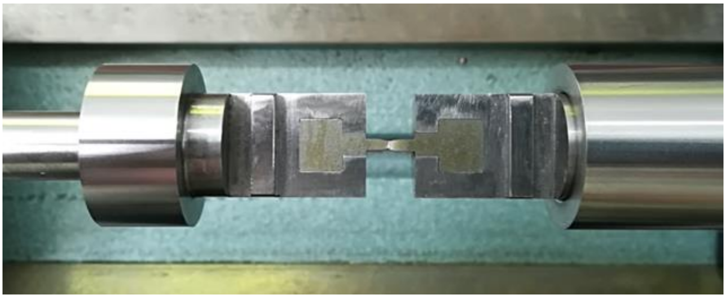

Fig. 9. View of the specimen fixtures and the specimen following the SHPB test

The authors chose electromachining cutting due to the need for high fabrication precision of the specimens and minimising the effect of heat on the specimen material. A detailed description of the SHPB test rig, its operating principle and specimen fixation is in [8].

4. TEST RESULTS

The assessment of the mechanical strength of laser welded joints in Docol 1200M began with the hardness distribution tests. The hardness was tested in the middle of the sheet metal thickness and included the base material, the HAZ and the weld. Fig. 10 shows the hardness test results for Docol 1200M, listed with the hardness test results for Strenx S700MC (Fig. 11) from [8] for comparative purposes. The curves show high non-uniformity of hardness distribution within the Docol 1200M weld. The base material hardness was within 400 and 440 HV1 (and the range partially included the weld), whereas inside the HAZ and the weld, the hardness was reduced to approx. 295 HV1 and approx. 360 HV1, respectively. The hardness variations of this magnitude were not evident in the welds of Strenx S700MC. The hardness within the HAZ and the weld was comparable to that of the base material, which was favourable given the weld strength. The foregoing results from the hardness testing of the weld in Docol 1200M lead to a conclusion that its quality is unsatisfactory.

For an ultimate quality assessment of the Docol 1200M weld, strength testing was performed under quasi-static and dynamic loads. The test results were compared to the results of similar tests of the Strenx S700MC weld detailed in [8].

In the quasi-static tensile strength tests of the Docol 1200M weld, all weld specimens ruptured within the HAZ, as a consequence of the hardness loss in the HAZ as observed in the tests.

For non-welded material specimens, the final tensile strength was 1260 MPa in the specimen orientation parallel to the rolling direction and 1290 MPa in perpendicular to the rolling direction. The strength parameters determined for Docol 1200M conformed to the material specifications certified by SSAB. Given the weakening of the specimens within the HAZ, the strength of the weld was weakened by approx. 140 MPa in parallel to the rolling direction and by approx. 170 MPa in perpendicular to the rolling direction. Significant degradation of weld ductility was found: 1.4% and 1% in parallel and perpendicular to the rolling direction, respectively.

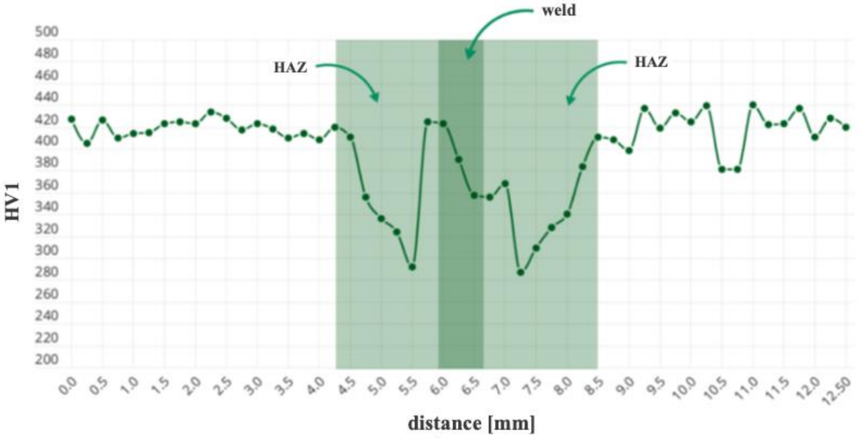

Fig. 10. Hardness distribution in the Docol 1200M welded joints

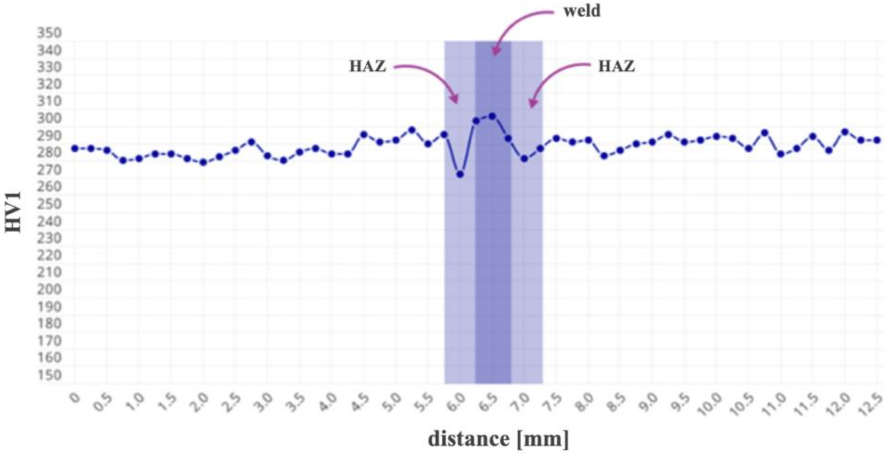

Fig. 11. Hardness distribution in the Strenx S700MC weld [8]

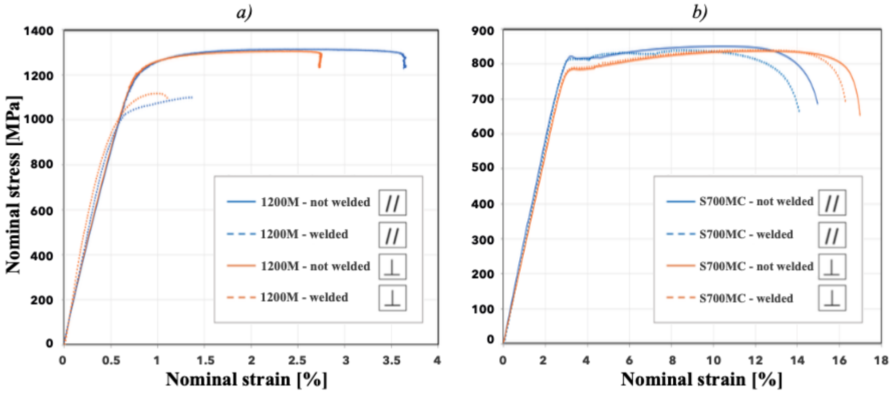

Fig. 12. Quasi-static tensile strength curves in welded and not-welded specimens made from (a) Docol 1200M and (b) Strenx S1700MC

When compared to the results of similar tests of Strenx S700MC, which only revealed a slight degradation of weld tensile strength and ductility [8], the quality of butt welds in Docol 1200M was much lower. It is a consequence of structural heterogeneity (notch) formed during the laser welding process, where stress was concentrated and resulted in localized weakening of the weld material.

The effect of the structural notch on the strength of the Docol 1200M weld was even more prominent in the dynamic strength tests. Fig. 13 shows the dynamic tensile strength curves for Docol 1200M, compared to the similar test curves for Strenx S700MC. The comparison revealed a disproportion of the stress levels of plastic flow between the welded and non-welded specimens.

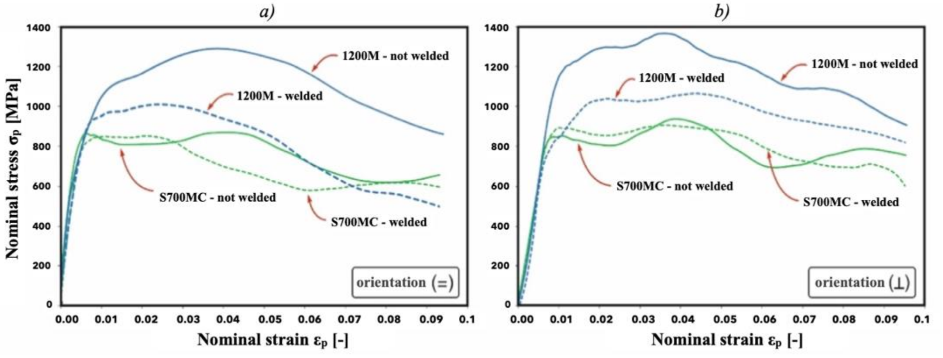

Fig. 13. Dynamic tensile strength curves of the welded and non-welded specimens of Docol 1200M and Strenx S700MC in (a) parallel and (b) perpendicular orientation to the rolling direction

The dynamic tensile strength of the weld was lower by approx. 300 MPa both in parallel and perpendicular orientations. For the reference steel grade (Strenx S700MC), no significant reduction in the weld strength was found: the strain hardening curves for the welded and non-welded specimens were at similar stress levels of plastic flow.

A noteworthy observation is that the dynamic tensile test results proved a low sensitivity of Docol 1200M to the strain rates applied in this work (not unlike Strenx S700MC, which was tested in prior). Given the specifications applicable to mechanical energy absorbers, this property of the tested steel grades is favourable.

A consequence of the weakening of the material within the HAZ was a significant degradation of dynamic ductility of the Docol 1200M welded specimens (Table 3). While the non-welded specimens maintained a high ductility (at approx. *A* = 17% and 15% in the parallel and perpendicular orientation, respectively), the elongation of the welded specimens was reduced to approx. 8%. A similar decrease (by approx. 44%) in the weld ductility was found in the Strenx S700MC sheets [8], which would seem rather surprising given the test results discussed herein.

A dynamic ductility reduction this high in the welds of both tested steel grades was unfavourable given the specifications for the welds of mechanical energy absorbers.

Table 3. Dynamic ductility of the Docol 1200M welded and non-welded specimens

Orientation relative to the direction of rolling	**Specimen gauge length [mm]**	**Specimen gauge length increase [mm]**	**Elongation, *A* [%]**	**Mean elongation [%]**
Parallel (non-welded)	7.02	1.08	15.4	**16.6**
	7.03	1.23	17.5	
	7.01	1.19	17.0	
Parallel (welded)	7.05	0.65	9.2	**7.6**
	7.03	0.51	7.3	
	7.05	0.45	6.4	
Perpendicular (non-welded)	7.03	1.12	15.9	**15.2**
	7.05	1.03	14.6	
	7.05	1.07	15.2	
Perpendicular (welded)	7.07	0.73	10.3	**8.4**
	7.06	0.55	7.8	
	7.05	0.49	7.0	

5. CONCLUSION

The tests of mechanical properties of the butt welds made with 2.0 mm thick Docol 1200M steel sheets revealed that the laser beam welding parameters required optimisation to develop a weld strength most approximate to the mechanical properties of the base material. The authors assume that this will be feasible by applying a laser beam (i.e. laser beam focal spot) of a lower diameter. This will reduce the linear energy input to the material, reducing the HAZ in which the material suffers from deterioration of mechanical strength.

The test results discussed here explicitly indicate a problem with poor ductility of welds in both tested steel grades. The problem was most prominent in Docol 1200M, which revealed extreme loss of elongation during the tensile strength tests at low (0.001 s^{-1}) and high strain rates (1000 s^{-1}). The observed reduced ductility in the welds of Strenx S700MC under dynamic loads requires further investigation. It is unknown why, despite the high ductility of the welded specimens tensioned under quasi-static conditions, similar specimens exposed to SHPB tension would fail at a relatively short elongation. The most likely cause could be an unfavourable geometry of the weld (which featured a sharp transition between the weld edge and the base material surface) which increased the proneness of the weld to rupture by the effect of the structural notch.

Given this, further processing tests of laser beam welding of AHSS steel grades discussed herein should focus on the reduction of ductility loss in welds exposed to dynamic loads.

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Ocena i porównanie właściwości mechanicznych połączeń spawanych wiązką laserową stali Docol 1200M i Strenx S700MC w warunkach obciążenia udarowego

Paweł PROCHENKA[1,2], Jacek JANISZEWSKI[1]

[1]*Wojskowa Akademia Techniczna, im. Jarosława Dąbrowskiego*
ul. gen. Sylwestra Kaliskiego 2, 00-908 Warszawa
[2]*BOZAMET sp. z o.o., Ujrzanów 282A, 08-110 Ujrzanów*

Streszczenie: W artykule dokonano oceny wytrzymałości i ciągliwości doczołowych złączy spawanych laserowo wykonanych z 2 mm blach z martenzytycznej stali Docol 1200 M na podstawie rozkładu twardości oraz wynikach quasi-statycznej i dynamicznej próby rozciągania. Badania technologiczne procesu spawania laserowego zostały przeprowadzone na stanowisku produkcyjnym wykorzystującym włóknowe źródło spawalnicze IPG o maksymalnej mocy 6 kW. Badania przeprowadzono dla próbek materiałowych zorientowanych równolegle i prostopadle względem kierunku walcowania stali. Ponadto, dokonano porównania otrzymanych wyników z analogicznymi rezultatami uzyskanymi podczas badań stali Strenx S700 MC. Badania dynamiczne wykonano za pomocą techniki dzielonego pręta Hopkinsona na rozciąganie z szybkościami odkształcenia rzędu 10^3 s^{-1}. Uzyskane wyniki wykazały, że wytrzymałość stali Docol 1200 M w warunkach dynamicznego rozciągania jest zbliżona do wytrzymałości materiału w warunkach statycznej próby rozciągania. Jednakże ze względu na zrywanie próbek w strefie wpływu ciepła wytrzymałość połączenia spawanego jest zdecydowanie niższa w stosunku do materiału rodzimego, czego nie zaobserwowano podczas badań stali Strenx S700 MC.

Słowa kluczowe: spawanie laserowe, stale wysokowytrzymałe, absorber energii udaru, technika dzielonego pręta Hopkinsona