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Deformation behaviour of welded stainless steel – carbon steel sandwich sheet material

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Formability of welded austenitic stainless steel (321 type) – low carbon steel (1010 type) sandwich sheet material was tested. Gas tungsten arc welding (GTAW) and shield metal arc welding (SMAW) procedures were used. After applying the GTAW welding process the weld metal hardness was found considerably higher than after using the SMAW process, due to a higher consumable fraction in case of the GTAW welding procedure. The bendability of the tested weldments appeared to be satisfying, but the biaxial stretchability of the welded sandwich sheets was considerably lower compared to the base material (33% - 45% degradation). The stretchability degradation brought by welding was found the lowest in the samples welded by the lowest heat energy input. The strain distribution after equibiaxial stretching of the welded sheets was very inhomogeneous due to different hardening abilities of the base and weld metal.

Key words: **stainless steel, carbon steel, sandwich sheet, welding, weldment, deformation, test results.**

Introduction

THERE is an increasing interest in replacing solid stainless steel sheets or plates by sandwich sheet composites due to the opportunity of producing different types of industrial vessels with improved properties at lower cost [1,2,3]. Carbon steel sheets plated with stainless steel on one or both sides take advantage of the corrosion resistance of the austenitic stainless steel while having the strength and low cost of carbon steel. Further improvements are related to the benefits as such improved heat transfer characteristics, good strength and ductility, improved electrical properties, improved vessel design at lower cost. One important point for the successful application of joined sandwich sheets is the ability of the material to sustain different shaping demands affected by the types of acting stress systems and the ductility of weldment.

In this work the AISI 1010 type low carbon steel has been cladded with the AISI 321 stainless steel without inter layer strip using the explosive bonding procedure. Such safely bonded sandwich slabs were further hot-rolled on a continuous hot-rolling mill, using on-line accelerated cooling (OLAC) at the end of the hot- rolling line, avoiding the traditional final heat treatment of austenitic stainless steel [4]. The considered sandwich material consists of components which exhibit good weldability and they are readily joined by standard welding processes in a wide range of applications, extending from thin sheet linings to relatively heavy section joints. The aim of this work was to study the formability of the welded stainless steel – carbon steel sandwich sheet material and the formability degradation in respect the full material, after applying the Shield Metal-Arc Welding (SMAW) and the Gas Tungsten-Arc Welding (GTAW) procedures [5,6,7].

Experimental work

Material

The stainless steel - low carbon steel sandwich slabs were produced by explosive bonding. The bonded slabs after ultrasonic control of the bonding quality were heated up to 1200C^{o} and hot-rolled down to 4.6 mm in the 6-stand tandem rolling mill. The chemical composition of sandwich components is given in Table 1. The stainless steel layers make 10.5% - 14% of the total thickness of the sandwich material.

Table 1. Chemical Composition of sandwich components

	AISI	C %	Mn %	P %	S %	Si %	Cr %	Ni %
Stainless steel.	321	0.10	2.00	0.040	0.030	1.00	18.00	10.00
Low-Carbon steel	1010	0.12	0.50	0.040	0.040	0.040	-	-

Welding

Two different welding procedures were applied to join the tested sandwich sheet: (i) Shield Metal-Arc Welding (SMAW) and (ii) Gas Tungsten-Arc Welding (GTAW) often called Tungsten Inert Gas welding (TIG) [6,7]. Double square-groove butt joints were designed, as shown in Fig.1. The samples were welded without preheat and post-weld heat treatment. Interpases temperatures are typically maintained bellow 100°C - 150°C. Austenitic, 2.5 mm and 3.2 mm diameters E18.8MnB20+ electrodes (ISO 3581 designation) were used in the direct current-electrode positive SMAW process, and the 18/8Mn6 TIG wires in the direct current-electrode negative GTAW process. The chemical composition of the used consumables is listed in Table 2.

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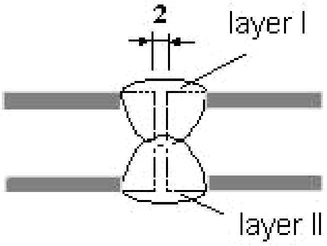

Figure 1. Drawing of the used double square-groove butt joint.

Table 2. Chemical composition of the welding consumables (wt %)

ISO 3581 Designation	Welding Process	C (%)	Cr (%)	Ni (%)	Mn (%)
E18.8MnB20+	SMAW	0.12	19	9	7
18/8Mn6	GTAW	0.12	19	9	7

The heat inputs of 13.4, 8.4 KJ/cm using 2.5mm wire, 17.9, 12.2 using 3.2-mm wire for SMAW and 22.5, 18.8 KJ/cm for the GTAW were applied for layer I and layer II, respectively. These two procedures were used to join the sandwich sheet samples for the uniaxial tension test, as well as for biaxial stretching. Also, all the welding joints were checked up by using liquid penetrantes and radiographic control, avoiding using samples for further testing with any defects in the surfaces or across the bulk. The experimental joints welded by the GTAW process were marked as T, the samples welded by the SMAW process using 2.5 mm and 3.2 mm diameter electrodes were marked as R and D, respectively.

Testing

Hardness measurement. The hardness profiles of the weldments were determined by the Vickers HV10 procedure.

Tensile testing. Sheet specimens with a gauge length of 100 mm were tested on the “AMSLER” tensile testing machine, at a crosshead rate of 10 mm/min. The tensile strength (UTS) of the butt-welded joints was determined on specimens shaped as shown in Fig.2.

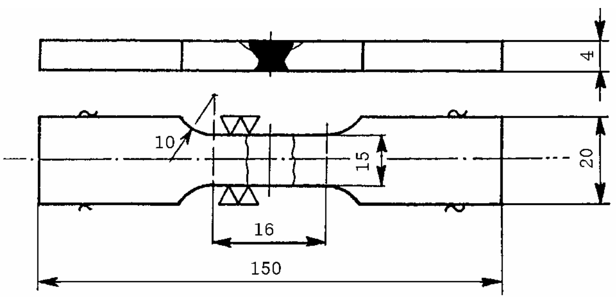

Figure 2. Tensile specimens used for the UTS measurement in butt-welded joints

Bend test. The face bend test and the root bend test (three-point bend) were corred out with a 12m diameter deflector bar.

Dome test - Biaxial stretching. Gridded rectangular blanks of 150 mm were firmly clamped and stretched in a "Hille" hydraulic press, over a 75mm diameter hemispherical punch (Fig.3) [8]. The punch rate was 8 mm/min. Polyethylene foil was used as lubricant. During stretching, the load-punch displacement was recorded. The sheet blanks were prepared from the as-received material, but some of them were cut in halves and then the two halves, were joined applying the considered welding processes.

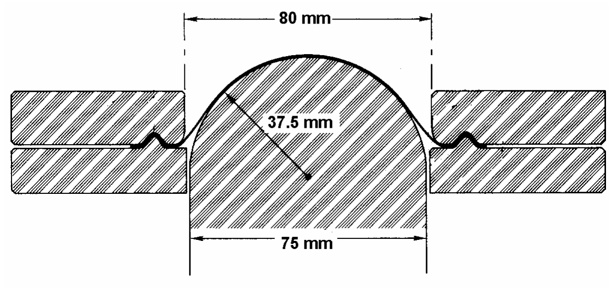

Figure 3. Drawing of the equibiaxial stretching over the hemispherical punch

Results and discussion

Table 3 shows that the ultimate tensile stresses (UTS) are very close for all three types of specimens (marked as T, R and D), ranged to 440MPa ÷ 450 MPa. In all cases fracture occurs in the position of base metal, implying deformation concentration in the softer base metal, which is assumed to be the reason for the very close UTS values.

Table 3. Welding conditions and mechanical properties of weldments

Welding method	Consumable (ISO3581)	Weld. current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (KJ/cm)	UTS (MPa)	Bend test: Face bend	Bend test: Root bend
GTAW	18/8Mn6 ϕ2.5 mm (T)	120	22	I layer-7	22.5	450	good	good
				II layer-8.4	18.8			
SMAW	E18.8MnB20+ ϕ2.5 mm (R)	80	28	I layer-10.0	13.4	440	good	good
				II layer-16.0	8.4			
	E18.8MnB20+ ϕ3.2 mm (D)	110	28	I layer-10.3	17.9	445	good	good
				II layer-15.1	12.2			

The hardness variation across the welded specimens after applying the GTAW welding procedure (T samples) and SMAW procedure (R and D samples) is shown in Figures 3 and 4, respectively. The base metal hardness was ranged to ~ 140-150 HV, while the hardness markedly increased in the weld metal, reaching ~ 240 HV in R samples, ~ 270 HV in D, or even ~ 500 HV in the case of T samples. The considerably higher hardness attained in the latest sample is attributed

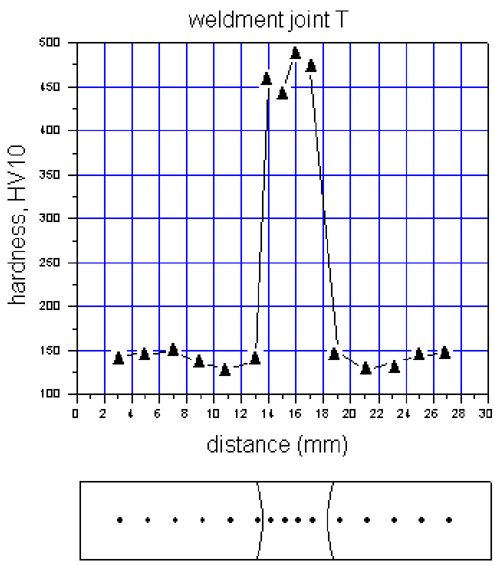

Figure 4. Hardness variation of the welding joint after applying the GTAW process (T sample)

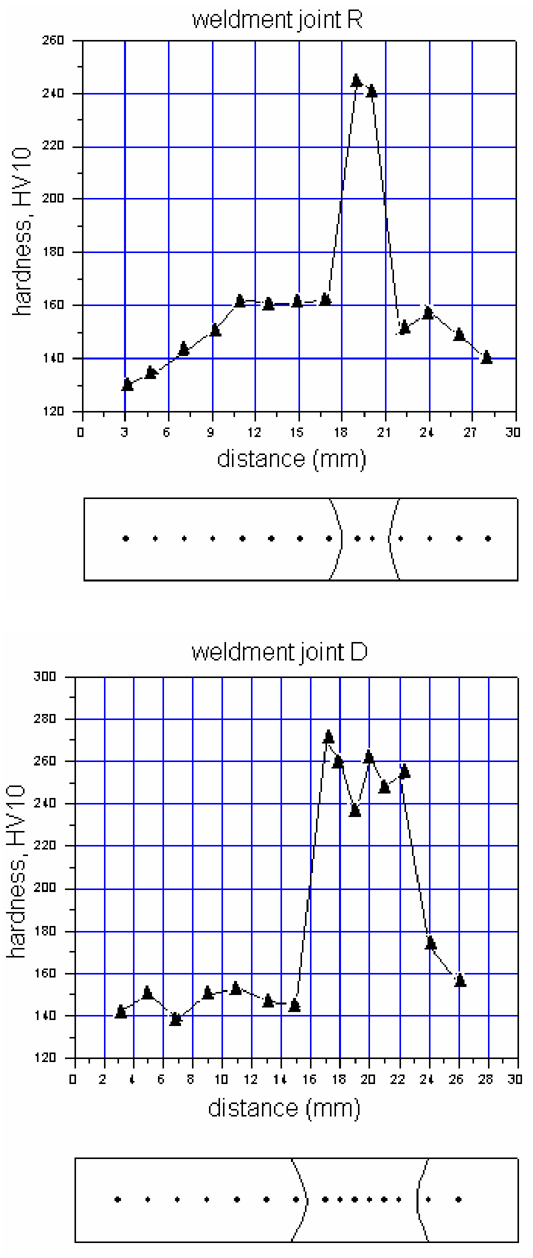

Figure 5. Hardness variation of welding joints after applying the SMAW process (R and D samples)

to the higher consumable fraction after applying the GTAW welding procedure compared to the SMAW process. Namely, the hardness of the weld metal mostly depends on the base metal portion melted in the weld metal (compared to the portion of the filler material) and also on the metallurgical reactions in the melting pool.

The bendability of the tested weldments appeared to be satisfying in all cases. Cracks were not detected on the tensile surfaces after bending more than 140° in both face and root bend tests.

Table 4 and Fig.6 show the load and dome heights (indentation depth) attained during equibiaxial stretching of the bulk sandwich material (base material) and the welded samples. The given results, showing degradation of dome heights in case of welded samples, make clear that the biaxial stretchability of the welded sheet samples is significantly decreased.

The biaxial ductility decreased for ~ 33% in the case of R weldments, and in the cases of T and D weldments for ~ 43% and ~ 45 %, respectively. The necessary stretching load is also lowered according to the lower degree of stretching attained in the welded sheets. It therefore seems that the SMAW welding process for the R condition (see Table 3.1) allows much better biaxial stretching properties of the tested sandwich sheets than after the D welding condition.

Table 4. Degradation of load and depth

Sample	Load [kN]	Dome height [mm]	Load degradation [%]	Dome height degradation [%]
Base material – A	78	42	-	-
weldments R	57	28	26.9	33.3
weldments T	51	24	34.6	42.8
weldments D	44	23	43.6	45.2

or after the T condition applied by the GTAW welding procedure. It was assumed that the superior stretchability brought by the R procedure is due to the lowest heat energy input and appropriately the narrowest heat affected zone (HAZ). This effect can be recognized as a shortest range of the risen hardness for the R sample in respect to the T and D samplkes (Figures 4 and 5).

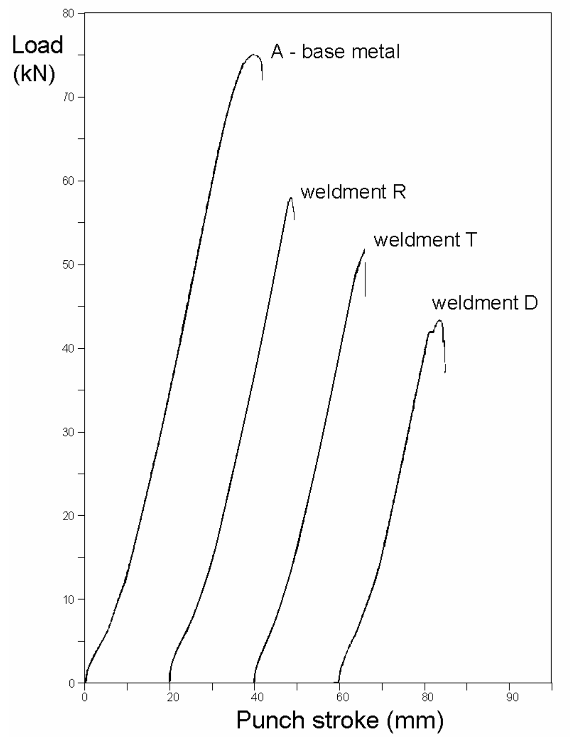

Figure 6. Load and dome height curves for the sandwich sheet materials and welded sheet samples after the application of different welding procedures.

It should be also noted that the influence of the heat energy input on the level of biaxial stretchabilty, it could be further improved, in case of the T samples as in the GTAW process the energy input can be more concentrated, i.e. the heat affected zone more reduced.

The HAZ influence on the stretchability of welded sheets can be recognized easily by following the strain distribution normally to the weld metal [9,10]. Such measurements are shown in Fig.7 for the R sample. The measurements in the transverse direction indicate an abrupt drop of the radial and circumferential strain components in the area of the weld metal. The noticed effect indicates that during equibiaxial stretching of the welded sheets, the deformation distribution is very

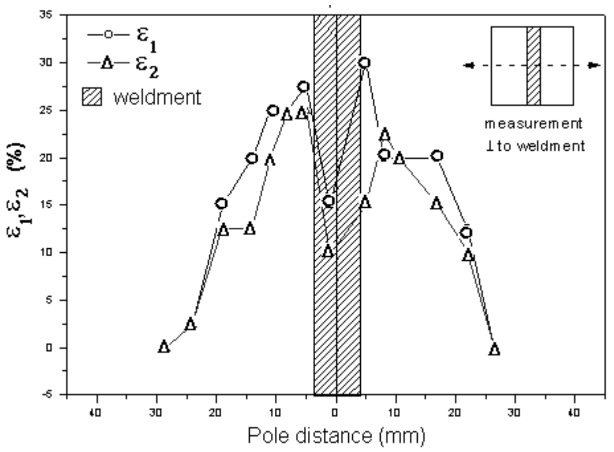

Figure 7. Strain distribution for weld metal R-90°

inhomogeneous, as the weld metal does not strain equally with the base material, because of the different structure and mechanical properties compared to the base material.

In Fig.8 comparison is made between the strain distribution in the base material and the one in the weldments (along the weld metal). The area difference under the strain distribution curves for the base material and the weldments basically reflect the stretchability difference of those materials [11,12]. Considering the strain distribution in Fig.8, besides the higher strains attained in the base material compared to the weldments, it is interesting to note that the ability of the strain

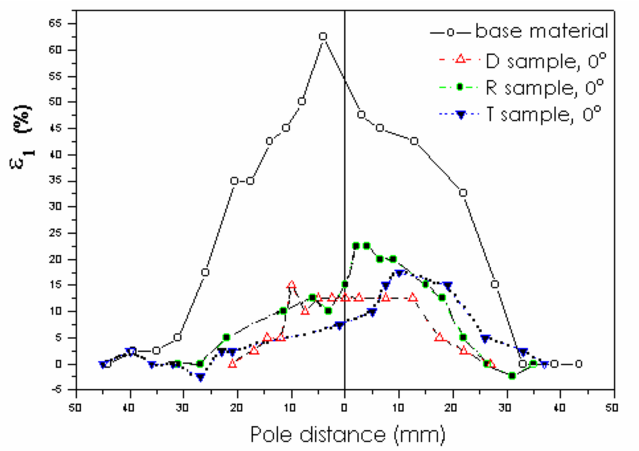

Figure 8. Comparison of strain distributions across the dome attained in the base material and the sheet samples welded by T, R and D procedures.

distribution of the tested weldments is basically in accordance with the considered effect of the heat energy input influences. It seems that the largest area appeared under the R-sample strain distribution curve, followed by the areas under the curves for T and D samples.

Such a formability limitation of welded sheets was recognized in suiting the so-called Tailor Welded Blanks (TWB's), for forming application in car industries [6,7,9,10]. Today they are joined by laser welding, producing the most localized HAZ [6, 8] and offer a good way to save the formability potential of the base material.

Summary

Formability of welded austenitic stainless steel (321 type) – low carbon steel (1010 type) sandwich sheet material was tested. Two welding procedures were applied: the gas tungsten arc welding (GTAW) and the shield metal arc welding (SMAW). The sandwich sheets were tested using uniaxial and equibiaxial stretching in order to asses the basic mechanical properties and stretching behavior of the welded sheets.

After applying the GTAW welding process the weld metal hardness was found considerably higher than after using the SMAW process, which is assumed to be due to the higher consumable fraction in case of the GTAW welding procedure compared to the SMAW one.

The equibiaxial stretching tests have shown that the biaxial formability of the welded sandwich sheets is considerably lower compared to the formability of the base material (33% - 45% is lower compared to the base material). It was also found that the ductility degradation brought by welding of the tested sandwich sheet material was the lowest in the samples welded by the lowest heat energy input, i.e. the most suppressed range of the heat affected zones.

The strain distribution measurements revealed that during equibiaxial stretching of the welded sheets, the deformation distribution is very inhomogeneous, as a result of the interplay of the deformation properties of the harder weld metal and the softer - more ductile sandwich base material.

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Deformaciono ponašanje zavarenog spoja sendvič lima nerđajući čelik – ugljenični čelik – nerđajući čelik

U radu su prikazani rezultati ispitivanja deformacionog ponašanja zavrenih spojeva platiranih (sendvič) limova nerđajućeg čelika (klase 321) - niskougljeničnog čelika (klase 1010). Zavarivnje je obavljeno u atmosferi inertnog zaštitnog gasa netopivom volframovom elektrodom (TIG postupak) i ručnoelektrolučnim postupkom bazično obloženom elektrodom (REL postupak).Tvrdoća metala šava kod spojeva zavarenih TIG postupkom je značajno veća nego tvrdoća metala šava kod spojeva zavarenih REL postupkom zbog većeg udela dodatnog materijala u metalu šava. Savojne karakteristike zavarenih spojeva mogu se smatrtati zadovoljavajući, ali rezultati dvoosnog razvlačenja zavarenih spojeva su značajno niži u odnosu na osnovni materijal (33%-45% niže vrednosti). Najmanji pad sposobnosti za razvlačenje je dobijen kod spojeva zavarenih uz najmanji unos toplote. Raspodela deformacija posle razvlačenja zavarenih spojeva je nehomogena zbog razlike u mogućnostima za ojačavanje osnovnog materijala i metala šava.

Ključne reči: **nerđajući čelik, ugljenični čelik, sendvič lim, zavarivanje, zavareni spoj, deformacija, rezultati ispitivanja, platirani limovi, zavarivanje, deformabilnost.**

Деформационное поведение - характер изменения сварного соединения слоистого листового металла нержавеющая сталь - углеродистая сталь - нержавеющая сталь

В настоящей работе показаны результаты исследования деформационного поведения - характера изменения сварных соединений слоистых листовых желез нержавеющей стали (класса 321) - низкоуглеродистой стали (класса 1010). Дуговая сварка сделана в атмосфере инертного защитного газа неплавким вольфрамовым электродом (ТИГ-поступок) и ручным электроннолучевым поступком базовым экранированным электродом (РЕЛ-поступок). Твёрдость металла шва у сварных соединений ТИГ-поступком значительно больше твёрдости металла шва у сварных соединений РЕЛ-поступком из-за большего расхода добавочного материала в металле шва. Характеристики на изгибе сварных соединений можно считать удовлетворёнными, но результаты двухосного расширения сварных соединений значительно ниже по отношению к основному материалу (33% - 45% ниже значение).
Наименьшее ухудшение способности расширения получено у сварных соединений со наименьшим вкладом теплоты. Распределение деформаций после расширения сварных соединений негомогенное из-за разницы во возможностях для усиления основного материала и металла шва.

Ключевые слова: нержавеющая сталь, углеродистая сталь, слоистое листовое железо, сварка, сварное соединение, деформация, результаты исследования.

Le comportement de déformation des soudures chez les plaques sandwich en tộle acier inoxydable – acier au carbon –acier inoxydable

Les résultats des essais sur le comportement de déformation des soudures chez les tộles en acier inoxydable (classe 321)- acier au carbon bas (classe 1010) sont présentés dans ce travail. Le soudage est effectué dans l'atmosphère du gaz inerte protectif au moyen de l'électrode en tungstène (procédé TIG) et par le procédé manuel du soudage électrique à l'arc(procédé REL) La dureté du métal de la soudure réalisée par le procédé TIG est considérablement plus grande que celle chez la soudure faite par le procédé REL, ce qui est dû à plus grande quantité du matériel supplémantaire dans le métal de la soudure. On peut considérer les caractéristiques élastiques des soudures satisfaisantes alors que les résultats de l'extension biaxiale des soudures sont beaucoup plus bas par rapport au matériel de base (dégradation de 33% à 45%). La plus petite dégradation de la capacité de l'extension est obtenue chez les soudures réalisées à la température plus basse. La distribution des déformations après l'extension des soudures est nonhomogène à cause des différentes possibilités de renforcer le matériel de base et le métal de soudure.

***Mots clés*: acier inoxydable, acier au carbon, tộle sandwich, soudage, soudure, déformation, résultats des essais.**