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Toughness of welded stainless steels sheets for automotive industry

E. Bayraktar [a,b,*], D. Katundi [a], B.S. Yilbas [c], J. Claeys [d]

[a] Supmeca -Paris, School of Mechanical and Manufacturing Engineering, France
[b] Chair of Industrial Materials, CNAM, Arts et Métiers, 75141 Paris 03, France
[c] KFUPM, Mechanical Engineering Department, Dhahran, Saudi Arabia
[d] ARCELOR Group, Stainless Steel Europe, France
* Corresponding author: E-mail address: bayraktar@supmeca.fr

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Properties

ABSTRACT

Purpose: In the automotive industry, more and more it is compulsory to develop new grades of stainless steels, such as high resistant Martensitic Stainless Steels (MA-SS) and Ferritic Stainless Steels (FSS) in order to realise certain or many complex deep drawn pieces. For these grades, resistance spot welding (RSW) is the most widespread process used largely for many parts of the car body in the automotive industry. This paper aims to characterise mechanical behaviour (toughness) of the different steel grades under dynamic test conditions.

Design/methodology/approach: A special crash test device is used in different temperatures and the simulated crash tests are performed at a constant speed of 5.52 m/s.

Findings: The specimen is submitted to impact tensile test at different temperatures. According to testing temperature, fracture mode varies: At low temperatures, brittle fracture occurs: due to stress concentration, fracture always occurs in the notched section. At high temperatures, the specimen fails by ductile fracture. Toughness of the steel sheets (base metals, BM or welded parts) is well compared at different materials and test conditions.

Research limitations/implications: Evaluation of welded thin sheets submitted to the dynamic loading in order to correlate in real service conditions in order to realize a useful correlation between the transition temperature and deep drawability can be used for evaluating of the welding conditions and also of the material characteristics. For detail study, this type of the test needs a standard formulation.

Practical implications: This is a new conception of specimen and of the impact/crash machine. It is widely used in automotive industry for practical and economic reason to give rapid answers to designer and also steel makers for ranking the materials.

Originality/value: New developed test called impact crash test for evaluating the toughness of thin welded joints (tailored blanks) / mechanical assemblies in high formability steel sheets for stamping submitted to dynamic loads such as experienced in real crash tests.

Keywords: Heat treatment; Resistance spot welding; Microstructure; Hardness

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1. Introduction

New grade sheet steels are generally deep-drawn in specific or complex form in the automotive industry and manufactured by welding more often followed by forming operations. In the automotive industry, it was necessary to develop new grades of steels such as high strength Interstitial Free Steels (IFS) and Ferritic and/or Martensitic Stainless Steels (FSS-MSS) in order to realise certain or many complex deep drawn pieces. Mainly, IF steels contain extremely low carbon and nitrogen values which make them particularly suitable for deep drawing operations. However, many parts used in the body car such as floor panel, tailgate, etc. are manufactured by stainless steel sheets essentially ferritic and martensitic stainless steel sheets (AISI 409-stabilised, 430Ti-stabilised and 430-non-stabilised, Martensitic - MA stabilised and non-stabilised) for the reasons of special characteristics anti-corrosion and toughness, high resistance against crash etc.). Former works have given some experimental results on the toughness and resistance during the choc on the different composites of the stainless steel sheets [1-14]. This paper reviews more details on the stainless steel and the relation between microstructure -toughness properties and heat treatment to optimise the formability and toughness properties.

2. Experimental procedures

2.1. Test conditions

Three grades of Ferritic stainless steels – FSS (AISI 409-stabilised, 430Ti-stabilised and 430-non-stabilsed) and Two grades of 410-MA (Martensitic Stainless Steel), MA1-without heat-treated and MA2 with heat treated conditions elaborated by ARCELOR have been studied. Their thickness varies between 1.2 and 2 mm. The carbon and manganese concentrations vary from $2.5*10^{-3}$ wt% to 40 $*10^{-3}$ wt% and from $150*10^{-3}$ wt% to 600 $*10^{-3}$ wt%, respectively. Welding speed for LASER CO_2 (Q=5.5 kV) varies from 4 to 11 m/min. Here, three grades of IFSs (IF-Ti, IF-HR and FEPO6G) used in automotive industry have been given for only comparison with that of stainless steels. The general compositions of the grades of stainless steels were given in the Table 1.

Hardness values were measured across the welds under 200 g of load (HV). Erichsen tests were carried out according to the norm of ISO R 149 on the base metal and welded sheets by LASER and TIG processes for measuring deep drawing capacity of the thin sheets. Finally, Impact Tensile Tests (ITT) was carried out at different temperatures on the special specimens taken from welded parts and base metals with a special device mounted on an impact pendulum.

3. Results and discussion

3.1. Microstructural evaluation

Evaluation of microstructure after LASER welding operations carried out on the FSS grades (AISI 409-stabilised, 430Ti-stabilised and 430-non-stabilsed) were given in the Figures 1 and 2 as a reference so as to explain the deep drawing capacity and the crash resistance of the welded parts of these steels. General microstructural observations indicate that a certain proportion of martensite is seen in the LASER welded parts of the non stabilised grade of 430 and the amount of martensite is higher than that of other results formerly given in the literature for GTAW (Gas Tungsten Arc Welding) and also RSW (Resistance Spot Welding) processes [1, 4, 9].

The stabilised grades of 409 and 430Ti present entirely ferritic structure with a reasonable grain size. The amount of the equiaxed zone in the centre of the weld bead increases with the welding speed of the LASER process. These Figures explain also the influence of welding speed (LASER) on the solidification mode (ferrite nucleation and equiaxed solidification-typical epitaxial nucleation during the solidification).

The chemical analyses carried in these grades showed that the appearance of the equiaxed grains at centre of the weld bead is related to the presence of titanium nitrite and/or oxide nuclei (Figure 2b).

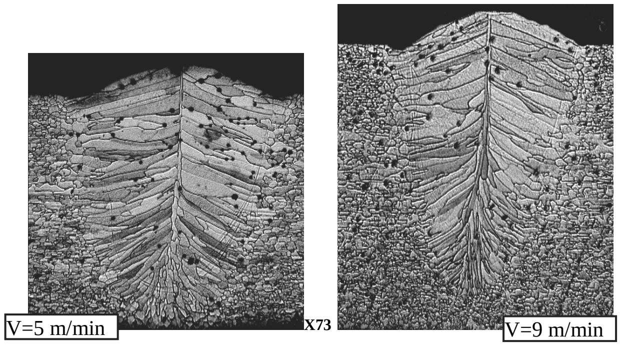


Fig. 1a. Solidification structure of weld bead (AISI 409, t=1.5 mm, LASER CO_2 Welding, Q=5.5 kW)

Table 1.
Chemical composition of stainless steel grades (10^{-3}%)

AISI	C	Mn	P	Si	Al	Ni	Cr	Cu	Mo	V	Ti	N_2	Co
409	11	160	24	400	34	80	11040	40	20	50	220	11	60
410-MA	125	405	32	360	-	293.3	12330	105	17.32	81.3	58.2	27.71	25.9
430	38.7	200	25	160	-	150	15250	80	-	73	10	43.1	60
430Ti	23	360	20	490	20	150	15470	50	20	85	290	14.3	70

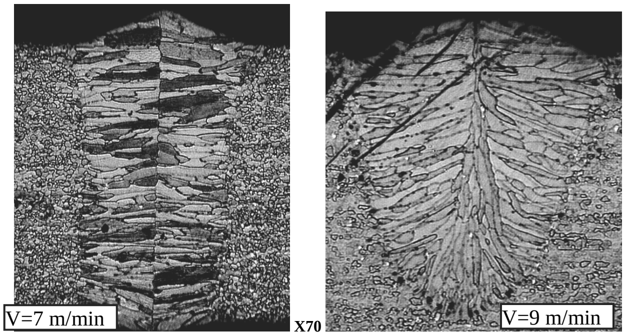


Fig. 1b. Solidification structure of weld bead (AISI 430, t=1.5 mm, LASER CO_2 Welding, Q=5.5 kW)

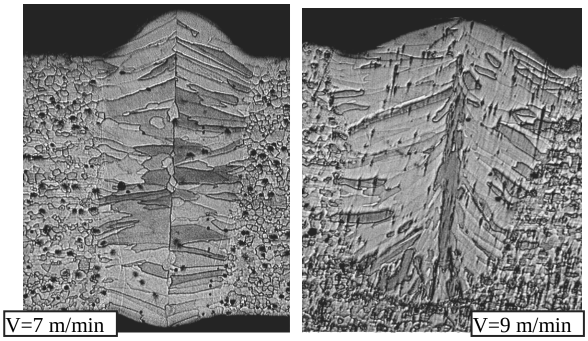


Fig. 2a. Solidification structure of weld bead (AISI 430Ti, t=1.5mm, LASER CO_2 Welding, Q=5.5 kW)

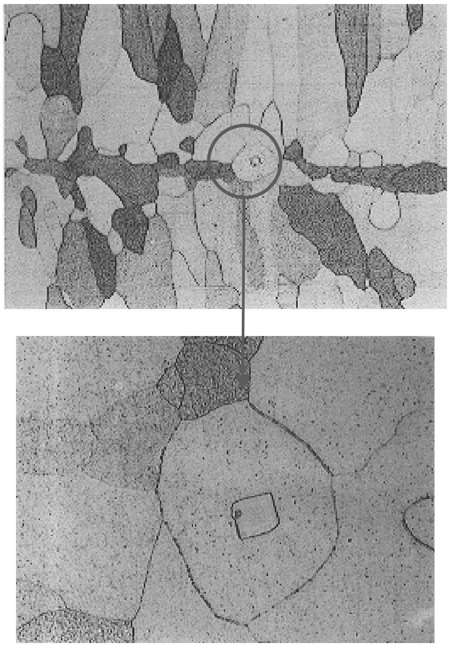
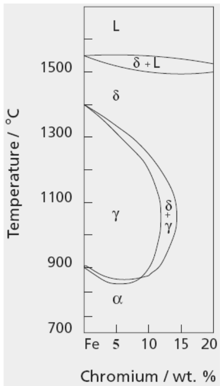


Fig. 2b. Titanium inclusion caused to the formation of equiaxed grain in weld bead (AISI 430Ti, LASER CO_2 Welding, Q=5.5 kW)

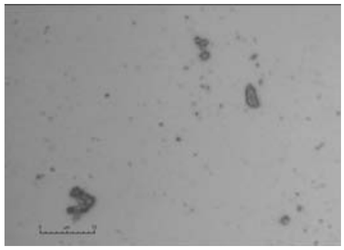
Low-carbon martensitic stainless steels are essentially alloys of Fe, Cr and Ni. Figure 3a shows that a pure Fe-12-13 %Cr binary alloy cannot be made fully austenitic at solution temperatures. During cooling from the melt, low carbon martensitic stainless steels first solidify as δ-ferrite followed by austenite precipitation. Further cooling below the martensite-start temperature (Ms), leads to the transformation of austenite into martensite.

The possible phases found in actual materials are therefore martensite, retained austenite and δ-ferrite but also carbo-nitrides such as Ti(C,N), because the low level of carbon and nitrogen coupled with the high stability of Ti(C,N) means that precipitation of other carbo-nitrides is very limited [1, 10, 11, 14].

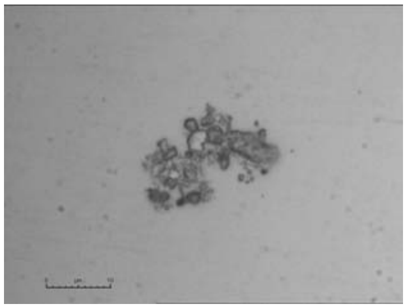
For martensitic stainless steel grade, 410 MA studied here, two different evaluations have been carried out. In the first series (410MA1), the initial microstructure has been analysed without heat treatment. In the second series (410MA2) has been analysed after heat treatment (>950°C, dwell time 15 minutes after quenching). Figures 3b and 3c shows the structure without etching for the 410-MA1 and 410 MA2.



a)



b)



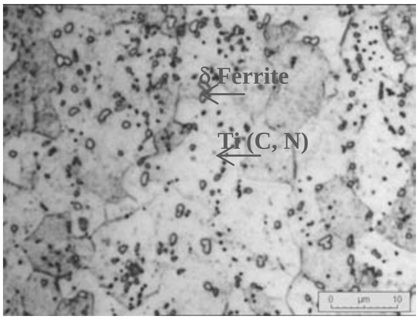
c)

Fig. 3. a) Fe-Cr phase diagram; b) microstructure of precipitations in 410MA1 and c) 410MA2 without etching

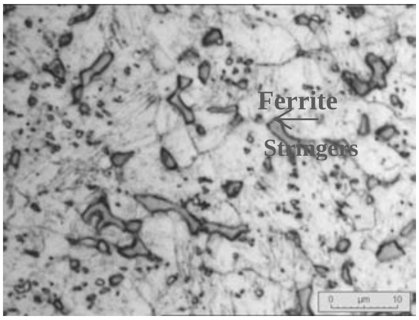
In these structures (Figures 3b and 3c), typical cuboid Ti(C, N) precipitates were the only observed non-metallic particles. These particles were up to 10 µm long and occurred in random dispersion or as small distinct clusters.

After that, the microstructure were exposed after polishing the specimen, to a 1 µm finish and by etching using the "Villella's reagent" modified by UGINE-ARCELOR (Figures 4a and 4b).

They consisted of tempered martensite with some occasional ferrite stringers in the matrix structure, in other words, the microstructures is very close to the martensitic/ferritic structure.



a)



b)

Fig. 4. a) Microstructure of 410MA1 and b) 410MA2 with etching

3.2. Impact Tensile-Crash tests (ITT) and correlations of the mechanical properties

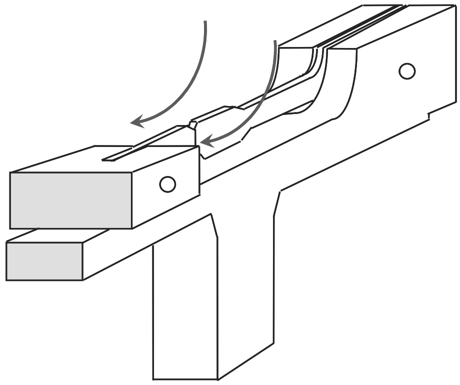
The main principles of the impact – crash tests (ITT) has been explained formerly in literature and recently applied with success for testing of welded thick and thin plates. This test is based on the use of a special tensile specimen (Figure 5) which includes a smooth part and a notched part. In this figure, impact test device has also been indicated.

In the case of weld testing, this latter part recreates the presence of strain concentrations, which may result from weld defects (cracks, porosity) or misalignment, imperfect geometry.

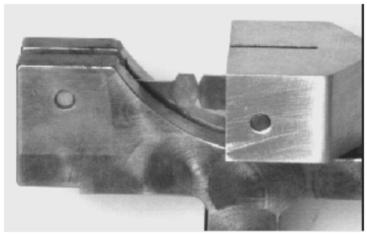
According to testing temperature, fracture mode varies: at low temperatures, brittle fracture occurs. Due to stress concentration, fracture always occurs in the notched section. Failure criterion is the attainment of the cleavage stress by the maximal local stress. This event happens before the smooth section has reached plastic yield.

In other words, notched section fails by brittle fracture while smooth section stress remains purely in the elastic domain. Fracture energy obtained is naturally low. In fact, stress applied in the notch area in ITT is limited by the load capacity of the smooth section.

Thus, this test should avoid the situation where ductile initiation occurs at the notch tip [2-3]. At high temperatures, the specimen fails by ductile fracture. At the first time, ductile failure will always occur in the smooth specimen. This can be derived from the plastic consolidation in the notched specimen, and because of the fact that ductile failure criterion at a given applied tensile load is satisfied primarily in the section of the smooth specimen [2-3, 9, 12, 13].



a)



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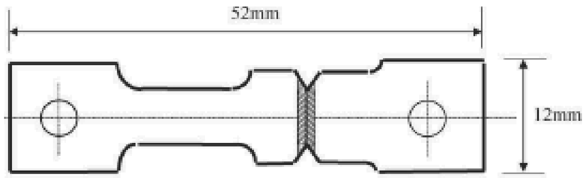


c)

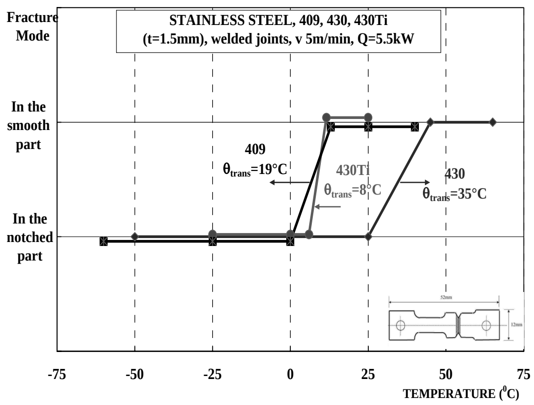
Fig. 5. a, b) Specimen and impact test device for fixation, c) example of specimen geometry used for testing welds in ITT

In accordance with the test principle, the specimens are submitted to impact tensile testing at different temperatures. In fact, the ductile-brittle transition temperature (DBTT) depends of course on various parameters such as temperature, specimen thickness, deformation rate, notch geometry, metallurgical factors etc. Additionally, the problem is not the base metal toughness but to be able to make a good estimate of the toughness of welded parts in the conditions of car crash. In the high strain-rate conditions, low toughness of welded zones and or base metals after heat - treatment for some sensitive steel grades favours localised fracture even at moderate temperatures.

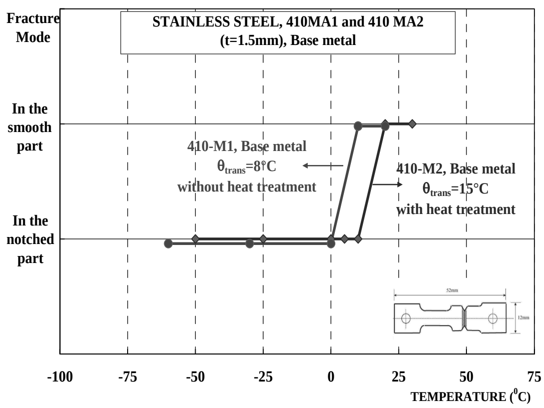
For that reason, evaluation of ductile-brittle transition temperatures of welded sheet is a sensitive parameter and is a very useful tool to qualify new welding processes especially for new steel grades. On the contrary to base metal testing, specimens including welds have heterogeneous structure because of local modification during welding. Fracture competition between these two sections during impact loading is more complex because of different mechanical properties [2-3, 9, 12, 13].

In this study, the ITT tests were carried out on the Stainless steel grades; welded FSS (409-430-430Ti) specimens including a smooth part and a notched (welded) part and also MA-SS base metal (410MA1-410MA2). Specimens with a special device have been mounted on an impact pendulum. According to testing conditions and material toughness, fracture occurs in one of these two zones with a very sharp transition.

The Figures 6a and 6b show the evolution of the DBTT of the different grades of stainless steel. DBTT are found to be around 8, 19 and 35°C for the grades of FSS, 430Ti, 409 and 430, respectively. These results are related also the percentage of the equiaxed grain in the centre of the weld bead as explained in the Figure 2. It means that the higher percentage of the equiaxed grains in weld bead gives the higher resistance to the impact conditions and naturally gives the lower ductile-brittle transition temperature due to improved structure in weld bead by LASER welding.



a) 409-430-430Ti

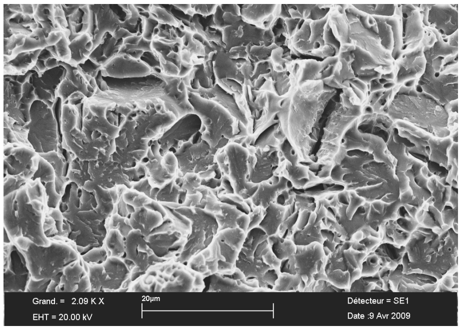


b) 410MA1-410MA2

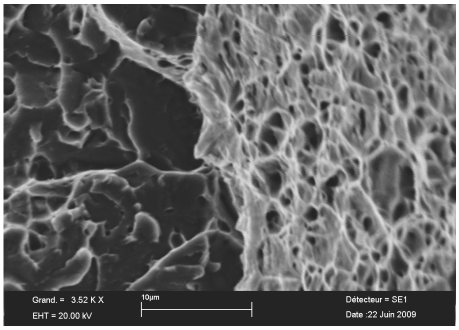
Fig. 6. Ductile-Brittle Transition Temperature (DBTT) of AISI steel grades welded by LASER, Q=5.2 kW

Meanwhile, these values are determined to be 8 and 15°C for the grades of 410MA1 and 410MA2, respectively. The lower resistance to impact conditions with 410MA is related to the heat treatment that is a future study of this project going on.

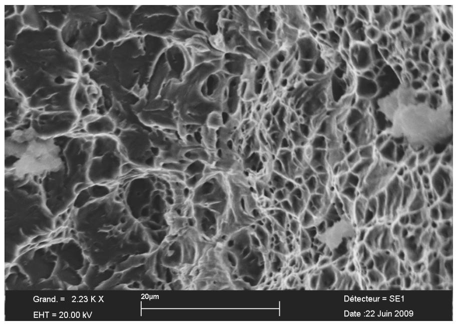
Fracture surfaces after impact crash test for the grade of 410MA have been shown in Figure 7 which indicates brittle fracture surface passage from brittle to ductile fracture etc. and also some of the specimens indicated two parts - passage from brittle to ductile fracture- have been prepared for microhardness evaluation (Figure 8). An indicative result can be obtained from this microhardness evaluation that can verify the effect of the heat treatment applied on this grade.



a) Brittle fracture



b) Passage from brittle to ductile fracture



c) Mixed; passage from brittle to ductile fracture

Fig. 7. Fracture surfaces after impact crash test on the steel grade of 410-MA, Base Metal

Another idea is given here with a correlation, between transition temperature and Erichsen indices (Figure 9) and a comparison of stainless steel sheets with IFS grades so as to evaluate mechanical and metallurgical properties. It seems that the ductile brittle transition temperature decreases when the deep drawing capacity of the steel sheets studied here. In fact, ITT and deep drawability tests can not be positioned on the same plane. In other words, ITT characterises a DBTT mode in fracture in dynamic loading conditions. Thus, it is sensitive to the physical parameters playing a role on the cleavage (grain size, other defects, etc.).

However, deep drawability test, of which ultimate stage is mostly the plastic failure by ductile fracture, is mainly sensitive to the flow rule of materials during the deformation and also to the presence of particles of the second phase. Meanwhile, Figure 9 shows a confidence correlation between these two variables and it should be considered as an indicative presentation, because it reflects micro-structural parameters which influent both of these two type of tests. These parameters are useful in practical press shop applications.

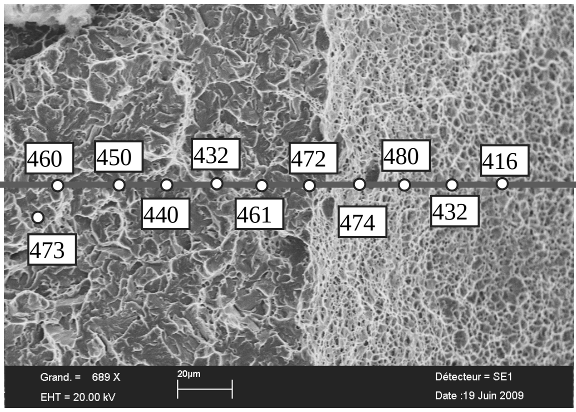


Fig. 8. Hardness evolution at the fracture surface HV, 200 g on the polished and etched surface

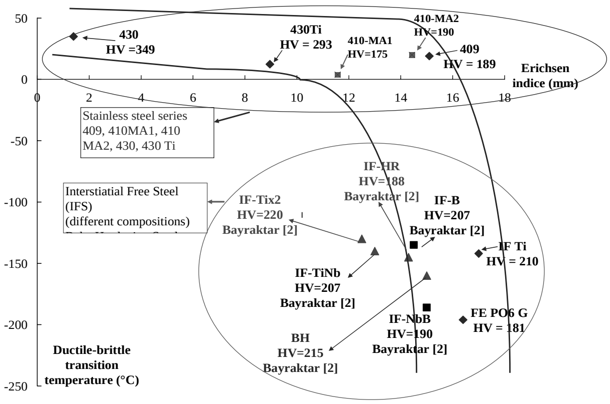


Fig. 9. Correlation between transition temperature and Erichsen values for IFS, Stainless Steel grades

4. Conclusions

Stainless steel grades are potential for applications in automotive industry. Welding process essentially LASER welded parts show higher quality. However, heat treatment (austenitising and quenching) conditions should be improved for the grades of 410MA. They have shown very brittle behaviour after treatment and also welding processes that were not presented due to our going on- research project. Impact Tensile-Crash Test with its own possibilities and limitations, can not suggest a complete satisfactory answer to this question and estimates simply the resistance of welded or thin plates to fracture in dynamic loading conditions in industrial applications.

It is very easy and practical tool to perform and provide a clear ranking, in terms of welding conditions and steel compositions to optimise design conditions in industrial applications.

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