Cold-worked austenitic stainless steels in passenger railcars and in other applications

Wladyslaw Jaxa-Rozen, P. Eng.

Bombardier Transportation – North America

Abstract

The structural applications of cold-worked austenitic stainless steels are reviewed in a historical perspective, with an emphasis on passenger railcars. The base materials are described, including their mechanical and technological properties. Some notions of carbody design are presented, together with the challenges related to design practices involving the discussed materials. The fabrication processes are described. Information on resistance and arc welding processes is provided, including a description of the equipment, procedures qualification and production control. Challenges relative to the wider application of cold-worked austenitic stainless steels are discussed.

Keywords

Cold-working, austenitic stainless steel, passenger railcars, design, welding, resistance welding, arc welding.

1 Introduction

Cold-worked austenitic stainless steels (CWASS) represent a remarkable structural material. They possess a unique assembly of advantages, namely high strength, high ductility, ease of metalworking and welding operations, and corrosion resistance.

The first CWASS structures were railway passenger cars made in the mid 1930's. It was a beginning of a great success story which continues to this day. CWASS also found applications in areas such as tubular structures, road transportation (buses, trailers, and tank cars), lightning (masts and poles), storage tanks, and others.

The first part of this paper is devoted to passenger railcars. Other applications are discussed in the second part of the paper. The last part is devoted to the challenges and opportunities relative to CWASS applications.

The overall goal of this paper is to increase awareness of CWASS properties and their advantages among the scientific community, and, first of all, among potential users. To this effect, the successful application of CWASS in passenger railcars should act as an encouragement for its successful extension to other areas.

2 Passenger rail cars

2.1 History

2.1.1 Beginning

The beginning of stainless steel application in passenger railcar fabrication represents a fascinating feat of engineering. It is linked to the creativity and vision of Edward Gowan Budd (1870-1946), founder of the Edward G. Budd Manufacturing Company of Philadelphia, Pennsylvania. His company was the first to produce all-steel automobile bodies, and one of the first to use resistance spot welding.

Fig. 1 Edward Gowan Budd (Courtesy of Hagley Museum & Library)

During his visit to Europe in 1930, Edward Budd became fascinated with stainless steel. At the same time, Ralph Budd, president of Burlington Railway, had the idea of applying stainless steel in railway car design and fabrication. Two important developments followed: the mastery of production of 18-8 cold-worked high strength austenitic stainless steel by the Allegheny Steel Co., and the growing experience and competence of the Budd Co. regarding formability and resistance spot welding of the material. As a final result, a new kind of passenger rail vehicle was created and put into service in 1934. This was the birth of the Zephyr trains (Fig. 2), which represented a major paradigm shift in passenger railcar design. In comparison with existing railcars, the weight of the train was significantly reduced, which in turn made possible the very first application of a diesel-electric propulsion unit. In a display of its speed, the first Zephyr made a 1632 km non-stop drive from Denver to Chicago at the record average of 125 km per hour [1]. The sleek silvery train was one of the forerunners of the "Streamline" tendency in industrial design. The Zephyr trains changed railway travel, due to their speed, comfort, and amenities such as careful interior design, air conditioning, and an audio system broadcasting radio, public addresses and music from wire recorders.

Fig. 2 Burlington Zephyr (Courtesy of Burlington Route Historical Society)

2.1.2 Progress

Budd's example was followed by the St. Louis Car Company and Pullman-Standard in the United States. Together they produced thousands of stainless steel passenger railcars. The next important development occurred in Japan, where stainless steel passenger railcars, mostly for subway and commuter trains, have been massively produced since the end of the 1950's. In Asia, stainless steel railcars are also produced in India and in South Korea.

In North America, Bombardier Transportation has been fabricating stainless steel cars since the beginning of the 1980's in its plants in La Pocatière, Québec, Canada and in Plattsburgh, New York, USA. These cars include shuttle cars for the Eurotunnel, the largest railcars of any kind ever produced (Fig. 3). Some Japanese companies also produce stainless steel cars at satellite plants in the United States.

In Australia there are over 2000 stainless steel cars in service. They represent above 80% of all passenger cars in the continent.

In Europe, for reasons which are associated with a traditional requirement for carbodies to be entirely painted, stainless steel cars gained only limited popularity.

Fig. 3. Eurotunnel shuttle cars. Locomotive is of standard size. (Courtesy of Nickel Institute)

2.2 Materials

2.2.1 Chemistry

The first stainless steel railcars were made from an austenitic 18-8 alloy produced by Allegheny Steel of Pittsburgh. Relatively high carbon content made this steel susceptible to chromium carbide precipitation in heat-affected zones (HAZ) of welds, and to subsequent intergranular corrosion. The need to limit dwell time in the critical temperature range led Budd's experts to invent the 'Shotweld' short-time spot welding process [2].

In the 1950's and 1960's, 201 and 202 Cr-Mn-Ni steels were also applied. Later, 17-7 type 301 (1.4310) steel was introduced. Since the late 1970's, argon-oxygen decarburisation has allowed the fabrication of low-carbon stainless steels containing less than 0.03% C. This carbon level prevents sensitisation in the HAZ of welds.

A significant nickel price increase in the beginning of the 21st Century has favoured a comeback of the Cr-Mn-Ni steels [3].

The chemical compositions of the austenitic stainless steels most used in passenger railcars fabrication are shown in Table 1.

Table 1. Chemical composition of austenitic stainless steels for passenger railcars

Element	Stainless Steel Grades			
	Allegheny 18-8 (Budd)	304 (1.4301)	301L (1.4318)	201LN (1.4371)
C	0.12	0.08	0.03	0.03
Cr	17.0, min	18.0-20.0	16.0-18.0	16.0-17.5
Ni	7.0, min	8.0-10.5	6.0-8.0	4.0-5.0
Mn	0.2-2.5	2.0	2.0	6.4-7.5
Si	0.2-1.5	0.75	1.0	0.75
Cu	0.5	-	-	-
N	-	0.10	0.20	0.10-0.25

Contents: % weight, maximum values unless otherwise specified [4] [5] [6].

With regards to other groups of stainless steels, duplex steels have potential for application, especially because of their high strength in larger thicknesses. However, where larger thicknesses are required in the carbody structures, high-strength low-alloy (HSLA) steels with yield strength up to 700 MPa are commonly used.

2.2.2 Mechanical properties

Stainless steel carbodies are produced almost exclusively from CWASS. Their strength levels are defined in ASTM A 666 *Standard Specification for Annealed or Cold-Worked Austenitic Stainless Steel Sheet, Strip, Plate, and Flat Bar*, [5] and in EN 10088-2 *Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion resisting steels* *for general purposes* [6]. The strengthening potential of cold rolling depends on the material thickness. As an example, in thicknesses up to 1 mm, tensile strength close to 1300 MPa and yield strength (0.2% proof) close to 1000 MPa may be achieved. For 5 mm thick materials, the respective achievable values are 1000 MPa and 750 MPa. The very high strength-to-weight ratio allows for considering cold-worked stainless steel as lightweight material. Actually, the first stainless steel moving object manufactured by the Budd Co. was the Pioneer amphibious plane launched in 1931. It was followed twelve years later by the Conestoga cargo plane, 20 of which were built (Fig. 4).

2.2.3 Physical properties

Three properties of austenitic steels are important for their welded fabrication: electric resistivity, thermal conductivity and coefficient of thermal expansion. In comparison with carbon steels, austenitic steels have their resistivity three and half times higher, thermal conductivity three times lower, and coefficient of thermal expansion 40% higher.

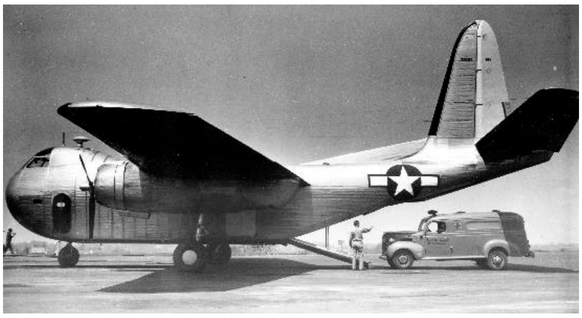

Fig. 4 RB-1 Conestoga (Wikipedia)

2.2.4 Weldability

Austenitic stainless steels do not undergo the γ-α transformation, which ensures their excellent metallurgical weldability. A limited recrystallisation occurs in the heat-affected zone (HAZ), leading to some softening. The HAZ remains ductile in all cases.

In resistance welding of austenitic steels, the high resistivity allows for rapid initiation and growth of the weld nugget. This is further enhanced by the low thermal conductivity, which limits heat dissipation into the surrounding material. As a result, relatively low amperages are required, and spot welding of multiple parts combinations of large total thickness is possible (Fig. 5).

The high coefficient of thermal expansion favors the appearance of nugget shrinkage discontinuities. Hence, to ensure the nugget soundness, high forging forces are applied at the end of the welding cycle.

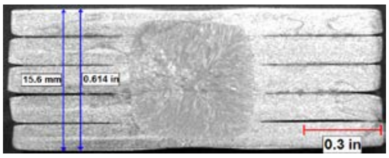

Fig. 5 Spot weld in a thick assembly totalling 15,6 mm (Bombardier)

In arc welding, the large thermal expansion coefficient and low thermal conductivity of the material may cause distortion of assemblies. To mitigate this, the application of arc welding is limited in favour of resistance welding, arc welds are located in the appropriate locations, and low parameters are employed.

2.3 Design

Since the beginning, stainless steel passenger railcars have been of monocoque concept (Fig. 6). The sides and roof consist of frames of cold-formed members, to which structural skin is attached. The floor structure is composed of crossbeams, which are fixed to side sills.

In North American practice, the design of welds is based principally on the American Welding Society standards. Design strength of resistance welds is defined in AWS D17.2 *Specification for Resistance Welding for Aerospace Applications* [7]. and in AWS C1.1 *Recommended Practices for Resistance Welding*[8]. The design of arc welds is in part governed by the AWS D1.6 *Structural Welding Code – Stainless Steel* [9].

The accuracy of the configurations and analyses is verified in North America through three standardised tests on the complete carbody structure: compression load, vertical load and diagonal jacking. In the compression load test, a longitudinal load (up to 3600 kN) is applied to the ends of the carbody underframe. The vertical load test consists of applying weights representing up to 200% of the maximum specified service load. Finally, in diagonal jacking, the carbody is lifted on two diagonally opposite corners. During each test, hundreds of displacement and strain gauges are used to assess the structural response.

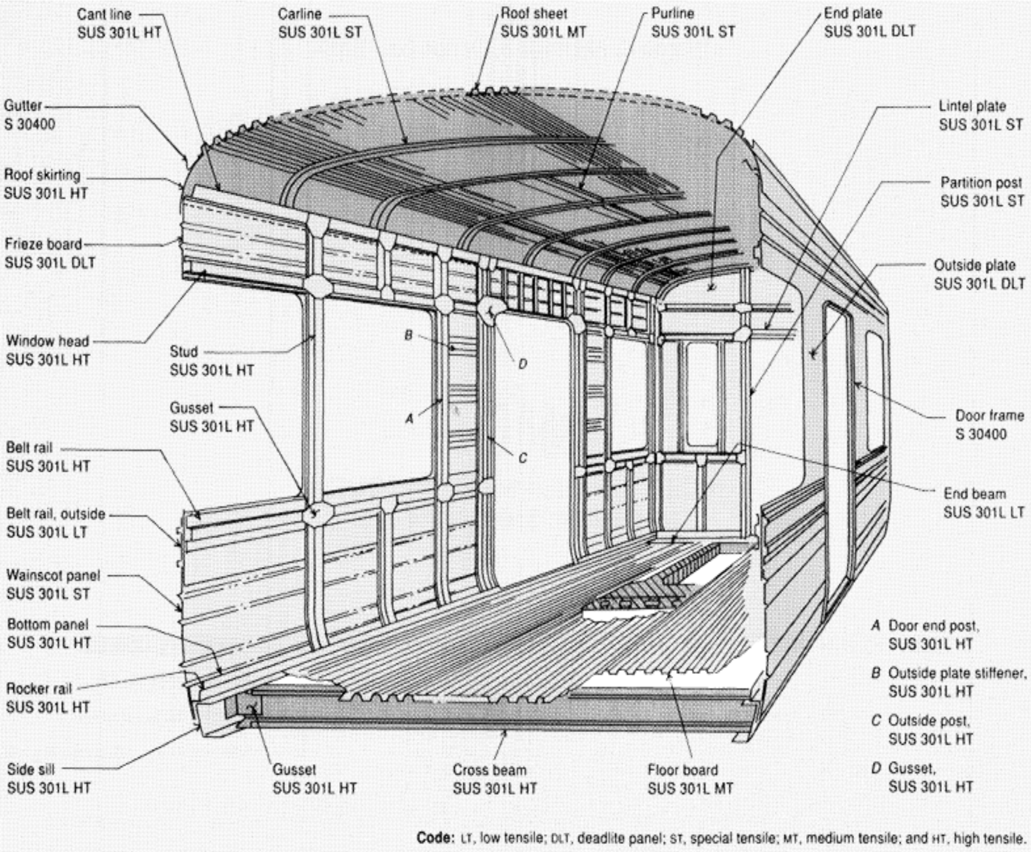

Fig. 6 Typical stainless steel carbody structure (Courtesy of Nickel Institute)

2.4 Fabrication

2.4.1 Cutting

Straight cuts are mostly made with guillotines. However, the majority of primary parts are of complex shapes, for which laser cutting is successfully applied

2.4.2 Forming

Austenitic stainless steels can be bent, roll-formed, stretch-formed and stamped with ease. Even in the cold-worked condition, material may be bent with an inside radius equal to twice its thickness.

Deformation induced by forming increases the strength of austenitic steels. The resulting properties of the material or parts may be considered during the design calculations.

2.4.3 Care for the services

The external surfaces of stainless steel carbodies should be scratch-free and flat. No thermal straightening such as used in fabrication of carbon steel cars is possible, and restoration of the original finish is very difficult. Also, spot welds indentations should be shallow and defect-free, and thermal discoloration (heat tint) on visible surfaces is not permitted.

Different precautions are put into place to meet these challenges. Materials are covered with protective plastic membrane, which is removed as late as possible during the fabrication process. Appropriate spot welding procedures are used, including the use of shielding gas. The number of arc welds exposed to the sight is kept to a minimum. Arc weld faces and heat tint on base metal are cleaned off to ensure their acceptable appearance and resistance to corrosion.

All necessary means are taken to avoid surface contamination resulting from fabrication processes, from handling and – if this is the case – from the vicinity of carbon steel manufacturing. Before leaving the fabrication plant, carbodies are thoroughly cleaned and protected against environmental elements and contaminants. Cars in service are periodically washed with solutions designed to remove dirt and contamination from exposed surfaces.

2.5 Resistance welding

2.5.1 Equipment

The equipment should have a very rigid structure, since high forces up to 20 kN are required.

For gun structures, especially large ones (Fig. 7), austenitic stainless steel or bronze are typically applied. The use of non magnetic material prevents loss of welding current due to electromagnetic induction

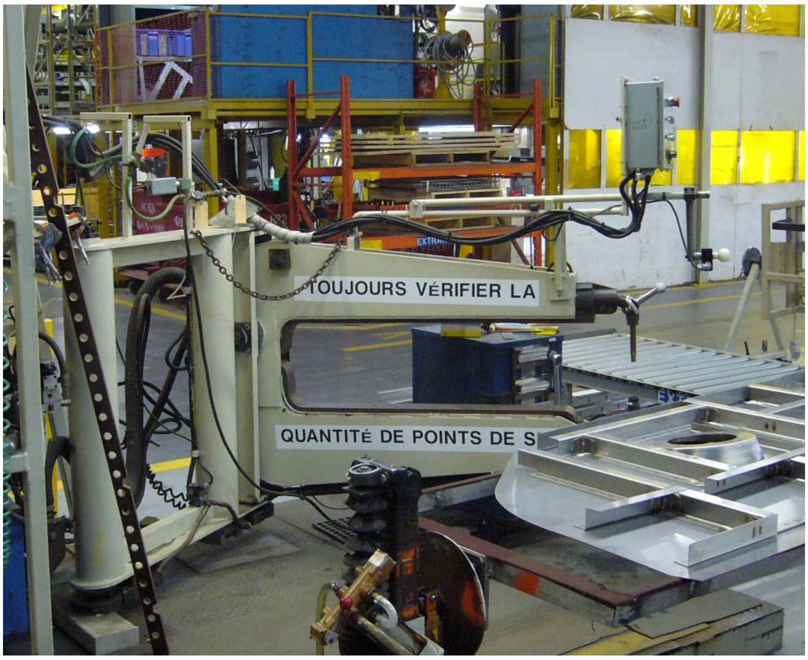

Fig. 7 Large C-type gun (Bombardier)

Electrode actuators should ensure rapid advance movement, high forces, and soft contact with welded assembly, and should have limited size. These contradictory conditions can be met by a pneumatic/hydraulic cylinder. The device makes a quick “soft touch” approach using compressed air. Upon contact between the electrodes and the assembly, the air pressure is converted into a high hydraulic force.

Electric servo-guns represent an interesting application potential.

Contradictory conditions also apply to the electrodes. They should have a good electrical and thermal conductivity, which is ideally met by pure copper. On the other hand, copper does not resist deformation under high forces and currents. The best compromise consists in the application of the copper-beryllium or copper-nickel-silicon bronze.

Guns for welding of large structures such as that of side wall and roof frames are displaced by automated gantry systems. This equipment has the capacity to exchange guns to respond to particular access restrictions.

In stationary machines used for smaller assemblies, spot welds are manually located with the help of templates made from nonconductive materials.

Welding roof and side skin to their structures represents a special challenge. Up to a certain width, large mobile C-type guns may be used. However, the most efficient solution consists of the use of specialised gantry machines with separate but synchronised mechanical systems for top and bottom electrodes (Fig. 8)

Fig. 8 Station for welding large sides and roof panels (Bombardier)

Seam welding is used to assemble the roof and sometimes the side skin. In this process, electrodes have the form of rotating discs. The considerable size of assemblies requires very large installations. Weld discoloration is prevented or limited by water jets from the top and bottom sides.

The resistance welding process is governed by electronic controls. They command or monitor all process variables: current, opening and closing of actuators, force, cooling water, and shielding gas. They can also detect anomalies and stop operations if they occur.

2.5.2 Quality

The high requirements for spot weld integrity and appearance require very stringent weld quality criteria. There can be no nugget expulsion. Indentation must be shallow and uniform. Discoloration at surfaces exposed to users is not permitted. There are precise limits of nugget strength, diameter, penetration and discontinuities.

Each welding procedure specification (WPS) is qualified to ensure that the criteria mentioned above are safely met. The high quality criteria must also be met by all production welds. This requires a thorough quality control during fabrication. Monitoring of parameters by the controls allows for a real-time verification of the process. Also, frequent testing is performed on samples.

The equipment operators' involvement and constant vigilance are equally important in ensuring quality of production welds.

2.5.3 Reference standards

The two basic standards used in North America for quality are AWS D17.2 [7] and AWS C1.1 [8].

In Canada, the CSA W55.3 standard *Certification of Companies for Resistance Welding of Steel and Aluminum* [10] is also used. It defines conditions regarding personnel, equipment and quality systems, which must be met by a company to be certified by the Canadian Welding Bureau.

The European Committee for Standardisation (CEN) and International Organisation for Standardisation (ISO) have published numerous standards for resistance welding. Typically, they are short documents linked through cross-references.

JIS standards published by the Japanese Standards Association resemble the North American standards.

2.6 Fusion welding

2.6.1 Processes

As mentioned in 2.2.4, the application of arc welding is limited. The main reasons are distortion, discoloration, and low speed. Arc welding is typically used in the structural frames of floors, sides and roofs for connections where resistance welding is impracticable.

The most widely used fusion welding process is the gas-shielded solid electrode wire process (AWS: GMAW [11]**;** EN: 135 [12]**;** customary: MAG). The high potential for distortion of assemblies requires the application of low-energy short-circuiting and pulse modes of the process.

For welding stainless steels in the short-circuiting mode, the old-style (not electronic) power sources had to use highly inclined characteristics and heavy inductance. Since the end of the 1980's, due to progress in electronic power sources, the implementation of controlled short-circuiting mode has been achieved by several producers of welding equipment. Developments in this area still continue.

The pulsed mode is used for somewhat higher parameters. Again, the progress in electronic power sources contributed to bringing this mode to maturity.

Another process which may be used for stainless steel uses a non-fusible tungsten electrode (AWS: GTAW [11]**;** EN: 141 [12]**;** customary: TIG). Its use for structural applications is limited, mostly due to the slow speed of the process.

Currently, laser welding is starting to find its way into passenger railcar fabrication.

2.6.2 Quality

The excellent weldability of austenitic stainless steels eliminates any potential metallurgical problems, especially when low-carbon base and filler metals are used. The risk of hot cracking may arise in dissimilar welding of stainless steels with carbon or high strength low-alloy steels if nominally austenitic filler metals such as ISO 14343-A 23-12L (ISO 14343-B 309L) [13] are used. The remedy consists in the application of their high ferrite variation.

The principles of welding procedure specifications (WPS) qualification for stainless steels follow the general rules for arc welding. The only notable exception is the allowance for butt joint undermatch in some standards. The strength of a joint determined in tensile test may be lower than the nominal strength of base metal, provided that the value required by the design is attained.

During welder training and in production control, emphasis is put on the avoidance of overwelding. The size of arc welds in stainless steels is typically small, so even its small increase corresponds to an important surplus of a weld cross section. Considering the sensitivity of stainless steels to distortion, this has a significant impact on weldment deformation.

3 Applications other than passenger railcars

3.1 High strength tubes

3.1.1 Principles

Welded stainless steel tubes (round or rectangular hollow sections) are generally produced by roll forming and seam welding strip on a continuous line. Most of the time, non-round shapes are produced from rounds by running them through a series of rolls and/or dies. This operation forms the round tube into rectangular hollow sections by exerting external forces onto the tube surface. During the deformation process the material undergoes work hardening. Depending on the degree of deformation, the mechanical properties of the final tube may be substantially higher than those of the original strip material.

Using the initial strip material which is already cold-worked, it is relatively easy to achieve tensile yield strength of the order of 500 MPa and above. In addition, in rectangular hollow sections, deformation of the corners further enhances the strength of the product.

The high strength of the product allows for lighter structures, with all related advantages.

If annealed strip material is used, there is no extra cost in obtaining medium-strength products. The only action required from the producer is to document and guarantee the increased properties. For high-strength tubes, there is a slight price increase for the cold-worked strip material. However, this is compensated by overall product cost reduction due to a significant decrease of its weight for a given strength.

Structural and cost utility of the high-strength CWASS rectangular hollow sections is discussed in more detail in [14] and [15]**.**

3.1.2 Applications

The most frequent application of CWASS tubes is in the construction industry. Examples include building structures, canopies, and structural elements inside buildings.

Stainless steel rectangular hollow sections are also used in bus construction. In this area, the actual mechanical properties, which are increased following the fabrication process, are advantageously applied.

Light poles and masts are produced using rectangular hollow sections or round tubes. For the round tubes, a very gradual diameter reduction is applied over the pole length. This deformation increases the mechanical properties, which are accounted for in the design.

3.2 Tanks

3.2.1 Principles

The size of tanks may vary from beer kegs to tank cars to storage tanks dozens metres in diameter. Contrary to mechanical structures, where butt joins submitted to transverse tension loads are rare, in tanks these joints are typical ones. This in turn may lead to the undermatching condition. The undermatch may be reduced or eliminated by a judicious choice of filler metal, by keeping the welds reinforcement, and by cold-working of welds by rolling or hammering.

3.2.2 Examples

Beer kegs. The majority of beer kegs in the world are made of 1.4301 steel. Their capacity is typically of 30 to 80 litres. The kegs are deep drawn products, with no butt welds submitted to tension. The high strength of the material decreases the weight of the product and increases its resistance to denting.

Trailer tanks. Application of the CWASS allows for a significant weight reduction. By the same amount, load capacity is increased.

Container tanks. Groth and Johansson [16] have collected statistics of the actual tensile properties of several sheet stainless steels. The advantage of using the actual properties instead of the nominal ones is shown through the example of a 30 000 liter storage container made of 316L steel. With the actual yield strength equal to 130% of the nominal value corresponding to the annealed condition, the container weight could be reduced from 1850 kg to 1425 kg. It may be added that for the considered thickness range of 4 to 5 mm, a cold-worked material can easily reach twice the nominal yield strength. This in turn would lead to a further decrease of the thickness and of total cost of the material.

Large storage tanks. As an example, a 33 m diameter open biomass digester was made of 304 steel, except for the upper ring made of 316 steel for a higher corrosion resistance. Application of 530 MPa yield materials instead of the annealed ones allowed for the weight reduction from 17 tons to 11,5 tons.

3.3 Road vehicles

3.3.1 Introduction

With their high strength, ease of fabrication, crashworthiness and corrosion resistance, CWASS represent a perfect material for all kinds of road vehicles.

3.3.2 Automobiles

It may be surprising that the Budd Co. did not venture into this area. The first stainless steel car, 1936 Tudor sedan, was built by Ford. It was followed by Ford's 1960 Thunderbird and 1967 Lincoln Continental. In the 1980's, the DeLorean Motor Company produced 9000 stainless steel DMC-12 sport cars. The material typically used in all these cars was 304 steel, which was brought to a higher strength by stamping operations. However, it was not a truly structural application, as stainless steel was used only as a body material. The situation was different in the project led by Autokinetics and AK Steel in the USA in the 1990's. This time the CWASS was used to produce an automobile space-frame. Tests have shown longitudinal and torsional stiffness of the structure superior to that of carbon steel automobiles of the time [17]. This project, however, did not result in an industrial application.

A large project was completed by a consortium of several stainless steel producers and automobile manufacturers [18]**.** It resulted in the establishment of rules for the application of austenitic stainless steels, including cold-worked ones, for automobile body components according to the criteria of strength, crashworthiness and fabricability. An interesting innovation reported in [18] is the fabrication of continuous coiled blanks composed of materials of different thickness and possibly grades. The application of tailored blanks could easily be extended to structural applications.

3.3.3 Buses

As mentioned in 3.1.2, CWASS are successfully used in bus structures. One example of development is a hybrid bus designed under a contract with the US government [19]. Extensive activity on application of stainless steel in buses was also launched in Europe [20].

3.3.4 Highway trailers

In 1934, the Budd Co. set up a Highway Trailer Division. Six years later it signed an agreement with Fruehauf for the delivery of 10 000 trailer bodies in kits [1].

Currently, utility trailers using CWASS are still being produced. In tank trailer construction, roll formed profiles are used for the frame. The tank itself is often made of commercial steel such as 1.4301. However, CWASS are also used, leading to lighter tank weight and decreased cost, and an increase in payload. CWASS are also successfully applied in construction of timber trailers.

3.4 Sandwich panels

Sandwich panels are composed of a corrugated core and two cover sheets. The lap joints between the panels and the core are made with laser welds which penetrate the sheets and the interface between the parts (Fig. 9). Such panels provide a very high stiffness-to-weight ratio. They have been successfully incorporated in ship structures improving the management of the centre of gravity [21]. Their application for mass transit vehicle floors was investigated with promising results [20], [22]. These two examples illustrate the important application potential of this innovative product.

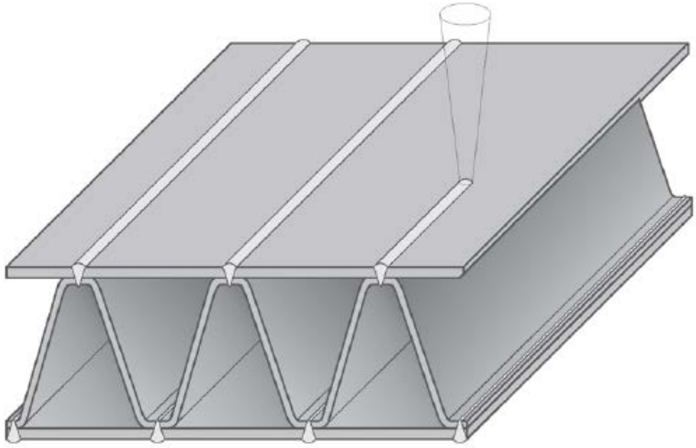

Fig. 9 Schematic view of sandwich panel being laser welded (Courtesy of the Pennsylvania State University)

4 Challenges and opportunities for CWASS application

4.1 Challenges for producers

CWASS introduce challenges for producers, especially of flat products. Obtaining precise mechanical properties requires a specific competence, and cold thickness reduction may result in material waviness. On the other side, the industry has over 80 years of experience in solving manufacturing challenges.

CWASS are typically made from leaner, hence lower price grades, and the extra value of cold working is relatively small. These factors negatively affect the profit margin.

4.2 User awareness

Many potential CWASS users are not aware of their very existence. Typically, in descriptions of stainless steels, mechanical properties of austenitic steels are only those in the annealed condition. As a result, for structural applications some users select zinc-plated carbon or low alloyed steel, or duplex steel. And yet, the CWASS up to 6 mm thick may reach a strength higher than that of duplex and carbon or low alloyed steels. Lean CWASS grades are less expensive than lean duplex steels. The extra cost of cold working is below 5 % of the total material price. In terms of corrosion resistance, CWASS are adequate for most structural applications, and better than 12% Cr steels. Finally, their life cycle cost is lower than that of painted or zinc plated carbon/low alloyed steels.

An example of action promoting the application of CWASS is the INSAPTRANS project funded by the European Commission [22]. The activity encompassed research projects relative to buses [20] and passenger rail vehicles [23]. Technical workshops were organised in several countries.

4.3 Design and welding standards

Design standards cover CWASS in different ways. In the Eurocode (EN 1993-1-4 *Eurocode 3 - Design of steel structures, part 1-4: General rules - Supplementary rules for stainless steels)* [24] nominal design values for materials listed in Table 2.1 correspond to their annealed condition or to a slight hardening from cold rolling. The highest yield strength value of 350 MPa is assigned to the 1.4318 material, while the most popular 1.4301 is limited to 230 MPa. Values resulting from cold working may be used only if justified by complex testing. Table 2.1 also contains the yield strength values of 420 MPa and 480 MPa for two duplex steels. All the above aspects may cause preference of the users for duplex steels to the detriment of CWASS.

EN 1993-1-4 [24]**,** through its reference to EN 1993-1-8 *Eurocode 3 - Design of steel structures, part 1-8: Design of joints*, [25] imposes weld filler metal mechanical properties at least matching those of base metal. In practical terms, this condition prohibits the application of CWASS in welded assemblies, even if only fillet or flare welds are used.

EN 1011-3 [26] *Welding - Recommendations for welding of metallic Materials - Part 3: Arc welding of stainless steels* suggests that "the proof and tensile strength of welds in austenitic stainless steels is generally similar to, or greater than, those of the parent metal".

SEI/ASCE 8 *Specification for the Design of Cold-Formed Stainless Steel Structural Members, American Society of Civil Engineers* [27] applies to CWASS covered by ASTM A666 standard [5]. For groove welds in butt joints, this specification limits the design tensile strength to that of the annealed material. Higher values may be established by tests, which are simpler than those of the EN 1993-1-4 [24]. Fillet welds strength is calculated on the basis of the filler metal tensile strength. For these welds, matching properties of filler metal are not required. This standard suggests conservative values for the CWASS longitudinal compression strength (see 4.4).

AWS D1.6 Structural Welding Code - Stainless Steel [9] retains the principles of the SEI/ASCE 8 [27] for butt joints in tension and for fillet welds. For procedure qualification tensile test, this standard allows for a result below tensile strength of base metal, provided the design value has been met. This corresponds to the undermatching condition.

On the other side, AS/NZS 1554.6 [28] requires the tensile test result to be at least equal to the strength of base metal.

In terms of fatigue performance of welded joints in stainless steels, the EN 1993-1-4 [24] refers to EN 1993-1-9 *Eurocode 3. Design of steel structures. Fatigue* [30]. The AWS D1.6 Code [9] contains a caveat relative to thin-walled structures, for which CWASS are typically applied: load-induced distortion may affect the actual fatigue performance as compared to the nominal values.

The above lists certain shortcomings of the current standards relative to CWASS. However, some remedial actions are underway. The advantages of using actual material properties instead of standard ones have been published by Groth [16] and Baddoo [30]. In addition, research projects on structural performance of CWASS sections were undertaken [14], [31]. Their results permit the extension of the design rules established for the standard-strength sections to cover also sections made of high strength (i.e., cold-worked) steels.

4.4 Directionality and asymmetry of properties

Tensile properties of CWASS differ to some extent as a function of direction. There is also an asymmetry in tensile and compressive yield strength in the longitudinal direction. For this case, The Euro Inox Design Manual for Structural Stainless Steel [32], in accordance with [33], specifies the compression/tension yield strength ratio equal to 0.8. Higher values, especially for profiles, may be established by testing. (In transverse direction, the compression/tension yield strength ratio is greater than 1.)

4.5 Properties of welded joints

As mentioned in 4.3, current rules limit the strength of CWASS butt joints in tension to the annealed material properties. In many instances, this single restriction may prohibit the application of CWASS. However, existing information (examples: [14], [22]) indicates that the actual tensile properties of the joints are significantly higher. If fracture occurs in the weld, the joint strength is above the conservative specification values for filler metals. An innovative project [34] has also shown that annealing of the heat-affected zones (HAZ) in CWASS is incomplete. All the above indicates a need for a larger project on the properties of fusion welds in CWASS. The objective of this project would be establishment of rules for assessing the anticipated tensile properties of welds in CWASS. The assessment would be based on the steel grade and its tensile properties, on the HAZ thermal cycle, and on the strength of filler metal. The project should consider original solutions for filler metals, such as applying duplex or even martensitic materials. The project should also include laser and hybrid laser-MAG welds. These welds, being narrow, develop higher strength than larger arc welds.

A comment may be made with regards to butt joints in aluminium alloys. In practically all instances, their strength is lower than that of base metal. This fact is considered as an obvious one, and the design rules and practices, as well as welding procedure qualification provisions take it into account. The situation regarding CWASS welds is more complex, but the analogy remains: a structure having joints of lesser strength than that of the unaffected base metal can perform satisfactorily.

5 Conclusion

Cold-worked austenitic stainless steels have a long history. Their original application in passenger railcars is a vivid example of human genius reflecting vision, bold management, technical and aesthetical creativity, and an open mind. This legacy of Edward G. Budd and his companions is still alive and well: thousands of shiny stainless steel cars are still being produced every year. In this way, high strength stainless steels have proven their extraordinary potential. Other applications appeared, but many potential uses are still awaiting their turn. It is up to all of us, who are passionate about stainless steels, to bring this potential to its manifestation.

Acknowledgements

The editorial assistance of Maryanne Roberts and Jacques Desjardins is gratefully acknowledged.

References

[1] Cobb H. History of stainless steel, ASM International, 2010 ISBN-13:978-1-61503-010-1.

[2] US Patent 1 944 106. Method and Product of Electric Welding, Earl J.W. Ragsdale. US Patent Office, 1934.

[3] Charles J, Mithieux JD, Krautschick J, Suutala N, Simón JA, Van Hecke B, Pauly T. A new European 200 series standard to substitute 304 austenitics? Proceedings of 6th European Stainless Steel Conference, Helsinki, Finland, 2008.

[4] Watter, M. Stainless Steel in Aircraft. Society of Automobile Engineers, 1940.

[5] ASTM A666. Standard Specification for Annealed or Cold-Worked Austenitic Stainless Steel Sheet, Strip, Plate, and Flat Bar. ASTM International, 2010.

[6] EN 10088-2. Stainless steels. Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes. CEN, 2005.

[7] AWS D17.2. Specification for Resistance Welding for Aerospace Applications. American Welding Society, 2007.

[8] AWS C1.1. Recommended Practices for Resistance Welding. American Welding Society, 2012.

[9] AWS D1.6 Structural Welding Code – Stainless Steel. American Welding Society, 2007.

[10] CSA W55.3 Certification of Companies for Resistance Welding of Steel and Aluminum. Canadian Standard Association, 2008.

[11] AWS A3.0. Standard Welding Terms and Definitions, American Welding Society, 2010.

[12] ISO 4063. Welding and allied processes - Nomenclature of processes and reference numbers, International Organisation for Standardisation, 2009.

[13] ISO 14343: Welding consumables - Wire electrodes, strip electrodes, wires and rods for arc welding of stainless and heat resisting steels - Classification. International Organisation for Standardisation, 2009.

[14] Gardner L, Talja A, Baddoo NR. Structural design of high-strength austenitic stainless steel, Thin-Walled Structures 44 (2006), 517-528.

[15] Talja A, Vilpas M. Huhtala L, Yrjölä P. Design of welded connections of cold-worked stainless steel RHS members. Proceedings of Stainless Steel in Structures International Experts Seminar, Steel Construction Institute, 2003.

[16] Groth HL, Johansson RE. Statistics of the Mechanical Strength of Stainless Steels-Sheet. Proceedings of Nordic Symposium on Mechanical Properties of Stainless Steels, Sigtuna, Sweden. 1990.

[17] Emmons JB, Douthett J. Automotive frames of stainless steel, Advanced Materials & Processes 1996; 150 (2).

[18] S. Schuberth S, Schedin E, Fröhlich T, Ratte E. Next generation vehicle - engineering guidelines for stainless steel in automotive applications. Proceedings of 6th European Stainless Steel Conference, Helsinki, Finland, 2008.

[19] Emmons JB, Blessing LJ. Ultralight Stainless Steel Urban Bus Concept, Technical paper 2001-01-2073, Society of Automotive Engineers.

[20] Kyröläinen A, Sánchez R, Santacreu PO. Stainless steels in bus constructions, contract 7210-PR-176 Directorate-General for Research and Innovation, European Commission, 2003. ISBN: 92-894-6635-9.

[21] Reutzel EW, Koudela KL. Lightweight Laser Welded Stiffened Structures (LASCOR). Presented at the American Helicopter Society 57th Annual Forum, Washington, DC, USA, 2001.

[22] Sirén M, de Wispelaere N, Rizzo L, Pauly T, Kosmac A, Taulavuori T, Sanchez R, Vliegen, R, Van Hecke B, Säynevirta, J, Hänninen H. Innovative stainless steel applications in transport vehicles. Publications Office of the European Union, Luxembourg. 2011 Research Fund for Coal and Steel series, 2011, EUR 24218.

[23] Gale A, Sirén M, Säynäjäkangas J, Akdut N, van Hoecke B, Sanchez R. Development of lightweight trains and metro cars by using ultra high strength stainless steels. Publications Office of the European Union, 2007. Technical steel research series, EUR 22837.

[24] EN 1993-1-4 Eurocode 3 - Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels. CEN, 2006.

[25] EN 1993-1-8 Eurocode 3 - Design of steel structures - Part 1-8 Design of joints. CEN, 2005.

[26] EN 1011-3 Welding - Recommendations for welding of metallic Materials - Part 3: Arc welding of stainless steels. CEN, 2000

[27] SEI/ASCE 8 Specification for the Design of Cold-Formed Stainless Steel Structural Members, American Society of Civil Engineers, 2002.

[28] AS/NZS 1554.6 Structural steel welding. Part 6: Welding stainless steels for structural purposes. Standards Australia, 2012,

[29] EN 1993-1-9 Eurocode 3. Design of steel structures. Fatigue. CEN, 2005.

[30] Baddoo NR. Stainless steel in construction: A review of research, applications, challenges and opportunities. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.07.011.

[31] Young B. Experimental and numerical investigation of high strength stainless steel structures. Journal of Constructional Steel Research (2008), doi:10.1016/j.jcsr.2008.05.004.

[32] The Design Manual for Structural Stainless Steel (Third Edition), Euro Inox, 2006

[33] Taulavuori T, Aspegren P, Säynäjäkangas J, Salmén J and P. Karjalainen P. The anisotropic behaviour of the nitrogen alloyed stainless steel grade 1.4318, Proceedings of International Conference on High Nitrogen Steels, Odense, Denmark, 2004

[34] Nevasmaa P, Laukkanen T, Andersson T and Sirén M. Influence of Weld Strength Mis-Match on Failure Behaviour of Strain Hardened Austenitic Stainless Steel. IIW Doc. X-1679-10. The International Institute of Welding, 2010.