Ultra High Strength Steel Sandwich (UHSS-S)



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1 Abstract

This project is aimed at developing competitive light weight steel solutions for the car body by reducing the density of the blank material without any major change in the elastic stiffness. The low density steel blank is a laminate (sandwich) with outer layers of ultra-high strength steel and low density core created by sintered metal powder.

The project has been divided into 5 steps, sintering, bonding, press hardening, deformation testing and simulation.

Sintering:

Several different alloy has been tested and the best seems to be an austenitic stainless steel quality. The sintered core turn out to be fragile due to the porosity.

Bonding:

In this case the goal has been to do the bonding before (at the sintering process) or during the press hardening process. Attaching the core to the outer sheets during to sintering process was not a success due to the long time in a high temperature which made the grain grow on the outer sheets which made the material more brittle. The other way, melting the brazing foil in the furnace at the same time as the blanks gets heated up for press hardening worked well. Two brazing foils were found for uncoated outer sheets, Metglas MBF62 and Vitrobraze VZ2170. For AISi and Zn coated no working brazing foil were found.

Press hardening:

Joining the previous stages together the final manufacturing step is the press hardening. The press hardening process works well with the sintered core and the brazing foil because it is floating when the forming takes place. When doing parts with more complex geometry, there will be limitation for the sintered core but patches might be used locally.

Deformation testing:

After the press hardening deformation tests followed. Unfortunately both the core and the brazing turned out to be too weak to hold the press hardened outer sheets together. If using a softer steel as outer sheets the results would be different but not as good regarding weight saving.

Simulation:

The focus has been modelling the defamation behavior. Three ways has been evaluated.

- 1. Shell elements
- 2. Solid elements
- 3. Shell elements (outer sheets) and Solid elements (core)

For modeling of the interface between core and outer sheets a tie-break contact in LS-DYNA has been used to virtually reproduce the cohesive behavior. This will probably make option 3 above the best option. Due to the brittleness of the sintered core it has been difficult to do material characterization.

The conclusion is that there is a good possibility to make a sandwich structure to be used for press hardening. Using a sintered core and brazing as bonding can still be a weight saver if the part only works in the elastic zone with small deformations. However for parts used in crash and high deformation, sintered core and Ni based brazing is probably not a possible solution due to the low strength compared to the press hardened steel.

2 Exklusiv sammanfattning

Målet med projektet är att ta fram en konkurrenskraftig lättviktlösning i stål för fordonsindustrin genom att utveckla en laminatplåt som ger likvärdig styvhet jämfört med en solid stålplåt men till lägre vikt. Konceptet som utreds i detta projekt är en laminatplåt som består av tre skikt. De båda ytterplåtarna är gjorda av ultra höghållfaststål (UHSS) och kärnan består av sintrat järn-/stålpulver. Ytterplåtarna erhåller sin styrka genom presshärdningsprocessen och kärnan sin låga densitet genom att sintringen ej sker fullt ut utan stannar vid en densitet på halva stålets.



Tillverkningsprocessen av den laminerade slutprodukten består av tre delar. Sintring av kärna, bindning av ytterplåtar till kärna samt presshärdning. Utöver dessa steg har även deformationstester samt simuleringmetodik undersökts.



Bilden ovan till vänster visar en sintrad kärna i mikroskop. Av de kärnor som testats visade sig en rostfri austenitisk var mest lämplig. För att binda samman ytterplåtarna med den sintrade kärnan har två olika folier använts, Metglas MBF62 och Vitrobraze VZ2170 båda fungerar bra i presshärdningsprocessen med en viss fördel för VZ2170. Loden påvisar en styrka likvärdig med limförband i dagens fordon. Det slutliga steget är presshärdningen. De ingående komponenterna i laminatet hade kravet på sig att kunna klara 940°C utan att fallera. Målet initialt var att en standard presshärdningslinje skulle kunna användas för att tillverka produkterna vilket även uppnåddes.

För att mäta prestandan på färdig produkt tillverkades hattprofiler som sedan utsattes för deformationstest. Styrka samt benägenhet till att spricka noterades. Det visade sig att den laminerade plåten håller ihop inom det elastiska området med små deformationer vilket var ett av målen. Vid större deformationer klarar kärnan och lodet ej att hålla ihop de presshärdade ytterplåtarna.

Vad gäller simulering så har en stor del av tiden lagts på hur laminatet ska modelleras på bästa sätt, skal, soild eller skal+solid, varvid det sista verkar vara det mest lämpligt. Att hitta en relevant materialmodell som ger en korrekt respons för den sintrade kärnan har även det varit ett prioriterat område. Materialkaraktärisering blev problematisk på grund av den sintrade kärnans sprödhet.

Det sammanfattade resultatet från projektet kan beskrivas med att en produkt tillverkad av en laminatplåt troligtvis har en framtid på grund av den viktbesparing som kan åstadkommas. Att använda sig av en sintrad kärna i kombination med lod och de presshärdade stålet som ytterplåtar verkar dock svårt. Lovande resultat kan ses vid små deformationer/töjningar men vid större så klarar den sintrade kärnan och lodet ej att hålla ihop de presshärdade ytterplåtarna. Med ett annat lämpligare koncept för kärna och bindning så finns det med säkerhet en framtid får stållaminatprodukter.

3 Background

Thermo-mechanical forming processes are being increasingly employed in the manufacturing of complex shaped ultra-high strength steel (UHSS) structural and safety components in automobiles. Press hardening, a special type of thermo-mechanical forming process invented in northern Sweden in 1970s, is a technique for producing UHSS components through simultaneous forming and hardening of steel sheet material. Blanks are stamped from rolled sheet material and heated. The hot blanks from rolled steel sheet are formed into desired shapes and simultaneously quenched by various types of water cooling systems, Fig. 1.



Figure 1. Schematic of the press-hardening technique

Some examples of the automotive components produced by thermo-mechanical forming processes are shown in Fig. 2.



Figure 2. Example of press-hardened automotive components.

4 Purpose, question and method

The proposed research is highly interdisciplinary and will require a thorough understanding of the thermomechanical effects for creating a low density steel material on thin steel sheets. Some of the salient research tasks to be carried out during this project include:

- Development of material models, simulation methodologies and methods for material characterization of sandwich materials.
- Development of process methods to create a low density metallic core on thin steel sheets.
- Development of a new hot stamping process for generating and forming a new metallic sandwich material.

Since the project is divided into four different topics sintering, bounding, press hardening and simulation each topic will have their own section regarding method will be handled individually and followed by a summery.

4.1 Sintered core

4.1.1 Cast core

Low alloyed steel is required from a cost standpoint with Ni and Cu being out of the question both from cost and recyclability standpoint. Several minor elements were tested and with target metals shown to be Si and P as alloying elements that provide best strength and ductility. Content ranges from 2 - 6% of each.

The metal is mixed with over 30% organics to create a slurry able to be cast into sheets up to 2mm thickness. Sheets must then be sintered at 1120°C or higher in order to both burn out the organic material as well as create the bond between the particles giving the sheets its final mechanical properties. The combination of low density metal (by volume) with organic that is removed via sintering, allows for final density of the steel structure to be roughly 50% porous. The image below shows a sintered cross-section of one sheet.



Figure 3. Fe + 2,7% Si. Sintered 1150°C for 45min in 90/10 N2/H2.

Possibilities extend to allow additional weight savings if patterns were introduced to the manufacturing method to remove unnecessary material. This concept could alternatively be used in order to add mass and strengthen critical areas.

4.1.2 Casting + Rolling

Secondary processes such as rolling was implemented to the as cast sheet prior to sintering. The intention is to increase surface area between the sintered core and the steel sheet therefore creating a better bond. Secondly, the closing of the surface pores prevents the braze alloy from leaving the surface and penetrating the core rather than bonding to the steel sheet.

Densification is the last feature of the rolling process. It creates a better inter-particular bond but at the same time, the density increase decreases the weight savings potential.

4.1.3 Outer sheets

Outer sheet thickness is in the range of 0.4-1.0mm. Since the process is to quench material boron steel will be used following the standard material 22MnB5.

Two different types are currently of interest, uncoated (known as 22MnB5) and AlSi coated (known as Arcelor Usibor 1500P) which is a coated 22MnB5. The main market for press hardened part are for AlSi coated since it has some passive corrosion resistance and don't get any scale during the press hardening process which eliminates the use of shot blasting which is an additional cost and might deform the part.

4.2 Bonding

A large number of different bonding methods were considered, e.g. explosive welding, resistance welding, brazing/welding with nano-foil and conventional brazing. However, the ultimate bonding process should be performed in line, and this might be possible with brazing during the austenitization step of the boron sheet steel. Therefore, the research effort was focused on to develop a brazing process that could be performed during the austenitization step of the boron sheet steel.

Boron sheet steel for the automotive industry is either aluminized zinc-coated or uncoated and therefore different brazing methods need to be developed. This project was therefore divided into three parts, Part 1 – Brazing boron sheet steel to boron sheet steel and Part II - Brazing aluminized sheet steel to aluminized sheet steel, Part III-Brazing zinc-coated sheet steel to zinc-coated sheet steel.

4.2.1 Part 1 – Brazing boron steel to boron steel

In this study experimental brazing was done to analyze the possibility of joining two USIBOR strips in a lap joint.

4.2.1.1Test material

The austenitization temperature of boron steel is in the range of 920 °C to 950 °C, and therefore the melting temperature of the brazing foils should be below that.

Two alloys manufactured by Metglas and one alloy produced by Vitrobraze with melting temperatures close to the austenitization temperature of boron steel were selected, see Table 1 and Table 2.

											ci micnic	
Alloy	AWS	Nom	Nominal composition, wt %							Melting Temp		Braze
	& ASM								c	°C	Temp.	
		Cr	Fe	Si	С	B	Р	Mo	Ni	Solid	Liq.	°C
MBF 60	AWS	-	-	-	0.1	-	11	-	Bal	883	921	950
	BNi-6											
MBF 62		21	< 1	0.5	-	0.5	8.0	1.0	Bal	878	990	1020
VZ2170		21		Χ		Χ	Χ			880	925	

Table 1. Chemical composition of the amorphous brazing foils used in the experiments

	Width (mm)	Thickness (µm)
MBF 60	77	25
MBF 62	216	38
MBF 60	51	38
MBF 62	45	51
VZ2170	108	50

Table 2. Alloy, thickness and width of the amorphous brazing foils used in the experiments

4.2.1.2 Preparation, setup and calibration

Braze joints and heat treatments were produced using a tube furnace with a maximum temperature of 1200° C and with a continuous gas flow of nitrogen at 3,7 L/minutes to mimic what is known as controlled atmosphere brazing (CAB) which is used today in aluminum brazing as well as steel brazing.

Joint preparation and fixturing

Strips of USIBOR were cut into lengths and burrs were ground down to ensure good fitting between sheets in the area to be joined. The substrates were then cleaned, first using acetone and then with ethanol.

The setup was placed in a fixture made out of sintered SiO2 and a steel weight of 252 g was placed on the joint area to apply pressure during brazing see Figure 4. This was then lowered into a furnace boat on top of a fixture with a thermocouple type-S see Figure 5 and Figure 5 and could be slid in and out of the tube furnace see Figure 6.



Figure 4. Fixture with samples and weight placed on joint area.



Figure 5. Thermocouple placed in the boat.

4.2.1.3 Evaluation methods

Tensile test, single lap joint

Tensile test was performed to evaluate the shear strength of the joint. The shear strength is estimated under the assumption the shear stress is distributed even over the entire joint area.



Figure 5. Fixture with braze samples placed in the boat.



Figure 6. The boat can be slid in and out of the furnace when samples have been loaded.

Vacuum furnace

A vacuum furnace was used for a part of the experiments, see Figure 7.



Figure 3. The vacuum furnace that was used for a part of the brazing experiments

Experimental set-up to simulate a hot stamping line

In a hot stamping line the boron sheet steel is heated to ~950 C and thereafter moved to a deep drawing press and cooled down (quenched) during the press sequence. In order to simulate the combined press and quench operation in a hot stamping line a combined press and cooling system was arranged, see Figure 8. With the present set-up it is possible to apply a pressure on the lap joint after brazing when the sample is still red hot and thereafter cool it fast to room temperature.



Figure 4. The combined press and cooling system for simulation of a hot stamping line.

A surface pressure of 5 -6 MPa was applied on the lap joint in some experiments after heating when the joint was still red hot, and thereafter the samples were water-quenched.

4.2.1.4 Evaluation methods

Tensile test was performed to evaluate the shear strength of the joint. The shear strength is estimated under the assumption the shear stress is distributed even over the entire joint area.



Figure 5. Size of joint.

Peel test

The maximum peeling force is normalized to MBF 62 1.76 inch x 2Mil, i.e. it is equal to 1. The peak force occur just in the initial first phase of the test. The evaluation of the peel test was based on the highest peak force out of three tests.



Figure 6. The peel test.

4.2.2 Part II - Brazing aluminized boron steel to aluminized boron steel

The approach for USIBOR® 1500P AS150 (Al-coated 22MnB5) would be to join the parts together with brazing in the austenitization process before the stamping and quenching process. This would indeed resemble that of furnace brazing which is extensively used for brazing of heat exchangers for the automotive and aerospace industries [2]. The difference being the elevated temperature of the furnace TAUS = 920 °C compared to typical aluminum brazing temperatures around 570-600 °C. In addition, at first glance the problem might seem to be brazing of steel sheets as in brazing of uncoated 22MnB5, but in fact is governed by the coating of the steel. The AlSi-coating (10 wt. % Si) with a typical melting temperature around 570 °C won't melt if heating rate is kept under 12 K/s due to diffusion of Fe from the steel substrate [3]. The brazing of two or multiple AlSi-coated boron alloyed steel sheets is therefore reduced to brazing of filler material to aluminum-silicon-iron surface coatings illustrated in Figure 11.





4.2.2.1 AISi-coating

The sheet steel is after the austenitization process exposed to an environment containing oxygen during the transport from furnace to pressing machine and to some extent also inside the furnace. This starts an oxidation process where the steel is decarburized and scale formation occurs. Non-coated 22MnB5 steel needs to have the scales removed with e.g. shot-blasting to allow painting of parts. In addition the scales also cause an increase of

abrasive wear on pressing dies. By using a heat resistant coating layer on top of the steel this can be reduced or avoided.

In addition to preventing scale formation during oxidation coatings are typically also applied to have corrosion resistant mechanics. The most used coatings are a Zn-based galvanizing coating and an AISi coating offering both corrosion resistance and protections towards oxidation, where the AISi protective coating sees the most widespread usage [9].

Contrary to Zn-based coatings, AlSi coatings are not suitable for use in the indirect process of hot stamping as the coating is not as formable as the boron steel and would break during deep drawing [9]. The fewer steps in the direct process make this the more preferred and used coating, unless there is a need for cathodic-protection. The appliance of the AlSi-layer is done by hot-dipping and manufacturers supply different thicknesses (9-35 μ m) with a typical Si content of 10 %, Fe 3 % and the rest Al [15].

As in the case of the Zn-based coating the AlSi also forms new phases during the heating to austenitization temperature due to Fe-diffusion in the interface between sheet metal and coating. Apart from the cool-down rate, mentioned earlier, being a crucial parameter the rate at which the furnace heats the steel blank is limited by the AlSi-coating. A heating rate exceeding 12 K/s will melt the coating as AlSi has a melting temperature well below the austenitization of steel, but by keeping it under the limit, Fe-diffusion will continually raise the melting point [3]. Already after the hot-dipping has been done an Al-rich intermetallic phase is formed in the region at the interface between steel and coating, as shown in Figure 12, containing mainly Al8Fe2Si [16]. These Al-rich phases have low fracture toughness and can cause cracks in the coating during pressing, which would reduce corrosion resistance and weldability as well as increasing abrasive wear on tools. When the austenitization temperature is reached, Figure 13 middle image, the Al-coating is completely transformed into intermetallic phases of the type Al5Fe2 and Al2Fe3Si3 and with continued dwell-time at, TAUS = 920 °C, further transformation into AlFe occurs. M. Windmann et al. have shown that after 6 minutes at TAUS (industrial production-standard) and press hardening, a 25 μ m thick layer increases to a mean of 35 μ m containing 34-38 % AlFe and 62-66 % Al5Fe2, Figure 13. At the interface between coating and base metal a 10 μ m Al-Si rich α -Fe layer is formed due to continuous diffusion of Al to the base metal and aluminum being a stabilizer for ferrite [16].



Figure 8. SEM micrographs of the AISi coating in hot-dipped condition [16].



Figure 9. SEM micrograph of AISi coating after different dwell-times at TAUS = 920 °C [16].

With increasing dwell-time more AIFe as well as α -Fe will form and it is desirable to have as much AIFe as possible, while still keeping production rates high, since it is more ductile than AI5Fe2. Further work done by M. Windmann et al. concluded that besides dwell-time, the coating thickness and amount of Si have an impact on the

magnitude of AIFe in the coating layer. Thinner coating thicknesses lead to shorter diffusion paths and thus promote AIFe transformation, while lowering silicon amount will provoke transformation of hard and brittle AI-rich intermetallic phases [15].

On the surface of the coating an Al2O3 oxide-layer is formed which provide protection towards scale formation when the blanks are exposed to an oxygen rich atmosphere and give good corrosion resistance by inhibiting further oxidation.

4.2.2.2 Brazing

Different materials are used as fillers during brazing depending on the base material and the mechanical properties the joint needs to for fill. What they all have in common is that their liquidus temperature is lower than the solidus temperature of the base material and when molten, the filler metal wets the surface between the metals to be joined via capillary action. This brings the materials within 4 Å of each other and inter-atomic attraction is the bonding force [2].

Both soldering and brazing works in this exact same manner and contrary to welding do not imply melting of the base material but only the filler is melted. The difference between brazing and soldering is defined by the temperature used to melt the filler material. The method is called brazing when conducted at a temperature above 425 °C and soldering at temperatures below [17].

The oxide-layer produced at the surface of the coating protecting against scale formation on the coated 22MnB5 steel becomes an issue during brazing. The high melting temperature of Al2O3 (> 2000 °C) [18] prohibits wetting of the surface and has to be removed by either mechanical means or by the use of a flux.

4.2.2.3 Flux

The main objective of a flux (chemical compound) is to dissolve the accelerated formation of oxide layers that forms when metals are heated to high temperatures and to cover the brazing joint preventing any new oxides from forming. There are numerous different types of fluxes that have different work-temperature, heating-times and other specific properties needed for brazing of all kinds of alloys [19].

For brazing aluminum there are two types of fluxes, corrosive and non-corrosive. Corrosive fluxes consist of Potassium chloride and when used provide good results during brazing in both mechanical properties of the joint and in appearance. They do however have a drawback in electrolytic-corrosion from left over residue after brazing. This requires a complicated cleaning process, rinsing the products in hot water is simply not enough. Non-corrosive fluxes on the other hand do not require the extra cleaning process, but do however leave a gritty surface finish. One of the more popular fluxes is NOCOLOK® due to its melting temperature being close to that of aluminum-silicon filler materials [20]

NOCOLOK® flux consists of a mixture of potassium fluoroaluminates, namely KAIF4 (70–80 %), K2AIF5·H2O and K2AIF5 (20-30 %). It is characterized by a melting point between 565 °C and 572 °C and is non-hygroscopic as well as earlier mentioned non-corrosive [21].

During the braze-cycle at 490 °C the flux chemically reacts as in Eq. 1 which gives the flux melting temperature range as described above ($565 - 572^{\circ}$ C). During brazing some of the KAIF4 evaporates and can react with the furnace atmosphere if it is moist and form hydrogen fluoride according to Eq. 2 which is toxic [21]. Therefor a need for low oxygen atmosphere is a need, typically nitrogen is used. Good ventilation could also be required. An outline of the flux transformation is shown in Figure 14.

$$2K_2AlF_5 \to KAlF_4 + K_3AlF_6 \tag{1}$$

$$3KAlF_4 + 3H_20 \rightarrow K_3AlF_6 + Al_2O_3 + 6HF$$
 (2)



Figure 10. Flux transformation during brazing [21].

NOCOLOK® is however not the only flux used for brazing of aluminum but what is also commonly used are varieties of fluxes alkaline chlorides or fluorides mixed with lithium salts, where the salts give the flux a low melting temperature close to aluminum [22].

4.2.2.4 Other surface activation processes

In vacuum brazing the protective Al-oxide layer on the surface is typically not dealt with by the use of a flux. The difference in thermal expansion coefficient between base material and oxide has the effect of cracking the oxide-layer during rapid heating, and since there is absence of oxygen no new layer will form [23]. It is possible to crack the oxide layer in a protective atmosphere furnace by using a joining partner with sharp edges and applied pressure. The sharp edge will induce a crack in the oxide and if enough pressure is applied it will be large enough to cover an area to be brazed which is not only limited to the sharp edge. A draw back to this method comparing to the use of a flux is that the flux lowers the surface tension which increases braze alloy flow [23].

4.2.2.5 Al-based filler material

Brazing of aluminum is done with filler material with a lower melting temperature than that of aluminum itself. Usually an aluminum based alloy is used for the brazing, with alloying elements lowering its liquidus temperature to not melt the base material [18]. The alloying elements used for lowering the liquidus temperature are mainly Si, Cu and Zn while other alloying elements are used for different purposes.

As mentioned silicon influence the melting mechanism of aluminum. As can be seen in the AI-Si phase diagram, Figure 15, an addition of around 12 wt. % Si will reduce the melting temperature from 660 °C to 577 °C. Studies have shown that filler metals with near eutectic composition have optimal flow and wetting ability, whereas those with hypoeutectic on the contrary have very poor fluidity and thus produce worse joints [24].



Figure 11. Al and of Al-Si phase diagram [25].

To further reduce the melting temperature of filler metal, investigations on addition of Cu to the alloy have been concluded. T.h. Chuang et al. [26] developed a filler metal with the composition AI-7Si-20Cu-2Sn-1Mg with a melting temperature range between 501 °C to 522 °C. Their investigation showed that with addition of Cu to AI-12Si the melting temperature would drop until 30 % Cu was added then it would increase with further addition. The 2 % Sn added in the filler contributed to reducing the melting temperature, but further addition resulted in the formation of pure Sn and Si phases which weaken the brazeability. The Mg addition was based on its effect of reducing the oxide layer when used in vacuum brazing, increasing the wetting of the surface. Their results showed that this particular composition when used for butt joining of AA6061 produced braze-joints with bonding strength 95 \pm 9 MPa compared to 59 \pm 18 MPa with conventional AI-12Si which could be further increased with T6-tempering.

Other alloys such as Ni and Re have been used in another investigation by G. Zhang et al. [27] to braze Al-6063 base material. This filler contained 25Cu-8.5Si-1.5Ni-0.2Re and is balanced with Al and has a melting range from 515 °C to 533 °C. Addition of Re has a positive impact on grain refinement and spheriodizes Si particles that prevent dislocation and adds strength to the joint. While addition of Ni was done to compensate the brittleness of CuAl2 formed during brazing. Cu or CuAl2 diffused into the base material where eutectic reaction of Cu and Al atoms result in lowering of the surface energy which would help in removing the oxide layer, thus improving wetting. The tests were also performed for two different heating rates, and it showed that a faster heating rate improved wetting for non-eutectic fillers. This brazing filler produced joints with average shear strength of 62.63 MPa compared to eutectic Al-Si-Cu filler with shear strength 54.69 MPa.

Apart from adding different alloying elements which lower the melting temperature and thus provide easier wetting of the surface or alter the formed microstructure in a beneficial way, there are other variables such as brazing time and joint thickness. These both have an impact on the mechanical properties of the brazing joint. For a typical eutectic Al-Si filler (11-13 % Si) used in brazing of AA3003 investigations by H. Nayeb and M. Lockwood [2] have shown increasing joint strength with increasing joint thickness and a reduction in strength for brazing times over 10 minutes. The increase in joint thickness resulted in a decrease in the Von Mises stresses, Figure 16, and increased joint strength which was validated both with FEM-analysis and tensile tests. Another phenomenon occurred with prolonged brazing time. The diffusion of silicon into the base material is believed to have reduced the melting temperature in the joining-zone which leads to shrinkage porosities in the region during cooling down, see Figure 17. Also diffusion leads to less strong eutectic microstructure in the joint with longer brazing times and is more apparent for joints with lower thickness.



Figure 12. Variation of Von Mises stress in the joint region vs. joint thickness [2].



Figure 13. Shrinkage cavities from a joint with brazing period 40 minutes [2].

4.2.3 Experimental

In this study experimental brazing was done to analyze the possibility of joining two USIBOR® 1500P AS150 blanks in a lap joint as an attempt to investigate the joining possibility of above mentioned material to a core and its usage in a sandwich structure. Further the strength of the coating after various heat treatments was tested both in shear and tensile pull off load using adhesive.

4.2.3.1 Material

For this study the following material was used:

- 22MnB5 steel (boron alloyed steel), see Table 3
- USIBOR® 1500P AS150, (aluminized 22MnB5 press hardening steel), thickness 1.15 mm, see Table 4.

Table3. Average chemical composition of 22MnB5 [%] (N, 2003).

	С	Si	Mn	Cr	Р	S	В	Al	Ti
22MnB5	0,225	0,25	1,25	0,155	<0,025	<0,008	0,0035	>0,015	0,035

Table4. Average chemical and dimensional composition of coating [%] (ArcelorMittal).

	Al	Si	g/m ²	Thickness [µm]
AS150	90	10	150	25

Two different brazing filler material:

Eutectic AlSi12 brazing foil with thickness 0,4 mm, see Table 5, which was chosen based on its composition being close to that of the coating and having an eutectic melting point promoting good wetting.

Table 5. Chemical composition and properties of eutectic AlSi12 brazing foil.

	Al	Si	Solidus temp. [°	Liquidus temp. [°	Rec. brazing temp.
			C]	C]	[° C]
Castolin Eutectic	88	12	575	585	593
AlSi12					

0

0

Amorphous NiCr-based brazing foil with thickness 0,05 mm, see Table 6, which was chosen based on good results of brazing on uncoated 22MnB5 in a previous project.

Table 3. Chemical composition and properties amorphous NiCr-based brazing foil [35].

	Ni	Cr	Si, B	Solidus temp.	Liquidus temp.	Rec. brazing temp.
			and P	[° C]	[° C]	[° C]
Vitrobraze	70	21	9	880	925	980 - 1100
2170						

• Two different flux paste, see Table 7, that differ in both active temperature range and typical usage area. Flux 190PF was chosen on its typical usage area which is brazing of aluminum whereas with Atmosin 181PF the active temperature range was the deciding factor.

Table7. Composition, active temperature range and usage of flux.

	Composition	Active temp.	Typical usage
		[° C]	
Castolin Eutectic Flux 190PF	25-50 % LiCl,	570 - 620	Aluminum
	15-20 % ZnF _{2,}		brazing
	1-5 % NaF		
Castolin Eutectic Atmosin	> 50 % Fluoroborate,	550 - 900	Reparation of
181PF	10-50 % Boric acid		steel

4.2.3.2 Preparation, setup and calibration

Braze joints and heat treatments were produced using a tube furnace with a maximum temperature of 1200° C and with a continuous gas flow of nitrogen at 3,7 L/minutes to mimic what is known as controlled atmosphere brazing (CAB) which is used today in aluminum brazing as well as steel brazing.

Joint preparation and fixturing

Substrates of USIBOR® 1500P AS150 were cut into lengths according to Figure 18 and burrs were ground down to ensure good fitting between sheets in the area to be joined. The substrates were then cleaned, first using acetone and then with ethanol. A flux was then added to the joint area see Figure 18 and the braze filler material was cut into strips of 20 by 20 mm and placed between the two steel substrates.



Figure 14. Lap joint of braze attempts.

The setup can then be placed in a fixture made out of sintered SiO2 and a steel weight of 252 g is placed on the joint area to apply pressure during brazing see Figure xx. This is then lowered into a furnace boat on top of a fixture with a thermocouple type-S.

Heat cycles

Calibration of the thermocouple type-S placed beneath the fixture holding the test-samples was calibrated using a second thermocouple type-S which was resistance spot welded (RSW) directly onto a 1,15 mm thick USIBOR® 1500P AS150 test piece. This piece was in turn resistance spot welded (RSW) to another USIBOR® 1500P AS150 piece with 20 mm overlap, as in Figure 18 to resemble the brazing setup.

The calibration was performed with the tube furnace set to two different temperatures, 800 and 950° C to validate to accuracy of the internal thermocouple of the furnace itself and also to see the difference in measurement of the welded onto substrate and beneath substrate thermocouples. The difference in measurement being particularly important as the thermocouple placed beneath samples is used as the measuring device during brazing and heat treatment cycles.

When the furnace thermocouple showed the preset temperature it was left for at least 30 minutes to make sure the heat zone was even. The boat with calibration sample and thermocouples was then slid into the furnace and when both thermocouples reached the furnace temperature it was pulled out. The sample with RSW thermocouple was quickly water quenched while the boat, fixture and steel weight were only cooled by the surrounding air. The process was then repeated when everything but the water quenched sample had an elevated temperature to simulate rapid testing where one sample is removed and another one is directly loaded into the still warm boat, this to simulate production flow in a high volume press hardening furnace. The heating curves of both thermocouples are shown in Figure 23 and Figure 24.



Figure 15. Thermocouples on and below sample with furnace temperature 800° C.



From Figure 19 and Figure 20 it is seen that the RSW USIBOR® 1500P AS150 sample is more rapidly heated than the thermocouple placed beneath the fixture. Closing in on the target temperature of the furnace the curves level out and show a difference of around 10° C between the thermocouple on the sample and the one beneath the sample as seen in Figure 21 and Figure 22. More accurately in the case of 800° C when the on sample thermocouple measured 798° C the below sample showed a reading of 790° C and in the case of 950° C the reading difference was 948° C to 940° C. It was decided that for both brazing and heat treatment a 2° C offset from targeted temperature was adequate enough to initiate timing of hold times. To avoid the need of attaching a

thermocouple to each sample, a stationary thermocouple mounted in the boat (below the sample) was used. Timing of hold times started when the stationary thermocouple in the boat had reached a temperature of 10° C below target.



Figure 21. Temperature difference close to 800° C.



Austenitization

For samples originally brazed at the lower temperature of 593° C, it was concluded that a second heat treatment was needed post brazing, at a higher temperature, to fully austenite the steel substrate.

The time that it takes for the sample to reach the targeted temperature of the furnace, as in Figure 20, was deemed too long and time consuming. Bigger variance in the austenitization process was therefore allowed and timing would start at a lower temperature, leading to the temperature of the sample constantly rising during the process and not levelling out before removal from the furnace. Upon studying the temperature curve for the RSW on sample thermocouple a time window of 4 min was found were the curve gradient had started to level out some and the temperature was above that of $Ac3 = 920^{\circ}$ C. The 4 min window was between 926 and 940° C for the on sample thermocouple and between 868 and 918° C for the one placed below sample, as is shown in Figure 27.



Figure 17. Austenitization temperature interval.

Estimated calibration of furnace at 1000° C

Previous brazing tests of uncoated 22MnB5 were made at 950° C but the total time in the furnace was considered too long. In an attempt to shorten the brazing time, the furnace temperature was raised above the target for austenitization, in this case to 1000° C. To further lower the brazing time, brazing was allowed to be conducted in a larger temperature interval then the previously used (target temp +- 2° C). In this case, for the NiCr-based brazing foil, timing of the hold time started at the liquidus temperature of 925° C. A new approximated calibration of the below sample thermocouple was done based on the readings from calibration at 800 and 950 °C. To acquire the approximated heating curves for the two thermocouples linear interpolation was used on the curves from Figure 21 and Figure 22 as here the difference of 150° C in the furnace had been measured and was known. Since the target temperature was 1000° C we have an increase of 50° C up from 950° C. This increase is a third of the known 150° C which would give the following formula for calculating the approximated curves:

$$T_{1000} = T_{950} + \frac{1}{3}(T_{950} - T_{800}) \tag{3}$$

In Eq. 3 T1000 is the new approximated thermocouple reading and T950 and T850 are the actual readings from calibration tests in 1.2.2. The new approximated heat cycle resulting from having the furnace set to 1000° C along with the used readings can be seen in Figure 24



Figure 18. Estimated heat cycle for samples in furnace at 1000° C.

4.2.4 Brazing

Attempts were made to produce braze joints with different combinations of temperature, hold times, filler material and fluxes. During brazing the tube furnace had a continuous gas flow of 3,7 L/minutes of nitrogen. Temperatures for each test were logged using the thermocouple type-S placed beneath the sample. Hold times were also based on the same thermocouple. The prepared samples of steel substrates with flux and filler material were placed in the fixture which was loaded into the boat. The weight was placed on the joint area and everything slid into the furnace, and when the desired hold time at a specific temperature had been achieved the sample removed and air cooled.

One step brazing above 900° C

Four tests setups were done to produce brazing joints between USIBOR® 1500P AS150 substrates with one heat cycle in the tube furnace with temperatures above 900° C. All tests were made with samples and joint fixture at room temperature, while everything else had an elevated temperature prior to entering the furnace. When the desired heat cycle had been performed samples were removed and air cooled. A test matrix for one step brazing trials is given in Table 8 and heat cycles in Figure 25 where the latter temperature was chosen based on braze attempts with Vitrobraze 2170 in an earlier project. Recorded temperature data of tests can be found in Appendix I.

	Samples	Filler	Flux	Temp. [° C]	Hold time [minutes]
Test 11	1	Vitrobraze 2170	Flux 190PF	950	10
Test 12	1	AlSi12	Flux 190PF	950	10
Test 19	3	Alsi12	Atmosin 181PF	900	10
Test 20	3	Vitrobraze 2170	Atmosin 181PF	950	10

Table 8. Test matrix for one step brazing tests.



Figure 19. Typical appearance of heat cycle used for brazing at 900 and 950° C for 10 minutes.

Brazing at or close to recommended temperature for AlSi12-filler

Three experimental tests were done when brazing was carried out at or close to recommended brazing temperature with three different base materials. First sample of each test was a cold start where everything but furnace had room temperature. The following two tests only had sample and joint fixture at room temperature, and all samples were air cooled. Parameter combination is given in Table 9 and difference of cold and hot start in Figure 26. Recorded temperature data of tests can be found in Appendix I.

	Samples	Base material	Filler	Flux	Temp. [°	Hold time
					C]	[minutes]
Test	3	USIBOR® 1500P	AlSi12	Flux	593	10
14		AS150		190PF		
Test	3	22MnB5	AlSi12	Flux	593	10
15				190PF		
Test	3	AA5754	AlSi12	Flux	586	10
16				190PF		

Table 9. Test matrix for brazing tests at recommended temperature.



Figure 20. Typical heat cycles for cold and hot start for brazing at 593° C for 10 minutes.

Two-step brazing

Five tests were done using USIBOR® 1500P AS150 as base material, when a combination of brazing at recommended braze temperature was used together with the austenitization heat cycle outlined in 1.2.3. The furnace was set to 593° C and samples were loaded into the already pre-heated boat. When the desired hold time at brazing temperature had been achieved the samples were removed and air cooled. The furnace was then set to 950° C and the same samples loaded, with the boat at an elevated temperature. After reaching 926° C the samples where left in the furnace for 4 minutes and were then removed and air cooled. The first heat cycle of Test18 was a cold start while all other heat cycles used a pre-heated boat. Test matrix is given in Table 10 and heating cycle of Test 18 is shown in Figure 27. Recorded temperature data of tests can be found in Appendix I.

	Samples	Filler	Flux	Temp. 1	Hold time 1	Temp. 2	Hold time 2
				[° C]	[minutes]	[° C]	[minutes]
Test	3	AlSi12	Flux	593	10	926-940	4
17			190PF				
Test	1	AlSi12	Flux	593	60	926-940	4
18			190PF				
Test	3	AlSi12	Flux	593	15	926-940	4
24			190PF				
Test	3	AlSi12	Flux	593	25	926-940	4
25			190PF				
Test	3	AlSi12	Flux	593	35	926-940	4
26			190PF				

Tahla	10	Test	matrix	for	two	sten	hrazing	tests
Lable	10.	rest	maurix	IOL	ιωυ	step	Drazing	iesis.



Figure 21. Heating cycle of Test 18 where T2 shows hold time 1.

4.2.5 Adhesive joint

To evaluate the adherence of the AlSi-coating to the steel substrate after heat treatment samples joined with adhesive were prepared. Three samples were first heat treated at 950° C for 10 minutes as in Figure 29 using a pre-heated boat. After removal and air cooling the samples were cleaned using acetone and an adhesive was applied on a 20 by 20 mm area to form a joint as in the brazing attempts see Figure 28. The adhesive used was 3M Scotch-Weld DP460, which is an epoxy based adhesive. After the appliance of adhesive, samples were left to cure at least 24 hours at room temperature, based on recommendations from 3M. Table 11 shows test parameters. Recorded temperature data of tests can be found in Appendix I.

Table 11.	. Test	matrix	for	adhesive	joint	testing.
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	Samples	Temp. [° C]	Hold time [minutes]	Adhesive	Cure temp. [° C]	Cure time [h]
Adhesive joint	3	950	10	3M Scotch- Weld DP460	~20	>24







Figure 23. Heat treatment 10 minutes at 950° C.

4.2.6 Tensile adhesion testing

To further evaluate the strength of the coating a tensile adhesion test was done. A test dolly is adhesively joined on to the coating of a sample and then pulled straight up perpendicular to the coating until fracture occurs, see Figure 30.

All samples were heat treated according to Table 12. Some samples were air cooled while others were quenched between two copper blocks with some small applied external pressure. The area to be adhesively joined on the dolly was 10 mm Ø and was roughened using sandpaper to improve adherence. Both dollies and samples were cleaned using acetone. A strip of Teflon-tape was added around the mantle of the dollies to prevent adhesive from sticking to the mantle, see Figure 31. The dollies were then adhesively joined onto the samples using 3M Scotch-Weld DP460 epoxy based adhesive and cured for 3 hours at 65° C and then left for 24 hours at room temperature. After curing all excess adhesive around the joint area was removed. Recorded temperature data of tests can be found in Appendix I.



Figure 30. Tensile adhesion test (Kopeliovich, 2014).



Figure31. Teflon-tape wrapped around dolly mantle.

	Samples	Temp 1 [°	Hold time 1	Temp 2 [°	Hold time 2	Cooling
	Samples	remp. r [Temp. 2 [Cooning
		C	[minutes]	[C]	[minutes]	
T1	2	593	15	926-940	4	Air
						cooled
T2	2	593	25	926-940	4	Air
						cooled
T3	2	593	35	926-940	4	Air
						cooled
T4	2	593	15	926-940	4	Cu-
						Blocks
T5	2	593	35	926-940	4	Cu-
						Blocks
T6	1	950	10	-	-	Air
						cooled
T7	1	950	10	-	-	Cu-
						blocks

Table12. Heat treatments of samples used for tensile adhesion testing.

4.2.7 Evaluation

Heat rate

The maximum heat-rate is 12 ° C/s above 600° C in order to avoid melting of the AlSi-coating [3]. The fastest measured heating rate occurs when the furnace is set to 950° C and as a check to determine the maximum heat-rate of this study the on sample thermocouple readings were approximated with three polynomials of 2nd degree, shown in Figure 32. The curve fittings were made using the method of least square.



Figure 24. Polynomial fitting of 950° C RSW on sample thermocouple see Figure 24.

The heating rate above 600° C is the limiting factor during heat treatment and thus the polynomials of interest are those connected to parts 2 and 3 of the curve in Figure 36. As can be seen the gradient of part 2 exceed that of part 3, which is why only part 2 will be investigated. The derivative of polynomial 2 will serve as a heat-rate in ° C/s, Eq. 4, and can be calculated for three steps where the temperature is 600, 700 and 800 ° C at x1 = 2086,5s x2 = 2173,5 x3 = 2288,5s in Eq. 5, 6 and 7:

$$y = -0,0026x + 6,6803 \tag{4}$$

$$y_1 = -0,0026 \cdot 2086,5 + 6,6803 \tag{5}$$

$$y_2 = -0,0026 \cdot 2173,5 + 6,6803 \tag{6}$$

$$y_3 = -0,0026 \cdot 2288,5 + 6,6803 \tag{7}$$

The resulting heat-rate at the three specific temperatures is thus $y1 = 1.2254 \circ C/s$, $y2 = 1.0292 \circ C/s$ and $y3 = 0.7302 \circ C/s$ and is well below the maximum heat-rate of $12 \circ C/s$.

4.2.8 Braze joints

Shear stress measurements

The evaluation of produced braze joints was done by measuring the shear stress required to cause fracture using two different tensile testers, Instron 5566 and 4505. The samples were clamped using an extra piece of base material with the same thickness in each clamping-tool to direct the force straight through the joint, see Figure 33. In the tensile tests, the pulling speed was set to 5 mm/min and used throughout all tests. After fracture had occurred the area of the joint was measured and combined with the acquired ultimate-force to calculate the shear strength of the joint see Eq. 8.



$$\tau = \frac{F}{A} \tag{8}$$

Light Optical Microscopy and Scanning Electron Microscopy

To further evaluate the braze joints and the coating resulting from the various heat treatments used, cross sections were cut both in and far from the joint, as shown in Figure 34. The samples were then first polished and then etched for 1 min using 10% NaOH and evaluated using a Light Optical Microscope (LOM), Leica DM IRM. LOM was used to acquire knowledge about joint geometry, eventual cracks and pores and locations of different phases.

Samples were also evaluated using a Scanning Electron Microscope (SEM), Leo 1530 Gemini. Again cross sections were cut both in and far from the joint. Only polishing was done before evaluation, no etching. The SEM evaluation was done to gather information about the chemical composition of phases identified using LOM, which could be compared to literature and also to investigate were fracture occurs. This was done using Energy Dispersive Spectroscopy-analysis (EDS) with line scanning, mapping and point analysis.



Figure 26. LOM and SEM cross section preparation.

4.2.9 Adhesive joints

For the adhesive joints the same evaluation procedure as with braze joints was used. Where the shear stress required for fracture was measured, also LOM and SEM were used to evaluate the coating after heat treatment. Lastly SEM was used to evaluate the fracture cross section.

4.2.10 Tensile adhesion

To measure the coating adherence the standard ISO 4624:2002 "Paints and varnishes -- Pull-off test for adhesion" was adopted. To measure the force needed to either remove the coating from substrate or cause fracture in the adhesive a manual hydraulic tensile adhesion tester for measuring of bonding strength, PAT model GM01/6.3kN, was used, as shown in Figure 35. As it was calibrated for dollies with a Ø 20 mm the readings were adjusted with a factor of 4 to match the Ø 10 mm used in testing.



Figure 27. Manual hydraulic tensile adhesion tester, PAT model GM01/6.3kN.

4.2.11 Part III - Brazing zinc-coated sheet steel to zinc-coated sheet steel

The Zn-based coatings offer cathodic corrosion protection, which is desirable for automotive parts, and is typically applied via hot-dipping or electrolytic deposition. A major drawback however, is that they can only be used in the indirect hot stamping process. If not cold-drawn before final pressing at austenitization temperature zinc adsorption at grain boundaries will occur, leading to cracks in the product [10]. In addition to only being suitable for the indirect process the final products also need to be sand blasted or shot peened in order to remove the Zn-oxide layer and promote good paintability [9]. However, investigations have been performed on the implementation of Zn-coatings in the direct hot stamping process [11].

During hot stamping heating rates and temperature exceed those used during normal galvannealing of steels and different intermetallic phases of Zn-Fe form by diffusion. Tests conducted by R. Autengruber et al. [12] on hot-dipped Zn-coated 22MnB5 steels showed that some Zn-Fe phases occurred in a temperature range above their normal stability zone (Zn-Fe equilibrium phase diagram, Figure 36 during the austenitization process. This was shown to be due to the increased heating rate prohibiting thermodynamic equilibrium. At elevated temperatures diffusion is more rapid than at room temperature. At 550 °C the coating contains 11 % Fe while at 900 °C two phases have formed with 29 % Fe (T-Zn-Fe) and 60 % Fe (α -Fe), where the amount of zinc-ferrite increases with dwell-time, Figure 88.



rigure 20 Zn-r e phase diagram [15].

As a result of Fe-diffusion the coating layer which at the start was 10 μ m thick grows to around 20 μ m containing mostly the Zn rich α -Fe phase and also has a 1-2 μ m thick Zn-oxide layer on the surface [3]. The combined layers offer good corrosion resistance.

However in contrast to the smooth coating and large grains typically found in hot-dipped coatings, an electroplated Zn-Ni coating shows finer grains and a micro roughness on the surface at the initial state. The phase transformation also differs during the typical heat cycle used in hot-stamping of boron alloyed steel. At 700 °C the iron enrichment in the electro-plated coating is less than in the hot-dipped especially closer to the coating surface [14]. At 800 °C the Zn-Ni coating consists of 85% intermetallic state and 15% zinc supersaturated solid solution, which is due to different variation of ZnxNeyFez have a higher melting point than the ZnFe phases present in hotdipped coating that slows diffusion. After a heat treatment of 5 minutes at 880 °C the electroplated Zi-Ni coating consists of three phases compared to the hot-dipped coating. They are characterized by a top layer of 13, 79 and 8 wt. % Ni, Zn and Fe (γ -ZnNiFe) and a second layer of 3, 26 and 71 wt. % Ni, Zn and Fe (α -Fe(Zn)) with scattered regions of 13, 74 and 13 wt. % Ni, Zn and Fe (γ -ZnNiFe). Further the protective Zn-oxide layer continues to grow with dwell time in the case of electroplated coating which is not the case for hot-dipped coating [14].

4.2.11.1 Experimental

In this study experimental brazing was done to analyze the possibility of joining two zinc-cooated USIBOR strips



Figure 29 SEM micrograph showing Zn-Fe phases at different temperatures and dwell-time [12].

in a lap joint.

Test material

Zinc-coated (Usibor GA). The preferred austenitization temperature of zinc-coated Usibor is 890 °C, which is just above when the Ni21Cr amorphous brazing foils starts to melt, see Table 13. and Table 14.The thickness of the zinc-coating was 10 µm.

Table 13. Chemical composition of the amorphous brazing foils used in the experiments

Alloy	AWS & ASM	Nom	Nominal composition, wt %								Melting Temp °C	
		Cr	Fe	Si	С	B	Р	Mo	Ni	Solid	Liq.	°C
VZ2170		21		Х		Х	Х			880	925	

Table 14. Alloy, thickness and width of the amorphous brazing foils used in the experiments

	Width (mm)	Thickness (µm)
VZ2170	108	50

Preparation, setup and calibration

Braze joints and heat treatments were produced using a tube furnace with a maximum temperature of 1200° C and with a continuous gas flow of nitrogen at 3,7 L/minutes to mimic what is known as controlled atmosphere brazing (CAB) which is used today in aluminum brazing as well as steel brazing.

Joint preparation and fixturing

Strips of USIBOR were cut into lengths according and burrs were ground down to ensure good fitting between sheets in the area to be joined. The substrates were then cleaned, first using acetone and then with ethanol.

The setup was placed in a fixture made out of sintered SiO2 and a steel weight of 252 g was placed on the joint area to apply pressure during brazing see Figure 19. This was then lowered into a furnace boat on top of a fixture with a thermocouple type-S.

4.3 Press hardening

All tests has been at Gestamp test facility in Luleå, Sweden. Common press hardening method has been used.

4.3.1 Hot forge sintering

Initially two tests were made using the method hot forge sintering. As powder, common shot blasting powder were used. The powder had the grain average grain size 0.3mm (0.2-0.6)

FERROSAD	С	approx.	0,095	%	Hardness:	HV1 in accordance
CHEMICAL	Si	approx.	0,15	%		with ISO 11125-3
ANALYSIS	Min	approx.	1,15		When new:	400-430
	P	approx.	0,015		In operation:	420-460
	S	approx.	0,015	%		
					Bulk weight:	4,35-4.55 kg/dm3

Figure 30 Chemical composition of shot blasting powder.



Figure 31. Shot blasting powder average grain size 0.3mm

4.3.1.1 Manufacturing of samples

Since the furnace used didn't have the ability to run a protective atmosphere the powder was wrapped inside a stainless steel foil to avoid oxide on the grain surface which would decrease the strength in the joining between the grains.





Figure 40 Powder package

Figure 41 Package in furnace.

Two different process setups were tested:

	Sample #1	Sample #2	
Furnace temperature:	940°C	940°C	
Time in furnace:	17min	10min	
Pressure:	10MPa	20MPa	
Cooling time*:	30s	120s	

* The tool used has no external cooling, only the mass of the steel dies

Table 15. Process parameters.

4.3.2 Test #1 with sintered core without brazing foil

Two uncoated 0.4mm thick 22MnB5 steel sheets were used as outer sheets and a 1.2mm thick sintered core. Sintered core specification: grain size 75µm, Fe and 0.3% C, 40% density of solid steel, heat treated 30min@1150°C. No brazing foil used. The main issue is to check the formability of the sintered core to know if it is possible to hot form.



Figure 42 Three layer



Figure 43 Packed inside stainless steel foil to avoid oxide.

4.3.2.1 Manufacturing of samples Hat profiles with a length of 100mm were manufactured



Figure 44 Hat profile tool



Figure 45 Presshardened sandwich part

Furnace temperature:	940°C				
Time in furnace:	15min				
Pressure:	N/A (stop distances has been used)				
Cooling time*:	120s				
* The tool used has no external cooling, only the mass of the steel dies.					

Table 16. Process parameters.

4.3.3 Test #2 with sintered core with brazing foil

Main target is to test how brazing foil works in the presshardening process. Two different brazing foils from Metglas has been evaluated. As outer sheets both uncoated t=0.4mm and AISi coated (Usibor) t=0.5mm has been tested. Core used is a 1.2mm thick sintered core.

Sintered core specification: grain size 75µm, Fe and 0.3% C, 40% density of solid steel, heat treated 30min@1150°C. Brazing foils tested: MBF-60 and MBF-62 with a thickness of 1.5 MIL (0.04mm).

4.3.3.1 Manufacturing of samples

Optimum conditions has been evaluated using a plane hardening tool. The pressure can also easy be controlled.



Figure 32 Plane hardening tool for small samples.



Figure 47Presshardened sample



Figure 48 Opened package

Furnace temperature:	940°C				
Time in furnace:	10min				
Pressure:	10MPa				
Cooling time*:	60s				
* The tool used has no external cooling, only the mass of the steel dies.					

Table 17. Process parameters.

MBF Alloy	IBF AWS & ASM Ilov Classifications		Nominal Composition, wt %							Melting Temp. C° (F°)		Braze Temp. (Approx.)	Density g/cm ³
		Cr	Fe	Si	C *	В	Р	Мо	Ni	Solidus	Liquidus	C° (F°)	(IDm/In ⁻)
15		13.0	4.2	4.5	0.03	2.8	-	-	Bal	965 (1769)	1103 (2017)	1135 (2075)	7.82 (0.283)
20	AWS BNi2 / AMS 4777	7.0	3.0	4.5	0.06	3.2	-	-	Bal	969 (1776)	1024 (1875)	1055 (1931)	7.88 (0.285)
30	AWS BNi3 / AMS 4778	-	-	4.5	0.06	3.2	-	-	Bal	984 (1803)	1054 (1929)	1085 (1985)	8.07 (0.291)
50	AWS BNi5a	19.0	-	7.3	0.08	1.5	-	-	Bal	1052 (1924)	1144 (2091)	1170 (2138)	7.70 (0.278)
51	AWS BNi5b	15.0	-	7.25	0.06	1.4	-	-	Bal	1030 (1886)	1126 (2058)	1195 (2183)	7.73 (0.278)
53		15.0	-	7.25	0.06	1.4	-	5.0	Bal	1045 (1900)	1127 (2060)	1195 (2183)	7.75 (0.280)
60	AWS BNi6	-	-	-	0.10	-	11.0	-	Bal	883 (1621)	921 (1688)	950 (1742)	8.14 (0.294)
62		21.0	<1	0.5	-	0.5	8.0	1.0	Bal	878 (1612)	990 (1814)	1020 (1868)	7.74 (0.280)
64		17.5	4.0	6.0		0.75	5.0	1.0	Bal	913 (1675)	978 (1792)	1010 (1850)	7.68 (0.277)
80	AWS BNi9	15.2	-	-	0.06	4.0	-	-	Bal	1048 (1918)	1091 (1996)	1120 (2045)	7.94 (0.278)

Table 18. Brazing foils from Metglas. 60 and 62 has been tested.

4.3.4 Test #3 outer sheets with brazing foil without core

The performance of the part will be connected to the strength of bond between the layers made by the brazing foil. To evaluate the shear strength, solid sheets of uncoated boron steel were plane hardened together with a brazing foil in between. 0.4mm in thickness is too thin to make shear tests with therefore 1.0mm was used instead. To prevent the influence of bending a specific setup of the sample were used, as explained in the figure x. Brazing foil used is MBF-62, 1.5 MIL.



Brazing foil between

Figure 49

4.3.4.1 Manufacturing of samples

Three uncoated sheets were put on top each other with brazing foil in between according to figure x. Overlapping area 13x20mm. Samples were wiped clean with ethanol. Press hardening were used according to figure x.

Furnace temperature:	940°C				
Time in furnace:	10min				
Pressure:	10MPa				
Cooling time*:	60s				
* The tool used has no external cooling, only the mass of the steel dies.					

Table 19. Process parameters.

4.3.4.2 Test setup



Figure 50 A dummy sheet were left to make a clean linear force.



Figure 51 Shear test setup

4.3.5 Test #4 Samples for 3-point bending

One way to determine the strength of the material is to make 3-point bending tests. By doing it this way it is possible to evaluate the bonding to the sintered core.

4.3.5.1 Manufacturing of samples Same way as in 4.3.3.1

4.3.5.2 Test setup

To do the 3-point bending test the setup on the figure below were used.



Figure 52. 3-point bending setup, c-c 75mm between supports (free to rotate), load device d=20mm

4.3.6 Test #5 Different sintered cores Part 1

Four different cores has been evaluated. In all samples 0.4mm uncoated outer sheets and MBF-62 1.5 MIL brazing foil has been used.

Α.	FeSi
В.	FeP
C.	Stainless steel austenitic
D.	Stainless steel ferritic (D1)

4.3.6.1 Manufacturing of samples

Hat profile tool has been used. The hat profiles manufactured is 40mm long.



Figure 53 Package.

Figure 54 Presshardened part still in stainless foil.

Furnace temperature:	940°C
Time in furnace:	10min
Pressure:	N/A (stop distances has been used)
Cooling time*:	60s
* The tool used has no external cooling, only the mass of the steel dies.	

Table 20. Process parameters.



Figure 55 FeSi


Figure 56 FeP



Figure 57 Stainless steel austenitic



Figure 58 Stainless steel ferritic.

All cores seems to work in the press hardening process. In this case bending the hot core over a 5mm radius. The bonding also appears to be OK after the forming.

4.3.6.2 Test setup

To evaluate the performance in strength between the hat profiles a compression test were made according to the figures below.



Figure 59 Test setup, the flanges are fixed to simulate a closing plate on the section.



Figure 60. Test setup.

4.3.7 Test #5 Different sintered cores Part 2.

Nine different sandwiches has been evaluated. The sintered core has been joined to either one of the outer sheets or both outer sheets as specified below.

Both sides of the core sintered to the outer sheets

- A. Fe 2 layers of rolled Fe, -75µm tape in between 2 Gestamp supports, 1 piece 50×200mm.
- B. Fe2.6%Si +0.4%P. 1 piece 50×200mm.
 C. Fe2.6%Si +0.4%P with BNi7 brazing paste in between 2 supports/powder in amount 3 gr per each plate, 1 piece 50×200mm.
- D. Fe2.6%Si +0.4%P+solid Fe Gestamp support with 2 layers. 1 piece 50x200mm.

One side of the core sintered to the outer sheets

- E. Fe + solid Fe Gestamp support 2 pieces 50×200mm.
- Fe + 0.6%P+solid Fe Gestamp support 2 pieces 50x200mm. F.
- G. Fe + 2.6%Si + 0.4%P+solid Fe Gestamp support 2 pieces 50×200mm.
- H. Fe + 2.6%Si +0.6%P+solid Fe Gestamp support 2 pieces 50×200mm.
- Fe + 5%Mo + 0.4%P+solid Fe Gestamp support 2 pieces 50x200mm. ١.

Outer sheets: 0.6mm uncoated 22MnB5 Brazing foil: Vitrobraze VZ2170

4.3.7.1 Manufacturing of samples

Hat profile tool has been used. The hat profiles manufactured is 50mm long.



Figure 61 Sandwiches wrapped in stainless foil..

Furnace temperature: 940°C Time in furnace: 10min Pressure: N/A (stop distances has been used) Cooling time*: 120s * The tool used has no external cooling, only the mass of the steel dies.

Table 21. Process parameters.

The position of the brazing foil has been according to the pictures below both in furnace and press.



Figure 62 Position in furnace and tool.



Figure 63 Position in furnace and tool



Figure 64 All manufactured hat profiles.



Figure 65 Sample B, example of no cracks.



Figure 66 Sample F, example of cracks.

Sample	Cracks	Note
А	No	
В	No	
С	No	
D	Yes	Minor
E	Yes	
F	Yes	
G	Yes	
Н	Yes	
1	Yes	

Table 22. Evaluation of feasibility in the press hardening process.

It looks like most of the cracks starts on the side where the brazing has been. This is probably because there isn't anything holding the sintered core outer surface together since the brazing foil is in fluid state. Complete Sandwiches (core sintered to both outer sheets) shows go formability hot without cracks in the radius.

4.3.7.2 Test setup Test setup according to 4.3.6.2.



Figure 67 Hat profiles after compression test.

4.3.8 Test of brazing foil strength.

To determine if the strength of the brazing foil is strong enough a test has been made by making a sandwich sheet were the core is made out of the same material as the outer sheets. It has then been compared with two soild sheets.

4.3.8.1 Manufacturing of samples

Hat profile tool has been used. The hat profiles manufactured is 50mm long.

4.3.8.2 Test setup Test setup according to 4.3.6.2

4.3.9 Verify the previous results. To confirm the results. Two more hat profiles were made and tested using the best sintered core so far.

4.3.9.1 *Manufacturing of samples* Hat profile tool has been used. The hat profiles manufactured is 50mm long.

4.3.9.2 Test setup Test setup according to 4.3.6.2

4.4 FE simulation

As a part of the research project Modeling and analysis of steel laminates with a core based on a porous steel material a Ph.D. research project is conducted at Luleå University of Technology (LTU). The purpose of the Ph.D. research project is to find a material model suited for modeling and analyzing a steel laminate with a core of porous medium.

Initially, LTU's part of the project can be divided into two areas. 1) The first area concerns modeling of the porous material itself, selecting a proper material model which will represent the porous medium in an acceptable manner during variable loading and deformation. 2) The second area concerns modeling of the interface between the core and the surrounding face plates, to properly predict delamination between the core and the face plates.

Initially a literature study is conducted, where methods of modeling porous material is investigated by reviewing previous work done on the subject. The application in the articles indicates if a material model is of interest or not.

After the material model is chosen proper input data must be generated for the model to correctly represent the porous material. Generation of input data is done through various methods, varying from tabulated data to implementing constitutive models into a software like MATLAB to generate desired data. Validation of any constitutive model is necessary, experimental data will be used in this research project (experiment have not been conducted yet).

4.4.1 Literature study

A literature study has been conducted where a variety of constitutive models, for modeling porous media, have been considered. Initially, a constitutive model, *MAT_BILKHU/DUBOIS_FOAM (MAT_075) from LS-DYNA's library, is chosen [L1]. A motivating factor for the selection is few input parameters, reducing the possible combinations when calibrating the material model, to fit experiments. In the work conducted by Bartl et al. [L2], the constitutive model is applied, for capturing the behavior of low density foams in a crash box structure. Results agree with experiments in an acceptable manner.

The constitutive model requires a set of input data, according to [L1], to predict the behavior of a porous material. A part of the input data set required are two curves: 1) Pressure vs Volumetric strain and 2) Uniaxial stress vs Volumetric strain. These curves are partly generated using the elasto-plastic stress-strain relationship suggested by Thanasis et al. [L3] together with data found in [L4], and partly by assumptions and boundary conditions suggested by the supervisors and the author of this report. These curves will be presented further in the coming section.

4.4.2 Constitutive model and input data

As a starting point the LS-DYNA material model *MAT_BILKHU/DUBOIS_FOAM [L1] was chosen. Motivations for the choice is its simplicity with respect to input data, requiring tabulated data and two stress-strain curves: 1) Pressure vs Volumetric strain and 2) Uniaxial stress vs Volumetric strain. The indata curves are created through the theories presented in by Thanasis et al. [L3].

To obtain the stresses required for the input data, an iterative process in the form of explicit integration is adopted, no further detail on the process will be presented here. For the interested reader some information can be found in [5]. In Figure 68 results for hydrostatic loading is presented, where it can be seen that the shear components are zero, as should be expected. A case with uniaxial loading is also conducted.



Figure 68. Stresses vs volumetric strain.

During the iterative process of generating the curves required as input data, some numerical errors are introduced, presented in Figure 69. These errors are deemed small enough to be ignored. Also, during the calculations a method for correcting for yield surface drift turns out to be required. Methods to be applied are presented in [L5].



Figure 69 Showing deviatoric stress invariants versus volumetric strain.

From the two cases, hydrostatic loading and uniaxial loading, the two input data curves are generated. The curves stems from the elasto-plastic constitutive relation presented by Thanasis et al. [L3] together with some data from Gibson et al. [L4], as well as assumptions and boundary conditions imposed by the authors of this report. The obtained curves are presented in Figure 70 and Figure 71.



Figure 70 Uniaxial stress vs Volumetric strain.



Figure 71 Figure 4. Pressure vs Volumetric strain.

4.4.3 Contact interface and shear model

For modeling of the interface between core and face plates a tie-break contact in LS-DYNA has been used to virtually reproduce the cohesive behavior. Initially, a shear model is used to investigate the distribution of shear in the interface, see Figure 5.Each steel sheet has a length of 50 mm and a width of 20 mm. The dimensions of the solid is (20 x 20) mm ^2. Thickness of the steel sheets are set to 0.4 mm and the solid has a thickness of 1 mm. The middle shell is subjected to a controlled displacement perpendicular to its normal causing shear stresses in the interfaces of the model. However, the mesh in the model presented in Figure 72 will have to be refined to better display distribution of shear stresses. Figure 73 presents the shear stress distribution for the coarse mesh. The stress distribution is approximately symmetrical, with stress concentrations at the edges of the diamond shaped solid, as would be expected.

At the moment the strength of the bonding is unknown and is therefore estimated to be stronger than both the core and the face plates. If failure occur it will not be in the bonding. The model will therefore not predict delamination of the model, but it will display the stress distribution in the interface.



Figure 72 Shear model, mesh size 2 mm.



Figure 73 Shear distribution.

4.4.4 Developed strategy for modeling UHSS based sandwich structure

In this section the modeling approach used for a laminate based on a porous core is presented. The simulations are performed on hat-profiles, see Figure 74, using the multi-physical solver LS-DYNA [L6].



Figure 74 Hat-profile used for simulations.

Performance of the hat-profile is investigate by subjecting the geometry to a crushing force in the form of a barrier. This is in accordance with the experimental setup used by Gestamp Hardtech, presented in Figure 75, Figure 76, and Figure 77. In Figure 10 the barrier crushing the hat-profile can be seen. Geometries are supplied by Gestamp Hardtech.



Figure 75 Experimental setup 1.



Figure 76 Experimental setup 2.



Figure 77 Experimental setup 3.

Since performance of a laminate with face plates made of UHSS, and a core of sintered porous steel, is to be investigated and compared to the performance of a hat-profile solely consisting of UHSS, two different modeling methods are required. The first modeling method represents the hat-profiles solely consisting of UHSS, where shell elements with a thickness of 2 millimeters is used, resulting in a total mass of 0.120 kg, this is presented in Figure 78. The second modeling method represents a laminate, consisting of a core of 1.2 millimeters thick, enclosed by face plates, each 0.4 millimeters thick. The mass of the laminate with a solid core is 0.120 kg as, as compared to 0.085 kg with a porous core, having a relative density of 0.5. The width of the hat-profile is presented in Figure 76. Solid elements, in four layers, are applied to model the core, and shell elements represent the face plates. This is presented in Figure 79.



Figure 78 Hat-profile - method with only shell elements.



Figure 79 Hat-profile - method with shell and solid elements.

Solid elements are introduced to model the porous core, thus it is of interest how these elements influence the behavior of the hat-profile when subjected to loading. A reference simulation, investigating a possible influence on the behavior, is presented in the coming section, followed by a section devoted to laminates with porous cores.

4.4.5 Hat-profile subjected to loading - influence of solid elements

To make a comparison between a hat-profile with and without solid elements, two simulations are required. Initially, a simulation with a hat-profile consisting solely of shell elements is solved. The material used for the shell elements is UHSS, as required. Furthermore, a simulation is run with a hat-profile consisting of shell elements and solid elements. UHSS is used to represent the material in the two kinds of elements. Thus, the two simulations are equal with respect to geometry and material, and are expected to generate similar output data.

A mesh size of 0.5 millimeter for the shell elements was chosen after a divergence analysis was conducted. The obtained results are presented in Figure 80. It can be seen that the mesh has converged for a mesh size of 1 millimeter. However, the solid elements are generated from the shell mesh. Thus, the element size of the solid elements depend on the size chosen for the shell elements. Due to this, a mesh size of 0.5 millimeters is chosen for the shell mesh. This will increase the resolution of the core.



Figure 80 Convergence for shell elements. 2 mm, 1mm and 0.5 mm.

To represent the core of the laminate 4 layers of solid elements have been adopted, with a mesh size of 0.5 millimeters. A comparison between 4 and 5 layers was conducted. Only a small difference was found, for large deformations, see Figure 81, thus 4 layers is used. To handle the interface between core and face plates, shared nodes are applied. Thus, no debonding will occur. Force versus displacement is used for comparison. The response obtained for the two simulations is presented in Figure \ref{fig:shell_vs_solids}. It can be seen that the solids produce a stiffer response for the first peak load. At the second peak load, a stiffer response is generated for the shell elements. The energy absorption is obtained by integrating the curves of Figure 82. The shell mesh and the mesh with solids absorb 1.64 kJ, and 1.62 kJ, receptively.



Figure 81 Comparing layers of solids, 4 layers vs 5 layers.



Figure 82 Comparing Shells and Solids.

4.4.6 Laminates with a porous core

To represent a porous core *MAT_075 in LS-DYNA is chosen, as mentioned in previous sections. The required input data is found in [L1], where it is stated that two curves are required, to describe the porous material in an acceptable manner: 1) Pressure versus Volumetric strain and 2) Uniaxial stress versus Volumetric strain, see Figure 68 and Figure 69.

In Figure 83, the response of the laminate with a porous core is presented. For comparison, the results presented is in Figure 82 are also presented.



Figure 83 Comparing response for Shells, Solids and Shells, and Solids (porous) and Shells.

5 Objective

The proposed research is aimed at developing competitive steel solutions for the car body by reducing the density of the blank material without any major change in the elastic stiffness.

The low density steel blank is a laminate (sandwich) with outer layers of ultra-high strength steel and low density core created by sintered metal powder in variable thickness.

Finite element (FE) models and testing methods for steel laminates are a necessary condition for efficient product development. FE methods will be developed in this project to support thermo-mechanical forming and crash analysis used for product development in the automotive industry. The specific aims with the project can be summarized in three main targets:

- 1. Development of powder technology to create a low density core on thin boron steel blank.
- 2. Develop and optimizing a joining method to create a bounding between the top layer of the laminate and the low density core in the hot stamping process
- 3. Develop simulation methodology for forming- and crash analysis of hot stamped steel sandwich.

Point 1,2 has been done although no "large" BIW part has been manufactured due to the low strength of the core and the joint between the outer sheets and the core. Regarding simulation, a methodology for crash has been done but not for forming.

6 Result and objective completion

A full investigation on how to make a sandwich blank that can be used in press hardening has been done. Although in the end the strength turned out to be too low for crash applications. The limits is the core material and the brazing foil. There is still though a possibility to use this type of sandwich on parts that only are used for stiffness and works in the elastic zone.

Since the project is divided into four different topics sintering, bounding, press hardening and simulation each topic will have their own section regarding method will be handled individually and followed by a summery.

6.1 Sintered core

6.1.1 Cast Core

Results from the testing suggested issues with strength. This is likely a result of a combination between low bond strength between powder particles as well as bonding between the sintered core and steel sheet (with and without brazing).

6.1.2 Cast + Rolling

Rolling improved all of the aforementioned properties as expected. Densification only affected the surface properties while leaving a low density region through the center cross-section of the sheet core. The result of this left the bond strength of the sheet to be superior to the sheet strength therefore splitting the sheet through the low density region. Only possible improvements to this are further densification to the material and closer to full density. The concept would then rely on pattern to remove the weight. This would also suggest a new approach to manufacturing the sheets entirely in order to reach higher density with pattern included.

6.2 Bonding

A large number of different bonding methods were considered, e.g. explosive welding, resistance welding, brazing/welding with nano-foil and conventional brazing. However, the ultimate bonding process should be performed in line, and this might be possible with brazing during the austenitization step of the boron sheet steel. Therefore, the research effort was focused on to develop a brazing process that could be performed during the austenitization step of the boron sheet steel.

Boron sheet steel for the automotive industry is either aluminized zinc-coated or uncoated and therefore different brazing methods need to be developed. This project was therefore divided into three parts, Part 1 – Brazing boron sheet steel to boron sheet steel and Part II - Brazing aluminized sheet steel to aluminized sheet steel, Part III-Brazing zinc-coated sheet steel to zinc-coated sheet steel.

6.2.1 Part 1 – Brazing boron steel to boron steel

6.2.1.1 Brazing foil MBF 62 compared with Vitrobraze VZ217

Table 23. Brazing foil MBF 62 compared with Vitrobraze VZ2170 , 950 $^\circ C$, holding time 4 minutes boron steel 1 mm. Tensile test.

		Time from	Time			
Brazing foil	Temp	Melting to holding temp	holding temp	Fracture MPa		
	°C	Minutes	Minutes	Min	Max	Average
Vitrobraze VZ2170						
108 x 50 µm	950	10	4	37.2	46.2	40.2
MBF 62 1.76 inch x 2Mil						
44.7 mm x 50.8 μm	950	10	4	32.4	35	33.8

Vitrobraze VZ2170 achieves higher shear strength than MBF 62. Cross-section images of the samples are presented in Figure 84 and Figure 85.



Figure 84. Light Optical microscopy (LOM). MBF 62 joint thickness 37 μm

Prov73_1





Figure 85. LOM. Vitrobraze VZ2170 joint thickness 66 μm

Element (Wt%)	1	2	3	4	5
С	5.05	7.69	3.98	4.62	4.61
Si	0.64	1.48	0.30	0.76	0.15
Р	0.63	7.21		0.72	9.10
Cr	17.60	43.68	0.49	18.10	62.94
Mn			0.88		
Fe	7.19	1.06	94.34	5.18	2.27
Ni	68.47	35.19		70.63	19.13
Мо	0.42	3.69			1.80
Total:	100.00	100.00	100.00	100.00	100.00

Figure 86. SEM compo mode. Brazing foil MBF 62, 950 °C , holding time 4 minutes boron steel 1 mm

Cross-section analysis of the joint reveals that the bonding layer is not homogeneous. The layer consists of nickel rich layers close to the boron steel substrates.

6.2.1.2 The effect of the time in liquid state

Table 24. The effect of the time in liquid state.	Brazing foil: MBF 62 1.76 inch x 2Mil. Tensile test, single
lap joint.	

Brazing	Time from melting to	Time	Fracture		
temperature	holding temperature	holding temperature	MPa	MPa	MPa
Celsius	Minutes	Minutes	Min	Max	Average
950	12	4	33	37	36
950	37	4	39	41	40
1020	13.5	4	51	62.5	55.5
1020	40	4	37	52	44.5

An increase of the time in liquid state from ~ 16 -18 minutes to

~ 40 - 42 minutes increase the average fracture strength by ~ 10 % at a brazing temperature of 950°C, while the average fracture strength is reduced by ~ 20 % at a brazing temperature of 1020°C

6.2.1.3 The effect of the brazing temperature

Table 25. The effect of the brazing temperature.	. Brazing foil: MBF	62 1.76 inch x 2Mil.	Tensile test, single
lap joint.			

	Time from melting to	Time			
Temperature	holding temperature	holding temperature	Fracture MPa		
Celsius	Minutes	Minutes	Min	Мах	Average
920	35	4	31	37	34
950	37	4	39	41	40
1020	40	4	37	52	44.5

An increase of the holding temperature from 920°C to 950°C increase the average fracture strength by ~ 17 %, and an increase from 950°C to 1020°C increase the fracture strength by ~ 11%.

6.2.1.4 Brazing foil MBF 60 compared with MBF 62

Table 26. Brazing foil MBF 60 compared with MBF 62 Tensile test, single lap joint

		Time from	Time			
		Melting to	holding	Fracture		
Brazing foil	Temp	holding temp	temp	MPa		
	°C	Minutes	Minutes	Min	Max	Average
	-					
MBF 60 2.0 inch x 1.5Mil	950	35	4	22	26	24

The MBF 62 (Ni21Cr) foil has a ~ 65 % higher fracture strength than MBF 60 (Ni) foil at a brazing temperature of 950° C.

6.2.1.5 The effect of 5 MPa pressure after brazing but before quenching

Table 27. The effect of applying a pressure of 5 MPa after brazing but before quenching in water Tensile test, single lap joint

Brazing alloy	Brazin	g	Aplied	Fracture		
	temperat	ure	pressure	MPa	MPa	MPa
	/ time		after brazing	Min	Max	Average
MBF 62 1.76 inch x 2Mil	950 /	4	5	33	36	34.5
MBF 62 1.76 inch x 2Mil	950 /	4	0	39	41	40

The applied pressure did not result in a thing brazing layer and thus the positive effect of applying the pressure was not seen.

Reasons: Brazing alloy solidifies before pressure is applied Too low pressure.

6.2.1.6 The effect of the brazing alloy and foil thickness evaluated by peel test

Table 28. The effect of the brazing alloy and thickness of the foil evaluated by peel test

Brazing alloy	Brazing temp	Holding time	Peeling force
	С	minutes	Maximum
			Normalized
MBF 60 3 inch x 1 Mil	920	4	0.24
MBF 62 8.5 inch x 1.5 Mil	920	4	0.35
MBF 60 2 inch x 1.5 Mil	920	4	0.40
MBF 62 1.76 inch x 2Mil	920	4	1

The highest shear strength is obtained for MBF 62 at a foil thickness of 2 Mil (50.8 μ m), followed by MBF 60 at a foil thickness of 1.5 Mil (38.1 μ m)

6.2.1.7 The effect of brazing holding time evaluated by peel test

Table 29. The effect of brazing holding time evaluated by peel test

Brazing alloy	Brazing temp	Holding time	Peeling force
	С	minutes	Maximum
			Normalized
MBF 62 1.76 inch x 2Mil	950	4	1
MBF 62 1.76 inch x 2Mil	950	20	1.05

Increased holding time at 950°C from 4 to 20 minutes increased the peeling force with 5%.

6.2.1.8 The effect of core material evaluated by peel test

Table 30. The effect of core material evaluated by peel test

Brazing alloy	Temp	Holding time	Core	Peeling force
	с	minutes	material	Maximum
				Normalized
MBF 62 1.76 inch x 2Mil	950	4	Sintered iron	0.23
MBF 62 1.76 inch x 2Mil	950	4	Boron steel	1

Sintered iron is too brittle to be used as core material.

6.2.1.9 The effect of the ambient atmosphere during brazing evaluated by peel test

Table 31.The effect of the ambient atmosphere during brazing evaluated by peel test

Brazing alloy	Temp	Holding time Ambient		Peeling force
	с	minutes	atmosphere	Maximum
			during brazing	Normalized
MBF 62 1.76 inch x 2Mil	950	4	Air	0.35
MBF 62 1.76 inch x 2Mil	950	4	N ₂	1

Brazing should be performed in inert atmosphere.

6.2.1.10 The effect of the brazing temperature evaluated by peel test

Table 32.The	e effect of the	brazing temperat	ture evaluated by peel te	est

Brazing alloy	Temp	Holding time	Peeling force
	с	minutes	Maximum
			Normalized
MBF 62 1.76 inch x 2Mil	950	4	1
MBF 62 1.76 inch x 2Mil	1020	4	1.73

Brazing at the recommended temperature for MBF 62 results in a 73 % higher peeling force, compare to brazing at the austenitization temperature.

6.2.1.11 The effect of the brazing alloy evaluated by peel test

Table 33. The effect of the brazing alloy evaluated by peel test

_			
Brazing alloy	Temp	Holding time	Peeling force
	с	minutes	Maximum
			Normalized
MBF 60 2 inch x 1.5 Mil	950	4	0.41
MBF 62 1.76 inch x 2Mil	950	4	1

The MBF62 (Ni21Cr) has a significantly higher peel force than the MBF60 foil (almost only Ni and 11 % phosphorus).

6.2.1.12 Measured joint thickness

Measured thickness of the joint for the MBF 62 was in the range of 30 μ m to 60 μ m, while the measured thickness of the joint for the MBF 60 was 7 μ m. The brazing foil thickness was 50.8 μ m and 38.1 μ m respectively. This might be due to that the MBF 60 brazing alloy has a wider and lower melting range compared to the MBF 62 alloy. MBF 62 is almost always only "partially melted" in the performed experiments.

6.2.1.13 Discussions

Brazing of uncoated boron sheet steel was performed with amorphous Ni/Cr brazing foils at a temperature equal to the austenitization temperature for boron steel. Brazing was conducted in a tube furnace with inert gas flowing through the furnace during the brazing process without adding flux.

The best result was achieved with a ~50 µm thick Ni/21Cr brazing foil in inert (nitrogen) atmosphere, out of which Vitrobraze VZ2170 (Ni21Cr), was better than Metglas MBF 62, due to a lower melting temperature of the brazing foil. The melting temperature was in the range of 880°C to 925°C for VZ2170 and 880°C to 990°C for Metglas MBF 62. Measured shear strength of single lap joints brazed with Vitrobraze VZ2170 (Ni21Cr) at a brazing temperature of 950°C and a holding time of 4 minutes was in the range of 36 MPa to 46 MPa.

6.2.2 Part II - Brazing aluminized boron steel to aluminized boron steel

In this section the results from tensile tests are presented.

6.2.2.1 One step brazing above 900°

The material combination for braze attempts using both NiCr-based and AlSi12 foil as filler metal in combination with Flux 190PF (aluminum-flux) directly at 950° C for 10 minutes did not yield very good results. The sample with Vitrobraze 2170 (NiCr-foil) did not produce any joint between the substrates as they were separated when removed from the fixture, no wetting, and although the sample with AlSi12-filler produced a joint it could however be peeled by hand, and as such no tensile test was performed.

Using the other flux (Atmosin 181PF) with a higher active temperature range provided different results. For the AlSi12-filler brazed at 900° C for 10 minutes one specimen broke prior to testing, when removed from the fixture while all three samples using Vitrobraze 2170 at 950° C for 10 minutes could be removed without issues. However performance was low with shear strength of around avg. 1,1 and 2,0 MPa for the two material combinations. It was decided that the poor performance of the joints did not validate LOM or SEM analysis.



material.

6.2.2.2 Brazing at or close to recommended temperature for AlSi12-filler

The material combinations tested at recommended brazing temperatures for AlSi12-filler (593° C) or a bit lower (586° C) when base material was AA5754 with melting temperature of 600° C produced joints. In the last case of aluminum as substrate one sample was peeled by hand and therefor lacks measured shear stress and is not included in the avg. shear stress. The base material did however bend before the joint was separated from one of the substrates. The best performing combination was with USIBOR° 1500P AS150 as base material with an avg. shear strength 7,2 MPa while the other combinations both ended up with an avg. 2,7 MPa shown in Figure 41. As no austenitization had been performed it was decided that LOM and SEM analysis would not be done.



Figure 88. Avg. shear stress (incl. min and max) using the same flux and filler material with different base materials when brazing at recommended temperature.

6.2.2.3 Two-step brazing

Using the same material combination of USIBOR® 1500P AS150, AlSi12-filler and Flux 190PF with varied hold times of brazing at 593° C, followed by an austenitization process of 926-940° C for 4 minutes resulted in varied shear strength. In the cases when brazing was done for 10, 15 and 25 minutes, one sample broke when removed from the fixture. Best performing were the samples with longer braze times 35 and 60 minutes, with avg. shear strength of 5,4 and 5,0 MPa while samples brazed for 10, 15 and 25 minutes showed strength of 1,4; 2,1 and 3,8 MPa.



Figure 89. Avg. shear stress (incl. min and max) from varied braze time at 593° C using the same material combination.

Inspection of the fracture surface shows that the fracture occurs somewhere in the interface between joint and substrate, i.e. the joint does not break, but delaminates from one of the substrates. The joints that broke when removed from fixture all show similar failure, which could be due to oxide formation when removed from protective atmosphere but has yet to be explained.



Figure 90 Fracture surface of joint brazed for 35 minutes at 593° C then heated through 926-940° C for 4 minutes.



Figure 91. Typical joint breakage when removed from fixture.

6.2.2.4 Brazing with reduced aluminum coating thickness

A single test was performed where the aluminum coating thickness partly had been reduced on the samples. Brazing with amorphous Ni21Cr brazing foils at 950 °C/ 10 minutes resulted in shear strength of 16 MPa, which is still too low but it indicates that the strength can be improved. it might be possible to braze aluminized boron sheet steels if the present coating thickness of 25 μ m is reduced.

6.2.2.5 Adhesive joint

Joints prepared with adhesive after following a heat treatment of 950° C for 10 minutes instead of brazing that were tensile tested showed some spread in the performance. With highest shear stress at 22,65 MPa and the lowest at 10,51 MPa, showing that the heat treatment produces variance in the coating strength of samples, see Figure 92. All fractures occur at the interface between joint and substrate, i.e. in the AlSi coating of substrate, see Figure 93 and the fracture surface shows variation within the coating which very well might be different AlFeSi-phases due to iron diffusion during the heat treatment, see Figure 94.



Figure 92 Avg. shear stress (incl. min and max) for adhesive joints prepared on USIBOR® 1500P AS150 substrates heat treated at 950° C for 10 minutes.



Figure 93 Fracture surface of adhesive joints.



Figure 94 Variation which could be different AIFeSiphases in the coating on the fracture surface.

6.2.2.6 Tensile adhesion testing

The tensile adhesion tests that were performed provided scattered results with a lot of variance between different heat treatments and cool down procedure. The adherence appears to have increased for two –step heat treatments (varied hold time at 593° C followed by heating through 926-940° C for 4 minutes) when they are pressed between copper blocks to increase cool-down rate. For samples heated directly to 950° C it seems as if the opposite is instead occurring where the air cooled samples show best results. Previous tests with uncoated samples using the same adhesive and following the outlined steps in 1.5 showed results were fracture would occur in the adhesive when tensile stresses of above 40 MPa could be measured. Knowing the strength of the adhesive and looking at the fracture surface of tests, which was the same for all tests, it is shown that fracture occurs in the AlSi coating of samples, see Figure 96.



Figure 95 Avg. measured stress (incl. min and max) from tensile pull off test on heat treated USIBOR® 1500P AS150.



Figure 96 Fracture of tensile adhesion test.

6.2.2.7 LOM analysis

In this section the images and results from Light Optical Microscopy (LOM) investigations are presented which were done on coating of samples heat treated for 10 minutes at 950° C and on both coating and joint prior and after austenitization of two-step brazing for 15, 25 and 25 minutes. **Coatings**

As the two-step brazing with AlSi12-filler included austenitization and produced the best result, LOM analysis was done on cross sections of samples from two-step brazing for 15, 25 and 35 minutes both for the joint and also for the coating far away from the joint. For comparison a coating cross-section of two-step brazing for 35 minutes prior to the second heat treatment step (austenitization) was also prepared. In Figure 97 and Figure 98 the coating of 35 minutes two-step brazing prior and after austenitization can be seen. At the interface between substrate and coating a visible change has occurred and a band like layer has appeared, also at the top of the coating there seems as if a more homogenous phase has taken form.



Figure 97 Coating of two-step brazing for 35 minutes prior to austenitization.



Figure 98. Coating of two-step brazing for 35 minutes after austenitization.

The coatings that have been brazed for 15, 25 and 35 minutes at 593° C and then austenized for 4 minutes show the same band like layer at the interface between substrate and coating (Figure 98, Figure 99 and Figure 100). However there seems to be a difference in the homogeneity at the top of the coating, where samples brazed for 25 and 35 minutes look more similar than those only brazed for 15 minutes.



Figure 99 Coating of two-step brazing for 15 minutes after austenitization.

Figure 100 Coating of two-step brazing for 25 minutes after austenitization.

The coating produced by the heat treatment from one-step brazing at 950° C for 10 minutes which was also used in the shear stress evaluation by tensile testing using adhesive as joint (Figure 101) looks different from the twostep heat treated coatings (Figure 98, Figure 99 and Figure 100). The band between substrate and coating is not as visible; also the top of the coating seems to have grown at the cost of the darker phase in the middle.



Figure 101 Coating of samples held for 10 minutes at 950° C.

Joints

The brazing joints from two-step brazing using AlSi12-filler show similar structure regardless of braze time prior to austenitization with the difference being the thickness of phases, probably due to iron diffusion from substrate into the joint, see Figure 102, Figure 103 and Figure 104. A clear band is visible separating joint from substrate followed by a different phase connected to what is believed to be an aluminium matrix with Si-rich scattered



Figure 102. Joint brazed 15 minutes prior to austenitization.

Figure 103. Joint brazed 25 minutes prior to austenitization.

Figure 104. Joint brazed 35 minutes prior to austenitization.

After austenitization, see Figure 105, Figure 106 and Figure 107, the same joints show differences. The differences can mainly be seen at the interface between substrate and joint where the previous joints had two layers separating substrate from what is believed to be aluminium matrix, there is now just one. The aluminium matrix has also transformed and is no longer visible and is replaced by at least two intertwined phases. Comparing the effect of braze time on the joints after austenitization, the only notable difference seems to be in the layer closest to substrate. At 15 minutes braze time clear grain boundaries are seen that disappear with longer braze time.





Figure 105 Joint brazed 15 minutes after austenitization.

Figure 106 Joint brazed 15 minutes after austenitization.

Figure 107 Joint brazed 15 minutes after austenitization.

Regarding joint thickness there is no clear correlation between braze time and subsequent austenitization as the shortest braze time without austenitization had the largest thickness of around 289 μ m which after austenitization was reduced by almost a third. In the case of 25 and 35 minutes braze times the behavior was opposite; with an increased thickness after being heated above 920° C. The thickness grew from around 214,5 to 273 μ m. Prior to austenitization prolonged braze times above 15 minutes show an increase in pores and cracks illustrated in Figure 108, Figure 110 and Figure 112. However, after being heat treated at temperatures above 920° C the opposite is visible where all joints have cracks and pores see Figure 109, Figure 111 and Figure 113; but joints brazed for 35 minutes have the most joints formed in between cracks.



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Figure 109 Joint brazed 15 minutes after austenitization.

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Figure 110 Joint brazed 25 minutes prior to austenitization.

Figure 108 Joint brazed 15 minutes prior to

austenitization.



Figure 111 Joint brazed 25 minutes after austenitization.



Figure 112 Joint brazed 35 minutes prior to austenitization.



Figure 113 Joint brazed 35 minutes after austenitization.

The braze joints made with NiCr-based filler material on uncoated 22MnB5 substrates show less cracks and pores compared to braze joints made with AlSi12-filler and USIBOR® 1500P AS150 substrates. However some were still visible as shown in Figure 114 and could be due to handling of the samples when removed from the fixture, but along most of the joint cross section there is good wetting without cracks and pores, Figure 68 and Figure 69. The average joint thickness for samples brazed for 10 minutes at 950° C is 69 µm while for samples using the faster heat cycle with 5 minutes above liquidus temperature (925-979° C for 5 minutes) it was 42 µm.



Figure 114 Braze joint with NiCr-filler on 22MnB5 held for 10 minutes at 950° C.



Figure 115. Braze joint with NiCr-filler on 22MnB5 held for 10 minutes at 950° C.



Figure 116 Braze joint with NiCr-filler on 22MnB5 heated through 925-979° C for 5 minutes.

6.2.2.8 SEM analysis

In this sections results from SEM analysis will be presented with images and chemical composition of different phases found. Samples investigated are: coating used for adhesive shear testing, coating from as received conventional press hardening, coating from best braze-attempts, joints of best braze attempts both prior and after austenitization and fracture of both best braze joints as well as adhesive shear test.

Coatings

By using EDS-analysis at different points of an electron image or by doing a line-scan one can get a grasp about which elements are present and compare the coatings resulting from different heat treatments. However, as an EDS-analysis is not very accurate compared to EBSD crystallographic analysis or X-ray diffraction analysis the atomic percent acquired by EDS is compared with known phases from literature that one can expect to find in AlSi-coating of USIBOR® 1500P AS150 after heat treatments above 900° C [16].

The samples heat treated at 950° C for 10 minutes that were used in one step brazing showed a composition of three phases, where the top most layer was identified as the AIFe phase with a chemical composition of AI 47,5; Fe 46,0 and Si 6,5 (at.%). Below the top layer a thinner layer could be identified as having a composition of AI 63,70; Fe 35,0 and Si 1,2 (at.%) which is close to that of AI5Fe2. Followed again by the AIFe phase but with less thickness compared to the top layer (6 µm compared to 8 µm). This is followed by a continuous decrease of AI-and increase of Fe-content which would typically be AI-rich α -Fe with AI 22,6; Fe 71,7 and Si 5,7 (at.%). This layer stretches for 28 µm until it reaches the base material, and the total coating thickness after the heat cycle is 45 µm. A SEM image of the coating with location of phases is shown in Figure 117 and EDS-result along the coating depth is shown in Appendix II.



Figure 117 SEM image of AlSi-coating held at 950° C for 10 minutes.

The coating as a result of two-step brazing where samples where held at 593° C for 35 minutes and then heated through 926-940° C for 4 minutes produced a coating with three distinct phases. The top most layer has a composition of Al 43,9; Fe 46,5 and Si 9,6 (at.%) and is close to that of the phase AlFe with a thickness of 9 μ m. This is followed by a phase which could be Al5Fe2 with a composition of Al 64,9; Fe 34,0 and Si 1,1 (at.%) and has a thickness of 11 μ m. Next the AlFe phase is present again but with a lower Si-content and less thickness of 3 μ m. From here to the base material (17 μ m) Fe-content increases at the cost of Al-content and Al-rich α -Fe composition was identified with Al 22,2; Fe 73,5 and Si 4,3. The total coating thickness is 42 μ m. In Figure 118 a SEM image of the coating is shown along with the location of the three phases, also EDS-result along the coating depth can be seen in Appendix II.



Figure 118. SEM image of AlSi-coating first held at 593° C for 35 minutes then heated through 926-940° C for 4 minutes.

As reference AlSi-coating of conventionally press hardened USIBOR® 1500P AS150 was also investigated using SEM with EDS-analysis in order to compare the result of heat cycles used in brazing attempts against what would be a more typical phase composition from the hot stamping process. The top layer has a composition of Al 67,8; Fe 27,9 and Si 4,3 (at.%) which is close to that of Al5Fe2 and is 8 μ m thick followed by a 4 μ m thick layer that probably is of the phase AlFe with composition Al 45,7; Fe 40,8 and Si 13,5 (at.%). Next another layer of Al5Fe2 was identified which is 13 μ m thick before a zone, 5 μ m, of Al-rich α -Fe with composition Al 15,6; Fe 78,3 and Si 6,2 (at.%) is encountered. This gives a total coating thickness of 30 μ m. Phases and locations are shown Figure 72 and an EDS-Line scan containing composition along coating depth can be seen in Appendix II.



Figure 119 SEM image of AlSi-coating from conventionally press hardened USIBOR® 1500P AS150.

Joints

SEM was used to gather information via EDS-analysis on the braze joints that underwent the two-step brazing at 593° C for 35 minutes both prior to and after the second heat cycle of 926-940° C for 4 minutes. The joints used AlSi12-filler material and Castolin Eutectic Flux 190 PF.

In the joint that was solely brazed for 35 minutes at 593° C without any extra heat cycle three particular phases where identified. An aluminum matrix is formed in the middle of the joint consisting of almost only aluminum, Al 98,2; Fe 0,2 and Si 1,6 (at.%). In the matrix there are scattered regions with high Si-content that were only visible in atomic mapping and can be seen in Appendix II, in addition SiO2 and flux residue were identified at some places in the matrix. Below the joint there is a phase which could not be determined from literature regarding the AlSi-coating, however it showed a composition close to Al14Fe3Si3 with Al 67,5; Fe 15,4; Si 17,1 (at.%) which can be found in Al-alloys [37]. Separating the base material from joint is a phase showing a composition close to that of Al5Fe2 with Al 68,9; Fe 28,9 and Si 2,3 (at.%) which is found in the AlSi-coating, and there is no presence of Al-rich α -Fe between base material and this phase. Phases and locations are shown in Figure 120 and an EDS-Linescan showing the composition along the joint depth can be found in Appendix II.



Figure 120 SEM image of braze joint using AISi12-filler and 190 Flux PF brazed for 35 minutes at 593° C.

After the austenitization step, i.e. brazing for 35 minutes at 593° C then heating through 926-940° C for 4 minutes 5 different phases could be seen. In the middle of the join there are various compositions where Fe- and Si-content vary contrary but all show a composition close to around AI 66,0; Fe 19,9 and Si 14,0 (at.%) which could be Al8Fe2Si. There is a band separating the former phase with the next which could be Al2Fe3Si3 which has a composition of AI 41,3; Fe 36,5 and Si 22,2 (at.%). Below the band a phase was found which is possibly Al5Fe2 with a stoichiometry AI 68,5; Fe 28,3 and Si 3,2 (at.%), this phase also includes scatters of the Al2Fe3Si3 phase. At the edge of the joint there is a small band of a phase containing significant amounts of all three components AI 35,6; Fe 45,7 and Si 18,7 (at.%), the structure was however not identified. Prior to the base material of Fe there is some Al-rich α -Fe with the composition AI 16,9; Fe 78,0 and Si 5,1 (at.%). Phases and their location are illustrated in Figure 121 and EDS-Line scan through the joint can be found in Appendix II.



Figure 121 SEM image of braze joint using AlSi12-filler and 190 Flux PF brazed for 35 minutes at 593° C then heated through 926-940° C for 4 minutes.

Fracture

Investigating the fracture surface of a braze joint which was brazed for 35 minutes at 593° C, then autenized through 926-940° C for 4 minutes one particular composition was identified. Apart from Al-rich α -Fe and base material the phase, which structure was not identified, had a stoichiometry of Al 34,4; Fe 49,1 and Si 16,5 (at.%), see right side of Figure 75. The composition resembles the one found at the edge of the joint in between Al5Fe2 and α -Fe with Al 35,6; Fe 45,7 and Si 18,7 (at.%). The fracture is also, as shown previously in 3.1.3, abrupt in nature which supports the fracture line following the line drawn to the left in Figure 122 and it propagates along the phase with composition shown to the right in the same Figure.



Figure 122 Fracture of two-step 35 minutes braze joint showing stoichiometry at fracture surface.

The fracture in joints where adhesive was used to evaluate the coating strength occurred in the coating. EDSanalysis showed two typical phases that were identified earlier when only the coating was investigated. The phase connected to the adhesive is probably AIFe with the stoichiometry AI 46,1; Fe 46,3 and Si 7,6 (at.%) and the second could be AI5Fe2 with contents AI 64,8; Fe 34,0 and Si 1,2 (at.%). As described earlier, in 3.1.4, the fracture is abrupt and when looking at both sides of the adhesive joint, Figure 76, it can be seen that the fracture propagates along the AI5Fe2 phase that used to be connected to the AIFe phase closest to the base material.



Figure 123 Fracture of adhesive joint where samples were held for 10 minutes at 950° C prior to applying adhesive.

6.2.3 Discussion

6.2.3.1Heat rate

In order to join USIBOR® 1500P AS150 or uncoated 22MnB5 within in the hot stamping production line brazing was chosen as a suitable approach, as it could be performed in the furnace heating of the production step, prior to stamping. The low oxygen containing atmosphere in the heating furnace would mimic the controlled atmosphere brazing used today to produce various aluminum and/or steel products. Typical for the hot stamping process is to not exceed a heat rate 12K/s [3] as this would damage the AISi coating of USIBOR® 1500P AS150. The setup used in this study with a tube furnace did not provide heating rates above 1,2° C/s 2.1 for furnace temperature 950° C. While a furnace temperature of 1000° C was also used for brazing of uncoated 22MnB5, this had no impact as it is the coating that governs the maximum heat-rate.

On the other hand the comparatively slow heat rate produced by the pipe furnace compared to an industrial roller hearth furnace used in hot stamping, means the substrates in this study receive prolonged heat treatments. In the one-step brazing setup the total time in the furnace was as much as 25 minutes and for two-step brazing it was 114 minutes when a 60 minutes braze time was adopted. When compared to industrial heat cycles where the steel is subjected to a furnace time of 7-13 minutes this means more diffusion of Fe from the substrate into the coating will occur with the setup used in the study. Further, close to or the same properties of the coating will most likely not be realizable as an effect of the slow heat rate. However, for the attempts where uncoated 22MnB5 were brazed using NiCr-based filler material a total furnace time as low as 9 minutes was accomplished.

6.2.3.2 One step brazing above 900°

Regarding the attempts of brazing using different fluxes and filler materials to join two sheets of USIBOR® 1500P AS150 directly at austenite temperatures, the results clearly show lack of potential with the material combination used in this study. The attempts using the flux which is made for aluminum brazing, Flux 190 PF, with both the AlSi12 filler (which has a composition close to the coating) and the NiCr amorphous filler, produced no good joints. The problem most likely being the active temperature range of the flux, 570-620° C, this result in the flux not being active during solidification. As such this flux is not suitable for brazing of aluminum at temperatures used in hot stamping as it results in joints with extremely limited wetting or no wetting at all.

The other flux tested, which is not specified for aluminum brazing (dealing with Al-oxide), but has a higher active temperature range produced joints, but with very poor performance. This flux Atmosin 181 PF is active between 550 and 900° C and the trial with AlSi12 was brazed at 900° C which resulted in joints with an avg. shear strength of 1,1 MPa. The trials with NiCr-based filler was done at 950° C, outside the active temperature range of the flux, simply since this was a temperature known to work well with the filler. This resulted in an average shear strength of 2,0 MPa. Both setups using Atmosin 181 PF flux showed limited wetting, which could be explained by the fact that the flux is not supposed to remove Al-oxide, but is recommended to be used for reparation of steel. Why the NiCr-filler performed better than AlSi12 is unclear but could be due to there being four surfaces of Al-oxide when Al-based filler is used (two at each interface between filler and substrates).

6.2.3.3 Brazing at or close to recommended temperature for AlSi12-filler

As joints with suitable strength and repeatability could not be realized when brazing directly at austenite temperatures, the temperature was lowered. This was done in line with what is typically used in Al-brazing and recommended by the filler and flux manufacturer, around 593° C. The best results were achieved when AlSi12 was used as filler together with Flux 190 PF as remover of the Al-oxide on USIBOR® 1500P AS150 substrates. This material combination showed that forming a joint between Al-coating and filler typically used for Aluminum brazing was possible. The joint however showed less strength than the coating itself as fracture occurred in the joint at an avg. of 7,2 MPa, which is probably due to the coating having good adherence and strength in hot dipped condition, prior to being subjected to Fe-diffusion during the austenitization of hot stamping. When the same setup was used on uncoated 22MnB5 instead of the coated substrates results were less promising, with an avg. shear strength of 2,7 MPa. The big difference between coated and uncoated is most likely due to the fact that the flux reacts well with Al-oxides and on the uncoated substrates other oxides form, causing insufficient wetting and lower strength as a result. If aluminum was used as a substrate instead of the boron alloyed steel it was believed that the typical strength of braze joints using the recommended Al-filler and Al-flux
could be investigated. The availability of AA5754 aluminum made it serve as substrates; this however required a lower furnace temperature of 586° C since AA5754 has a melting temperature of 600° C. The lower brazing temperature caused insufficient melting of the filler material which in turn resulted in poor adherence between filler and substrate. In this case fracture occurred in the interface between braze material and substrate. The joint stayed intact but separated from one of the substrates (delaminated) at an avg. shear stress of 2,7 MPa and thus no ultimate strength for the filler could be acquired.

However as joints could be made on the USIBOR® 1500P AS150 substrates the next step was to have them survive the austenite temperature of > 900° C in order to be able to implement the joining method in the hot stamping process.

6.2.3.4 Two step brazing

By brazing at recommended temperature on USIBOR® 1500P AS150 substrates with AlSi12-filler and aluminum flux in a first step, then having the samples go through an austenitization process it was believed joints could be realized compared to brazing directly at austenite temperature. Brazing done at 593° C for 10 minutes gave poor results after being subjected to the second heat cycle. An avg. shear strength of 1,4 MPa was achieved where one out of three samples broke prior to testing when removed from the fixture. This was a big step down from 7,2 MPa prior to austenitization. The reason for the joint breaking prior to testing is believed to be caused by the high temperature of the sample when removed from the furnace, as the filler has a liquidus temperature of 585° C. When the weight placed on top the joint is removed the area is still red hot, thus it is believed that when removed from the fixture the joint may not be in a solid state causing fracture and instant oxidation of the surfaces, see Figure 124. However this was not proven by letting the joint cool down in a protective atmosphere. Brazing hold times were increased to investigate if longer braze times could improve the performance of joints by an increase of Fe-diffusion into the joint prior to austenitization, much like the AlSi-coating survives the high temperatures of the hot stamping process by continued Fe-diffusion from substrate into coating. The braze time at 593° C was increased to 60 minutes, which provided a joint which did not break when removed from the fixture and had a shear strength of 5,0 MPa. This indicated that a longer braze time could be a solution, but as 60 minutes being too long for the hot stamping process another set of trials where the braze time was varied for 15. 25 and 35 minutes provided some interesting results. The best results were achieved with a braze time of 35 minutes and provided an avg. shear strength of 5,40 MPa with adequate variance, whereas both 15 and 25 minutes still had one sample suffer from joint breakage when removed from the fixture and the shear strength was on avg. 2,13 and 3,82 MPa. Inspection of the fracture surface showed that the joints failed somewhere in the interface created between braze filler and coating of the substrate, see Figure 125, probably in the coating. A major drawback, also visible in Figure 78, with the usage of the flux is that the area around the joint corrodes after austenitization. This removes any corrosion resistance provided by the AISi coating, but is however not as apparent after brazing 593° C which has yet to be explained.



Figure 124 Joint fracture when removed from fixture.



Figure 125 Fracture surface of sample brazed for 35 minutes at 593° C then austenized.

Analysis using LOM showed a big difference in joint thickness (distance from substrate to substrate) between the two step braze joints between USIBOR® 1500P AS150 substrates and those brazed between uncoated 22MnB5. The former having a thickness, after austenitization, varying between 205 and 279 µm and the latter between 42 and 69 µm. Regardless of the two fillers being different alloys this is one reason for the joints on coated boron alloyed steel having less strength. The increased distance between substrates increases the lever-arm for shear force during tensile testing, and is likely due to the thickness of brazing foil, were AISi12 is 0,4 mm thick and Vitrobraze 2170 is 0,05 mm. In addition to the brazing foil thickness the coating thickness which forms part of the joint is on avg. 25 µm thick on each side of the joint.

Comparing cross sections of the three different braze times (15, 25 and 35 minutes at 593° C) a growth of the interface (coating and filler) between substrate and filler material can be seen with longer braze times, which could indicate an increase of diffusion. Prior to austenitization the joints brazed for 15 minutes showed less cracks and pores compared to those brazed for longer periods and should be the best performing. However after austenitization the opposite was visible, while all samples contained cracks and pores, the longest braze time of 35 minutes at 593° C proved to form the most joints in between the cracks. This could be due to increased diffusion as a result of the longer hold time as the cracks most likely occur due to thermal expansion mismatch during cool down, were the increased diffusion reduced the mismatch. A way of reducing the effect of the thermal expansion mismatch would be to reduce the joint thickness which would have required a thinner brazing foil. From SEM analysis it is clear that during the austenitization process the joint is subjected to excessive Fediffusion from the substrate. Where there once was an Al-matrix in the middle of the joint, see Figure 126 (prior to austenitization), there is now various compositions of AIFeSi with stoichiometry close to AI8Fe2Si. This structure is typically found in the coating of USIBOR® 1500P AS150 in the hot dipped condition prior to heat treatment close to the substrate but is now found in the middle of the joint, probably due to the diffusion-distance from the substrate to the middle of the joint. Also typically found in the coating after austenitization is AI5Fe2 which was also found in the joint. This can contain Al2Fe3Si3 precipitates due to low Si-solubility in Al5Fe2. As such the joint formed with AISi12 filler brazed at 593° C for 35 minutes then heated through 926-940° C for 4minutes, see Figure 127 contains phases that have been previously found when only studying the coating of USIBOR® 1500P AS150 by M. Windmann et al. [16] for various hold times at 920° C.



joint prior to austenitization.

Figure 126 SEM image of 35 minutes at 593° C braze Figure 127 SEM image of 35 minutes at 593° C braze joint after austenitization through 926-940° C for 4 minutes.

6.2.3.5 Fracture analysis

For some of the heat treated substrates (10 minutes at 950° C, adhesive joints were prepared to investigate coating adherence. The joint prepared with adhesive after substrates had been subjected to the heat cycle of 10 minutes at 950° C can be compared with the best performing braze joints from the two-step braze setup as it is believed limited Fe-diffusion occurs at 593° C.

Between the two joints there is a large difference in avg. shear strength with the adhesive joint at 17,7 MPa and the Al-braze joint at 5,4 MPa. This could have a variety of explanations such as differences in joint thickness or composition and location of intermetallic phases. However, after investigating fracture cross sections of the samples one common denominator was found, namely the Al5Fe2 phase which the fracture propagates along as shown in Figure 128 and Figure 129. In the case of the adhesive joint this can be explained by the fact that it is the harder and more brittle of the two phases present: Hardness; Al5Fe2: 1133 \pm 83, AlFe: 521 \pm 30 (HV0,03) [16]. Comparing the hardness of the two phases present in the brazed joint the difference is less: Hardness; Al5Fe2: 1133 \pm 83, Al8Fe2Si: 873 \pm 105 (HV0,03) [16], however as the fracture line is close to the steel substrate the shear force will be greater in this region.



Figure 128 Fracture line of adhesive joint.

Figure 129 Fracture line of Al-brazed joint.

As such, the fracture in the adhesive joint occurred between the Al5Fe2 and AlFe phase closer to the steel substrate whereas in the braze joint it is closer to the substrate next to the α -Fe region. The fracture propagating along the Al5Fe2 phase is also in good agreement from work done by M. Windmann et al. where investigation concerning laser beam brazing of AlSi-coated 22MnB5 steel was made [38].

The difference in shear strength can be due to the difference in strength between phases, mainly the difference in strength between Al5Fe2 and AlFe compared to the strength between Al5Fe2 and the unidentified phase Al 35,6; Fe 45,7 and Si 18,7 (at.%) which has not been investigated. However, it could also be the amount of Al5Fe2 present where it in the case of the adhesive joint is 4 μ m thick compared to 35 μ m for the brazed joint, combined with greater joint thickness of the braze joint increasing shear load. The amount of cracks and pores throughout the braze joint should have little to no effect as the fracture occurred away from them. The fracture surface of the adhesive joints also indicates that both phases may not be present throughout the entire coating, which means that at some areas there may be a lack of the thinner Al5Fe2 phase and the cracks thus continues through the AlFe phase instead, see Figure 130.



Figure 130 Fracture surface of adhesive joint, showing variation within the coating which could be different phases.

6.2.3.6 Coating

The fear concerning heat rate for the tube furnace used was justified when comparing composition of the coatings as a result of different heat cycles used in this study to that of conventional press hardening in the industry. Comparing the EDS results from SEM it shows that the two coatings produced from one-step and two-step heat cycles are similar in composition. However, they are at the same time vastly different from a coating produced from conventional press hardening. Both the coating from 10 minutes at 950° C and the coating from 35 minutes at 593° C then heated through 926-940° C for 4 minutes show a middle layer of Al5Fe2 which according to the stoichiometry also could have been Al2Fe but according to M. Windmann et al. [16] the formation of Al2Fe is counteracted by the high Si-content of the coating. This middle layer is surrounded by the more Fe-rich AlFe phase; see Figure 131 and Figure 132. On the other hand the coating produced from a conventional press hardening procedure show the opposite, a middle layer of Al5Fe2, see Figure 133. An explanation to this is that the Fe-diffusion from substrate into the coating continues and is proportional to the time at high temperatures.

The more Fe that diffuses into the coating, the more formation of the phase AIFe, which also is in good agreement with a study by M. Windmann et al. where coating composition as a result of time at 920° C have been studied [16]. Therefore the heat cycles used in this study should show more AIFe than AI5Fe2. This can also explain the difference in AI5Fe2 layer thickness between the one step heat cycle with 10 minutes at 950° C and the two-step with 35 minutes at 593° C then a faster heating through 926-940° C for 4 minutes. In the former heat cycle the AI5Fe2 layer is around 4 μ m thick whereas in the two-step method it is almost 10 μ m which is due to the faster rate of diffusion at high temperatures, one-step: 14 minutes above 920° C; two-step: 4 minutes above 920° C.





Figure 131 Coating from 10 minutes at 950° C.

Figure 132 Coating from 35 minutes at 593° C then austenitization.



Figure 133 Coating from conventional press hardening.

The interface between coating and substrate where Al-diffusion has created Al-rich α-Fe is a lot deeper in the coatings from this study compared to the conventionally press hardened coating, and the total diffusion depth from top of coating down to substrate is; one-step: 45, two-step: 42, conventionally press hardened: 30 (µm). This is also matches well with the work by M. Windmann et al. [16] and is connected to the time at a high temperature. Tensile adhesion tests were also conducted to see if there was any variety in the strength (adherence) of the coatings produced. The worst performing was the coatings from two-step heat cycle where samples heat treated for 15 and 25 minutes at the lower temperature fractured at avg. around 5 MPa, and the 35 minutes at an avg. 2 MPa. The coating from one-step heat cycle at 950° C performed better but fractured at 18,4 MPa. This indicated that what was discussed earlier, regarding the amount of AI5Fe2 in the fracture of joints might have an impact on the strength. But from an earlier project it is known that the conventionally press hardened coating does not fracture until stress levels of up to 40 MPa have been reached, and it contains more AI5Fe2. As an attempt to see if the press hardening would have an impact on coating strength, samples were heat treated, both by the oneand two-step brazing cycle then quenched between copper blocks. This gave contradictory results where the coating strength of two-step heat cycles improved while it for one-step regressed and as such no conclusion regarding the quenched samples could be drawn. However heat treatments used in this study provided coating with far less performance than that of conventionally press hardened USIBOR® 1500P AS150, with the two step heat-cycle being the worst performing.

6.2.4 Conclusions

In this study an investigation was carried out concerning the ability to braze AlSi-coated and uncoated 22MnB5 steel in a controlled atmosphere furnace. Performance was evaluated in shear strength using tensile testing with lap joints and adhesion pull-off testing. Chemical composition of phases appearing the joint and surface coating was identified using SEM with EDS-analysis and compared with literature. The following conclusions can be drawn:

- Braze joints could not be made between USIBOR® 1500P AS150 substrates using AI- or NiCrbased filler material in combination with flux for AI-brazing or steel reparation if a one-step brazing approach at austenite temperature is adopted.
- Joints with a shear strength 5,4 MPa, c was obtained with a two-step brazing approach using Alfiller and Al-brazing flux. This requires; first: brazing at recommended temperature, 593° C, for 35
- minutes; second: heating up to austenite temperature (926-940° C) and held for 4 minutes.
 The coating of USIBOR® 1500P AS150 substrates resulting from the one step and two step heat cycles show different structure compared to conventionally press hardened USIBOR® 1500P AS150. Coatings resulting from brazing heat treatments consist of more AIFe than AI5Fe2 While the opposite is true for conventional coatings. This is connected to the amount of Fe-diffusion from substrate into the coating which depends on time at elevated temperature. Concluding that heat cycles used are longer than those used in hot stamping.
- The fracture occurred along the AI5Fe2 phase inside the coating for both braze and adhesive joints between USIBOR® 1500P AS150 sheets
 - The strength of the coating was evaluated using tensile adhesion test. This showed that the two step heat cycle resulted in the poorest coating strength at avg. 5,44 MPa while the one step heat cycle had strength of avg. 15,4 MPa. Both far from conventionally press hardened coating that has shown strength above 40 MPa.
 - The total time in furnace could be reduced by 16 minutes giving a total furnace time of 9 minutes for brazing of uncoated 22MnB5 while sustaining the same shear strength. This was done by using a higher furnace temperature (1000° C) and a constantly increasing temperature of the samples during brazing.

6.2.5 Part III - Brazing zinc-coated sheet steel to zinc-coated sheet steel

Brazing experiments were performed in inert atmosphere at temperature from 890 °C up to 950 °C, and the holding time was 10 minutes. One test was performed for each temperature. Brazing at 890 °C was not enough to melt the brazing foil, but a weak bond was achieved at 896 °C. Increased temperature increased the shear strength up to a brazing temperature of ~925 °C, while brazing at 950 °C resulted in a reduced shear strength compared to braze at ~925 °C, see Figure 89. The shear strength at a brazing temperature of ~925 °C was 38 MPa.



Figure 134. Brazing of zinc-coated Usibor with NiCr21amorphous brazing foil.

6.2.5.1 Discussion

Brazing of zinc-coated Usibor with NiCr21amorphous brazing foil in inert atmosphere seems possible. The shear strength at a brazing temperature of ~925 °C was 38 MPa. However, the austenitization temperature for zinc-coated boron steel used today is 890 °C, and therefore further work is needed to verify if it is possible to go up to 925 °C.

6.2.5.2 Conclusions

Based on the performed experiments it is possible to braze zinc-coated Usibor with NiCr21amorphous brazing foil in inert atmosphere. The shear strength at a brazing temperature of ~925 °C was 38 MPa.

6.3 Press hardening

6.3.1 Hot forge sintering

6.3.1.1 Results and Conclusion

- Seems possible to get the grains to stick to each other in a common press hardening process without any binder.
- Larger grains could be tested to reduce the density of the core.
- Difficult to handle blanks filled with loose powder inside.
- More tests needed to get more knowledge about the influence of time/temp/pressure.

At the moment there is probably no practical use since it will be hard to keep the powder in the correct position when the blank travels through the furnace and on the transfer into the presshardening tool.

6.3.2 Test #1 with sintered core without brazing foil

6.3.2.1 Results and Conclusion



Figure 135 Part taken apart.



Figure 136 Cracks can be seen on the sintered core.

The sintered core is surprising ductile @940°C.

6.3.3 Test #2 with sintered core with brazing foil

6.3.3.1 Results and Conclusion

As can be seen on the pictures below the brazing foil has melted and filled out the cavities. It seem that the strength of the joint is depending on both the brazing material and strength inside the sintered core between the grains.



Figure 137 Cut out

Figure 138 Cut out

6.3.4 Test #3 outer sheets with brazing foil without core

6.3.4.1 Results and Conclusion

A shear strength of 15-20MPa could be seen which is about equal to what could be expected for common adhesives used in the automotive industry.

6.3.5 Test #4 Samples for 3-point bending



6.3.5.1 Results and Conclusion

Figure 139.3-point bending results.



Figure140. 3-point bending Test01 after test.



Figure 331.3-point bending Test09 after test.

- Brazing foil MBF62 works well with the presshardening process.
- The sintered material is either too brittle for the brazing to stick or the mating surface is to small due to the 40% porosity material tested.
- Sintered core is currently (40% porosity) to brittle for mechanical testing (Sintered core specification: grain size 75µm, Fe and 0.3% C, 40% density of solid steel, heat treated 30min@1150°C).

6.3.6 Different sintered cores Part 1

6.3.6.1 Results and Conclusion

As can be seen on the results below, the stainless steel austenitic works best.



Figure 142 Test resultat



Figure 143. FeSi



Figure 144. .FeP



Figure 145 Stainless steel austenitic



Figure 146 Stainless steel ferritic

6.3.7 Test #5 Different sintered cores Part 2.

6.3.7.1 Results and Conclusion.



Figure 147 Hat profiles after compression test.



Figure 148 Test results. Not same length on the hat profiles as in test #5.

Sample	Crack on core*	Delamination	Crack on outer sheets
А	No	Yes	No
В	No	Yes	Yes
С	No	Yes	Yes
D	No	Yes	Yes
E	Yes	Yes	No
F	Yes	Yes	No
G	No	Yes	No
н	Yes	Yes	Yes
1	No	Yes	No

* Not connected to outer sheet crack

Figure 149 Evaluation of cracks after compression test.

Delamination is found within the sintered core and between the brazing and the sintered core. Where the outer sheets has been cracked probably is a caused by grain growth due to long time at high temperature in the sintering process.

6.3.8 Test of brazing foil strength

6.3.8.1 Results and Conclusion.

As can be seen below the brazing foil Vitrobraze VZ2170 is not strong enough to hold the press hardened sheets together. The stiffness seems to be OK up to about 1mm intrusion, after that the delamination appears.



Figure 150 Hat profile test.

6.3.9 Additional hat profile test.





Figure 151 Hat profile test.

6.4 FE simulation

6.4.1 Experiments and Results

In previous sections experiments were been carried out on hat-profiles made of solid steel sheets and laminates with cores of sintered steel powder. From these experiments it was found that the core of the laminate, consisting of sintered steel powder, exhibits brittle behavior/failure, reducing its ability to absorb energy during crash loading. Thus, the material was deemed unsuitable to be used in laminate configurations for crash applications. Despite the sintered powder displaying brittle behavior, an attempt to characterize the material and to calibrate the material model was made. The intention was to recreate the input curves for the material model, presented in Figure 70 and Figure 71. Due to the complexity of loading specimens in hydrostatic pressure, only uniaxial loading (compression) is applied.

The sintered material, based on FeSi with a relative density of approximately 0.5, is produced in thin layers, with a maximum thickness of 1.6 millimeters. This made it necessary to stack layers of the material on top of each other to create a specimen with a height approximately equal to its side lengths. Squares with a side length of 12.5 mm was chosen, see Figure 152, since tools with such dimensions were available in the workshop at LTU. A specimen was also created using stamped circles. However, this geometry was only used once since DSP, Digital Speckle Photography, was to be used, and the plane surface of the cubic specimens was preferred. In total, seven specimens were loaded until failure: 6 squares and 1 cylinder. The thickness of each sheet varied between 0.50 and 0.60 millimeters. The number of layers were chosen so the height would be approximately equal to the side length, thus forming cubes.

In the first run the cylindrical specimen was loaded, due to its face being curved, which must be taken into consideration when considering the strain-fields obtained from the DSP, this geometry was only used once. The second run was on a cubic specimen, and a Teflon spray was applied on its top and bottom to reduce friction between tools and specimen, which would reduce barrel effects. However, when studying the film from the experiment it seemed to have little impact. Furthermore, the spray seemed to be absorbed by the material, and was abandoned in favor of a paste. The paste was easier to apply, and seemed to do a better job of reducing the friction. This paste was used for the remaining tests.

A total of five runs were performed with the paste on the top and bottom of the experiment to reduce friction. The third and fourth run were performed, and generate similar force-displacement response. Only at the stage of failure did the response differ, see Figure 153 and Figure 154, where a constant tangent can be seen until failure. To investigate whether this tangent is associated with elasticity or not, a fifth specimen was prepared. On the fifth run the specimen was loaded until 6 kN, see Figure 153 and Figure 155, and then unloaded and loaded again until failure. Initially, the response was equal to that of run 3 and 4, when the strain reached a value of 0.075 it started to deviate away from run 3 and 4. Furthermore, the failure load was lower than run 3 and 4. To further investigate the influence of unloading on the specimen, the number of loading cycles were increased. Unloading was set to occur with an interval of 1 kN. For the sixth run, an error had been made so that the first load cycles were not saved. The test was rerun with a seventh specimen, this can be seen in Figure 153 and Figure 155. When studying the images from the camera used for the DSP, it could be seen that cracks, on the surface, appeared before the peak load. This is presented in Figure 156, Figure 157, and Figure 158, where it can be seen that despite presence of cracks, the tangent of the load curves remains constant up to a value of 2.80 mm on the horizontal axis, similar behavior was observed for all the tests with DSP. At a given displacement the cracks have grown in size, and large parts of the specimen starts to fall off.

From the DSP it was evident that the specimen did not behave as a homogenous body, see Figure 159 - Figure 161. Furthermore, it was noted that the stacking of layers was problematic, since the gaps between the layers were perceived as areas with great deformation. An effort was made to remove the gaps, through filtering, and only measure on the layers, this can be seen in Figure 162 - Figure 165. From the filtered data it is seen that the strain is not homogenously distributed throughout the entire body. Certain layers are subjected to greater levels of strain, which will cause these layers to fail early during the loading procedure.

Considering the random distribution of the specimen, the force response is quite similar for all runs, with only the response from the fifth run being a bit lower. Even when subjecting the specimen to a number of load cycles, the agreement between the specimens is quite good. It appears that approximately two tangents can be identified

from the experiments: 1) a plastic tangent which is present from stage one of the experiment until failure/unloading, and 2) an elastic tangent, which is present during unloading, and during loading up until the current maximum strain of the specimen, after which the plastic tangent is again present. In Figure 155 Engineering stress/strain has been calculated. A trend line has been added for one of the unloading paths, from which the tangent modulus during unloading is found to be approximately 10.6 GPa. Since uniaxial compression is assumed, the tangent modulus during unloading should correspond to Young's module for the porous material. In the literature expressions for calculating Young's module for porous material as a function of the solid material's properties can be obtained. Such an expression can be found in [L4]:

$$E^* = E_s \left(\frac{\rho^*}{\rho_s}\right)^2 \qquad \qquad Eq \ 9$$

Quantities with a star (*) are associated with the porous material, whereas quantities with a subscripted "s" are related to the solid material's properties. Using Eq 1 a Young's module of 52.5 GPa is obtained, approximately 5 times greater than that observed in Figure 155. This might be due to the fact that the expression given is suited for foams with relative densities lower than 0.5. Furthermore, due to the distribution of the powder a homogenous specimen is not obtained, it is also possible that the stacking of the layers may contribute to this. If the DSP measurements of Figure 159 and Figure 162 are studied, it is found that localization of strains occur, they are not evenly distributed throughout the specimen, as would be expected for a homogenous body. Due to the localization of strains, certain layers will fail quite early during loading. This may also affect the assumption of uniaxial compression, as a more complex loading condition may arise.

From the experiments performed, on the sintered powder, it was found that the initial response of the test specimen exhibited nonlinear behavior. This nonlinearity is illustrated in Figure 153, which arose during the initial loading, for displacement lower than 0.5 mm, of the test specimens. During this state, up to a displacement of 0.5, three tangents of the curve are observed: 1) the initial onset of the load up to approximately 0.12 mm where the tangent is increasing, 2) between 0.12 mm and 0.5 mm with a constant tangent, and 3) at 0.5 mm and beyond where the tangent is lower than at stage 2), and remains constant until failure or unloading. The change of tangent may depend on friction between the layers, and that the layers settle during loading. This may also explain the reason why plastic deformation occurs as early as at the first unloading of the specimen, seen in Figure 153.

If the initial nonlinearity is assumed to arise due to friction and settling of the layers, an idealized response curve be obtained, see Figure 154, which better agrees with the general behavior of porous material. The initial behavior is elastic, followed by a plastic response, during which the pores collapse, this would be followed by a rise of the load as the pores disappear (densification) and the behavior of the material converges to that of the solid material. Due to the brittle behavior of the test specimens, it is not possible to observe the last stage of densification.

The DSP showed that cracks are visible before the peak force is reached. The selected material model is not suited to capture the behavior of such a material. The input curves are generated from the assumption of linear elasticity until a plateau is reached where the pores sizes approach zero, at which time an ideal-plastic behavior is assumed, until almost full densification where the load starts rising again, and the porous material should approach the solid material. Thus, the calibration of the material model was not done, since the assumptions on which it is based, as well as the input curves in Figure 70 and Figure 71, are fundamentally different than the behavior of the sintered powder.

Future work will involve the implementation of linear hardening of the material model, in an attempt to capture the response of the test specimens up until failure. Tests will also be performed on single layered specimens, to investigate whether or not it is possible to reduce the initial nonlinear behavior of the material.



Figure 152 Squares stamped to make up the test specimen.



Figure 153 Load as a function of displacement for 4 of the cube specimens.



Figure 154 Load as a function of displacement for the 7th specimen. The initial nonlinearities are removed to form an idealized response curve.



Figure 155, Engineering stress vs Engineering Strain for cubic samples, a trend line has been added along one of the unloading paths. From the equation of the trend line, the tangent modulus during unloading is found.



Figure 156 Illustrating the early state of compression for third run, the red line corresponds to the position on the load curve.



Figure 157. Cracks are visible at the bottom left are of the specimen for the third run. The red line illustrates where on the load curve the state is located.



Figure 158 Cracks have increased in size for the third run, and the maximum load has almost been reached. The specimen starts to crumble, big parts are falling off.



Figure 159. Second run, von Mises strain at the beginning of compression.



Figure 160. Second run, von Mises strain at stage 80/151.



Figure 161. Second run, von Mises strain at stage 105/151.



Figure 162. Filtered data for the second run, showing von Mises strain at stage 20/151.



Figure 163. Filtered data for the second run, showing von Mises strain at stage 80/151.



Figure 164. Filtered data for the second run, showing von Mises strain at stage 105/151



Figure 165. Filtered data for the second run, showing von Mises strain at stage 151/151.

6.4.2 Validation and Results

Initially, validation of the numerical models are performed for hat-profiles with solid steel through the thickness. Data from simulations are compared to experiments conducted by Gestamp Hardtech. Three numerical models are compared with experimental data, the models consist of:

- Shell elements
- Solid elements
- Shell elements (face plates) and Solid elements (core)

The comparison is conducted to investigate any differences in response between the two types of elements. The geometry was supplied by Gestamp Hardtech, presented in Figure 156, where the flanges have been cut, as compared to Figure 74, to reduce nodes needed to be constrained. The thickness of the hat-profile in consideration is 1.5 mm. Under integrated elements have been utilized in the three different models, since hour glassing was less than 10 % of internal energy, as recommended by LS-DYNA. In the experimental setup the hat-profile was loaded with a velocity of 2 mm/s, and a simulation was run with the same velocity resulting in a simulation time of approximately 3.5 hours. The simulation was run with both under integrated and over integrated elements. To reduce simulation time, the velocity of the barrier was ramped up, and similar results was found as for the case with a velocity of 2 mm/s. This is illustrated in Figure 157 where force versus intrusion is presented for the simulations with a mesh consisting of shell elements. Data obtained from experiments is also included. Quite good agreement is achieved between experiments and simulations. Furthermore, in Figure 158 results obtained for a model with solids representing the hat-profile is presented and compared with experimental data. The response of the solid is a bit stiffer than the response of the shell elements seen in Figure 157. In Figure 159 the laminate setup, with solid elements in the core and shell elements for faceplates, is compared to the experimental data, as for the solid elements, a stiffer response is obtained for the peak force.

In general, the obtained results from the simulations corresponded well with the experimental data, with respect to behavior as well as the value of the force. A comparison was also performed to investigate differences in response with respect to mesh size and layers of elements. The obtained result is presented in Figure 158 and Figure 159 where it was noted that the response did not change much when refining the mesh from 2 mm with 3 layers to 1 mm with 5 layers. It is thus concluded that a mesh size with 2 mm and three layers of solid elements through the thickness gives reasonable results which correspond well reasonably well with experimental data.



Figure 156 Modified hat-profile



Figure 157 Force response from numerical simulations compared to experimental data. Shells are utilized to represent the hat-profile.



Figure 158 Force response from numerical simulations compared to experimental data. Solids are utilized to represent the hat-profile.



Figure 159 Comparing all meshing approaches with experimental data.

6.4.3 Conclusions and Discussion

It was found that convergence is achieved for a mesh size of 1 millimeters. However, to increase resolution in the core of the laminate a mesh size of 0.5 millimeters was adopted. An analysis was performed to find the influence of the amount of layers used for the solid elements in the core. The simulations show equal response for 4 and 5 layers. Due to this, 4 layers are used since to difference in behavior was found. This also reduces simulation time. The methodology adopted for simulating laminates seem to be acceptable. In Figure 15, similar response for a hat-profile consisting of shells, as compared to one using solid elements to represent the core, is obtained. However, further work will be applied through investigating the impact on the response by the amount of Gauss points through the thickness. At the moment, equal amounts of Gauss points through the thickness is not used, perhaps this generate a stiffer response for the solids. Further work is required to model debonding, between core and face plates, in a satisfactory manner. At the moment shared nodes have been adopted, and so that no debonding occurs.

Moving from a controlled displacement to ramping up the velocity of the barrier reduces dynamic effects and makes it possible to use an even coarser mesh than 1 mm for solids and laminates, while still obtaining quite good results when compared to experiments. This can be seen in Figure 32 - Figure 34. Thus, the models are quite accurate as well as computationally efficient.

To further predict the behavior of the hat-profile with a porous core, and also the interface between core and face plates, further work is required. Experiments on the porous core material are required so that the material model, describing the porous media, can be calibrated. Furthermore, experimental data for the bonding between core and face plates is required.

As already mentioned, no experiments have been conducted for the porous core material. Therefore the constitutive model, representing the porous core, is not calibrated. Thus, no meaningful conclusions can be drawn considering weight saving or energy absorption for the laminate with a porous core. However, a theoretical yield function has been chosen, where the input data is derived from initial porosity and properties of the solid material. This yield surface is applied to generate part of the input curves for a porous medium, required for the chosen constitutive model. The missing parts, at high volumetric strain, is generated from the assumption of how such a material should behave at full densification. It was assumed that at high volumetric strain, the behavior and properties of the porous medium should converge towards the behavior of the solid material itself. These assumptions are deemed physically acceptable, and should not be too far off from the true behavior of the cellular material.

7 Distribution och publication

7.1 Knowledge and result distribution

Hur har/planeras projektresultatet att	Markera	Kommentar
användas och spridas?	med X	
Öka kunskapen inom området	Х	Ökad kunskap om kraven på kärna samt bindning mellan ytterplåtarna och kärnan
Föras vidare till andra avancerade	х	Kunskap förs vidare till andra laminatprojekt.
tekniska utvecklingsprojekt		
Föras vidare till		Teknik ej redo.
produktutvecklingsprojekt		
Introduceras på marknaden		Teknik ej redo.
Användas i utredningar/regelverk/		
tillståndsärenden/ politiska beslut		

7.2 Publications

Two master thesis has been made.

Modelling and analysis of steel laminate with a core based on porous steel material by Samuel Hammarberg Furnace Brazing of AlSi-coated and Uncoated 22MnB5 steel at austenite temperatures. by Adam Häggqvist

8 Conclusion and continued research

Using Ni-based brazing foil and sintered core is not strong enough to hold press hardened outer sheets together to get the full advantage of a sandwich structure to use in crash situations. However it works on parts with low deformation to increase the stiffness to weight ration.

The search will continue to find a stronger and more ductile core and stronger joining between the core and the outer sheets. If that is found a laminate sheet for press hardening will be interesting and would have its share on the market.

9 Participation partners and contacts

Gestamp Hardtech Höganäs Luleå Tekniska Universitet Luleå Tekniska Universitet Luleå Tekniska Universitet SWEREA KIMAB SWEREA KIMAB SWEREA KIMAB Lars Wikström Shawn Miller Samuel Hammarberg Mats Oldenburg Pär Jonsen Göran Lindkvist Tag Hammam Paul Janiak Joakim Hedegård Iwikstrom@se.gestamp.com shawn.miller@hoganas.com samuel.hammarberg@ltu.se mats.oldenburg@ltu.se par.jonsen@ltu.se goran.lindkvist@ltu.se tag.hammam@swerea.se paul.janiak@swerea.se joakim.hedegard@swerea.se

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