THERMAL BEHAVIOR OF POLYMER METAL HYBRIDS OF HOT STAMPED STEEL AND FIBER-REINFORCED THERMOPLASTICS

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Abstract

Hot stamping constitutes a manufacturing process for both high strength and lightweight automotive structural components and is used to produce some 40 % of today's structural components in car bodies. Lightweight approaches aim at weight reduction by reducing steel thickness and applying fiber-reinforced plastics (FRP) to regain structural stiffness and strength. Inherent thermal metal processing renders hot stamping an adequate process chain for the manufacturing of hybrid metal polymer composites. Thereby, residual heat in metal parts is used to enhance adhesion between polymer and metal. In fact, the temperature of the parts after hot stamping is in the range of the processing temperatures of several technical polymers, thus providing process conditions suitable for thermal direct joining or activation of adhesion promoters. The temperature specification of the realized metal polymer composites equal specifications for vehicle bodies in the temperature range from - 40 °C to + 80 °C.

In this paper, the thermal behavior of polymer metal hybrids of hot stamped steel and FRP in means of deflection is investigated. Also the influence of mechanical interlocked and adhesively bonded hybrid specimens are investigated. Therefore, hybrid specimens are manufactured under realistic industrial conditions, varying the manufacturing process parameters. The specimens are tested with respect to temperature load investigating thermal expansion using optical measuring techniques.

1. INTRODUCTION

Production volumes of passenger vehicles are expected to increase from 89 million units in 2015 to 113 million units in 2025 [1]. While the production volumes are increasing, a reduction of greenhouse gases emitted by combustion engines is in contrast to achieving targets of global climate conventions [2,3]. Lightweight design is an approach to reduce the mass of vehicles resulting in a decreased need of fuel and emitted greenhouse gases [4]. Reducing masses in vehicle structures offers the opportunity to enhance the effect of lightweight design by decreasing also additional components mass [1,5].

Typical vehicle structures are made of steel or aluminum alloys. Lightweight design in the area of steel is primarily aiming at a reduction of material thickness by using other new high strength steel alloys [6,7]. Hot stamped steels reach very high strengths and opportunity to reduce material thicknesses. Steel sheets are heated in a roll furnace to approximately 950 °C to transform the microstructure to austenite. The heated steel sheet is then rapidly transferred and hot stamped thus creating strengths between 1,500 MPa to 2,000 MPa, reaching similar behaving parts compared to non-hot stamped parts with reduced masses [8-11]. Another approach to reduce vehicle structure mass is the use of high performance FRP [12-14]. The use of a multimaterial design consisting of a metal- and a FRP-component can realize advanced lightweight body parts able to be processed in state of the art body shops realizing economically advantageous lightweight design for large-scale production [15].

Inherent thermal metal processing renders hot stamping an adequate process chain for the manufacturing of hybrid metal polymer composites. Thereby, residual heat in metal parts can be used to enhance adhesion [16] and mechanical interlocking [17] between polymer and metal. In fact, the temperature of the parts after hot stamping is in the range of the processing temperatures of several technical polymers, thus providing process conditions suitable for thermal direct joining or activation of adhesion promoters. The temperature specification of the realized metal polymer composites equal specifications for vehicle bodies in the temperature range from -40 °C to +80 °C [18].

In this paper, the thermal behavior of adhesively bonded and textured polymer metal hybrids of hot stamped steel and FRP are investigated. Therefore, hybrid specimens are manufactured under realistic industrial conditions, varying the manufacturing process parameters. The specimens are tested with respect to thermal expansion using optical measuring techniques.

2. EXPERIMENTAL SETUP

2.1 Realizing hot stamped plastic metal hybrids

Figure 1 shows the schematic experimental setup based on hot stamping industry applications. First, a boron-manganese steel blank is cut to specimen dimensions and eventually austenitized at a temperature of approximately 950 °C. After allowing a sufficient heating time of at least 10 minutes, the flat specimen is rapidly transferred into a press where it is hot stamped. After hot stamping in a flat die, the specimen is quenched and kept in its flat dimension, finishing the quenching process when the specimen’s surface temperature reaches 250 °C. The semi-finished part leaves the press at a temperature range which offers the potential to melt adhesion promoters and polymer surfaces, and to integrate an adhesive bonding process of thermoplastic FRP. In a final step, FRP adherends and metal adherends are joined to hybrid specimens using a hot press and eventually are tested with respect to thermal expansion using optical measuring techniques.

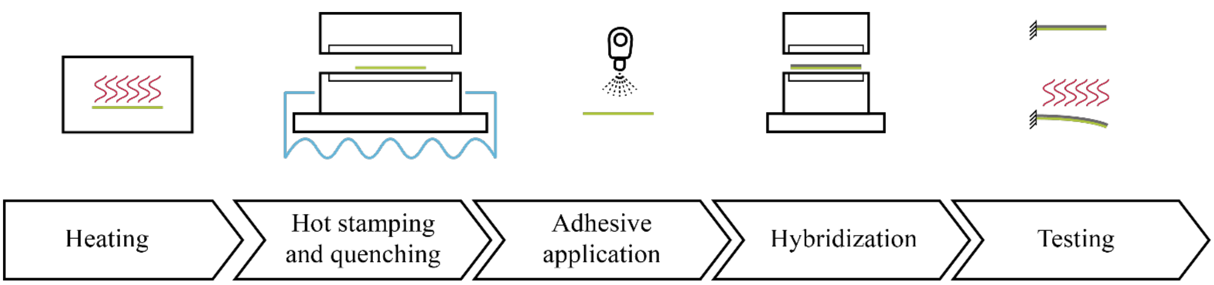


Figure 1: Experimental Setup

2.2 Hot stamping

Figure 2 shows a schematic of the temperature profile and condition of microstructure of a hot stamping process. In the as-delivered condition and at room temperature (RT) the boron-manganese steel specimen is showing ferrite and pearlite microstructure. After austenitization in a furnace at 950 °C, the temperature is kept to ensure fully austenitization of the specimen [2,19]. In a subsequent step the specimen is rapidly transferred into a flat press where it is kept in flat form and quenched until it reaches 250 °C [20]. After successful hot stamping the specimen microstructure developed a fully martensite microstructure.

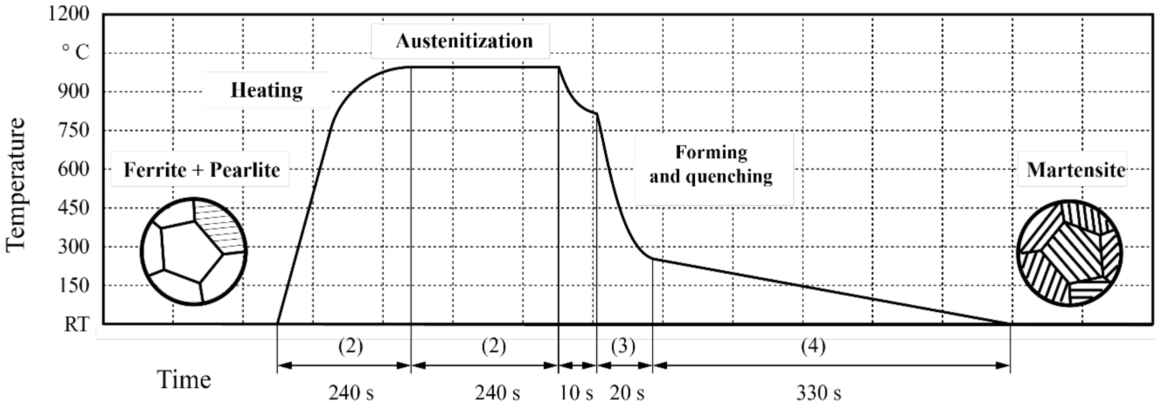


Figure 2: Hot Stamping

2.3 Materials and structures and combinations

To bond the metal component to the FRP adherend, an adhesion promoter in combination with a structured surface and type of steel´s microstructure are investigated. The adhesion promoter is a cross-linkable powder-based agent which is based on a reactive co-polyamide (Vestamelt X1333, Table 1).

Table 1: Adhesion promoter material properties [21]

				Temperatures	
Brand name	**Adhesive**	**Chemical base**	**Initial condition**	**Precoating**	**Activation**
Vestamelt®	X1333	reactive co-polyamid	powder	150 °C	> 165 °C

As FRP a consolidated composite laminate (CCL/organic sheet) consisting of multiple layers of continuous reinforcement glass fibers embedded in a polyamide 6 (PA 6) matrix is used. The metal component is a boron-manganese steel (22MnB5) with an aluminum-silicon coating (150 gm^{-2}). The tensile strength in as-received condition is 532 MPa. In Table 2, the material properties of the applied materials are shown.

Table 2: Adherend’s material properties

	FRP materials	Metal materials	
	CCL	22MnB5 (as-delivered)	22MnB5 (hot stamped)

Fiber	glass	-	-
Density [g·cm^{-3}]	1.8	7.9	7.9
Polymer	PA 6	-	-
Melt temperature [°C]	220	-	-
Glass Content [vol. %]	47	-	-
Thickness [mm]	2.5	1.5	1.5
Tensile Strength [MPa]	404	532	1518
Coefficient of thermal expansion 10^{-6} [1/K]	17.3	11.7	11.7
Young's Modulus [MPa]	22,400	210,000	210,000

The setup of adhesive and structures on metal specimens is shown in Figure 3. In total six combinations of adhesive and structure application are inspected. To investigate the influence of the steel´s microstructure specimens in as-delivered condition (ferrite + pearlite) and after hot stamping (martensite), quenched in water, are used. Flat specimens without structured surfaces are investigated with only adhesive application. Structured specimens are investigated, structured with 0.08 structures/ 1 mm² and a structure height of 1.0 mm, with and without application of additional adhesive.

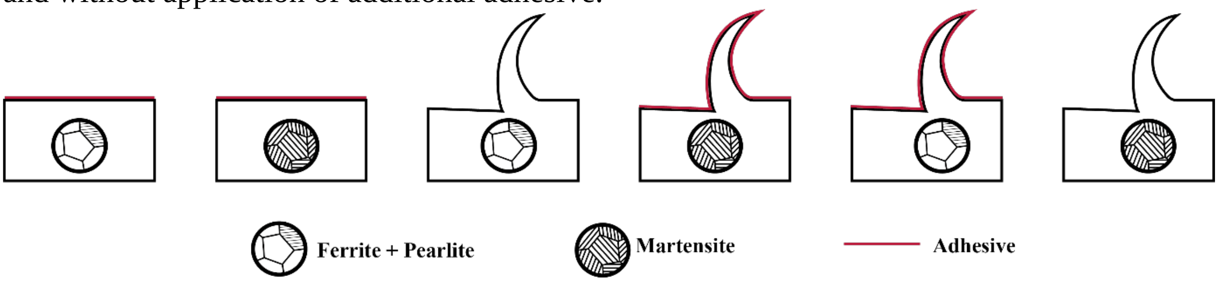


Figure 3: Combination of adhesive and structures on metal specimen

2.4 Hybridization

The metal and FRP adherends are joined using a hot press (Vogt LaboPress 400). Both adherends are heated up to 250 °C in the die of the hot press and joined with a press pressure of 3.0 MPa and a press duration of 20 s creating each five specimens per setup. After joining the specimen is cooled to 150 °C before being unmolded.

2.5 Thermal expansion

By using a theoretical approach, the thermal deflection is calculated for the hybrid beam structure. With the theoretical approach, an estimation of the expected deflection can be given. It is reliable for two homogenous materials with a stiff bond without a transition thickness. The equation for the thermal deflection can be written as follows [22]:

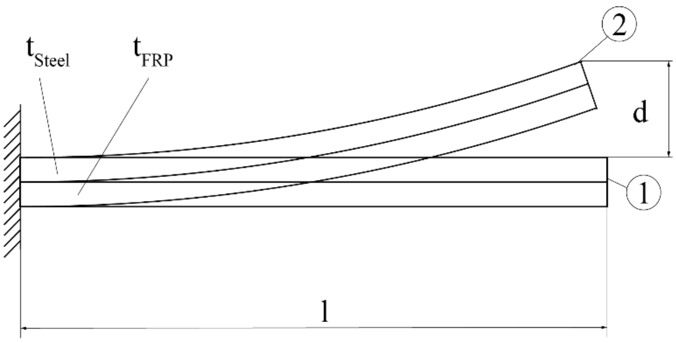
$$d = \frac{12 \cdot E_{Steel} E_{FRP} \cdot (\alpha_{FRP} - \alpha_{Steel}) \cdot \Delta T}{\frac{t_{Steel} + t_{FRP}}{2} \cdot (E_{Steel}^2 + 14 \cdot E_{Steel} E_{FRP} + E_{FRP}^2)} \cdot \frac{l^2}{2}$$

The result of the equation is the thermal deviation d. Moreover, E is the elastic modulus, α the thermal expansion coefficient, ΔT the temperature difference, l the specimen length and t the material thickness.

By inserting the value of table 2 the deflection d is calculated to:

$$d = 1{,}71\ mm$$

The calculated thermal deflection gives an orientation for the following experimental work and is validated by a homogenous hybrid structure without the structuring on the metal part.



Specifications

Temperature:	t_1 = 21 °C	t_2 = 80 °C
Length:	l = 180 mm	
Width:	w = 25 mm	
Thickness:	t_{Steel} = 1.2 mm	
	t_{FRP} = 2.0 mm	
Steel:	22MnB5 (Ferrite + Pearlite)	
	22MnB5 (Martensite)	
FRP:	Polyamide 6 47 (fibre vol.) %	

Figure 4: Homogenous hybrid structure without structuring under temperature load (2)

3. RESULTS AND DISCUSSION

To investigate the thermal behavior in means of deflection of the specimens, GOM ARAMIS®, an optical measuring technique is used. Each five specimens per setup are fixed in a furnace with room temperature (21 °C) showing a free length of 180 mm. In the next step the furnace is heated up to 80 °C simulating one of the highest assumed temperatures for automotive structure components. When the furnace reaches 80 °C the temperature is kept for 10 minutes to ensure fully heated specimens. In the lowest area of the specimen a virtual measuring point is set detecting total deflection of hybrid specimens. Figure 5 shows the specimens installed in the furnace at a temperature load of 80 °C. The value in the yellow boxes is indicating the maximum measured deflection at the determined point (yellow point).

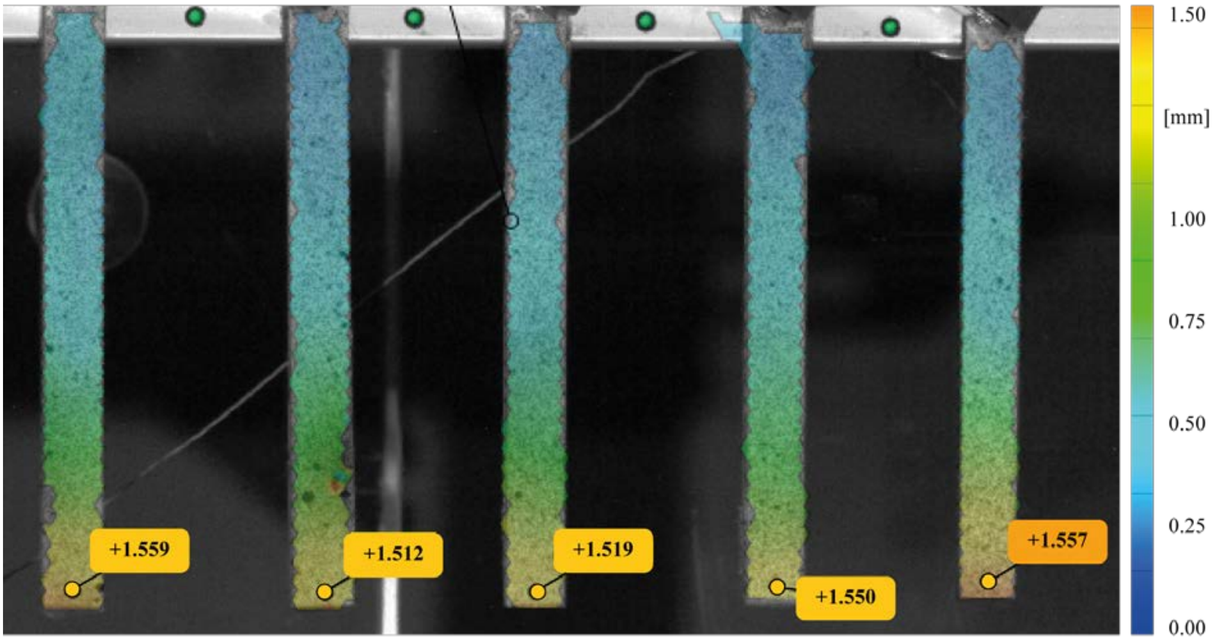


Figure 5: Specimens (no adhesive, structured) at temperature load (5 equal specimens, 80 °C)

The mean value of the maximum deflection in the lowest of each five specimens is determined and shown in figure 6. The maximum average deflection of 1.75 mm is occurring at adhesive-only bonded specimens. The lowest average deflection of 1.57 mm is shown at structured specimens without adhesive. The deflection of as-delivered steel specimens (ferrite and pearlite microstructure) and hot stamped steel (martensite microstructure) are in the range of the mean variation and are not showing an influence on deflection. Structured specimens with an applied layer of adhesive are showing a maximum deflection of 1.64 mm.

Comparing the results: Maximum deflection can be reduced by using structured metal components. The application of an additional adhesive smoothens the load transition between the two adherends but is resulting in a larger deflection. The larger resulting adhesive layer and FRP adherend are resulting in a larger total FRP component and larger deflection. The theoretical approach for a deflection determination is only suitable for the bonded materials. In case of inhomogeneous surface structure a numerical simulation of the deflection have to be performed.

Discussing the results: All structured specimens showing lower deflection at 80 °C compared to adhesive only bonded. This can be caused due to changed characterisicts of the boundary layer resulting of the clamped materials. The larger deflection of adhesive bonded specimens is caused by a larger total thicknesses of the specimens.

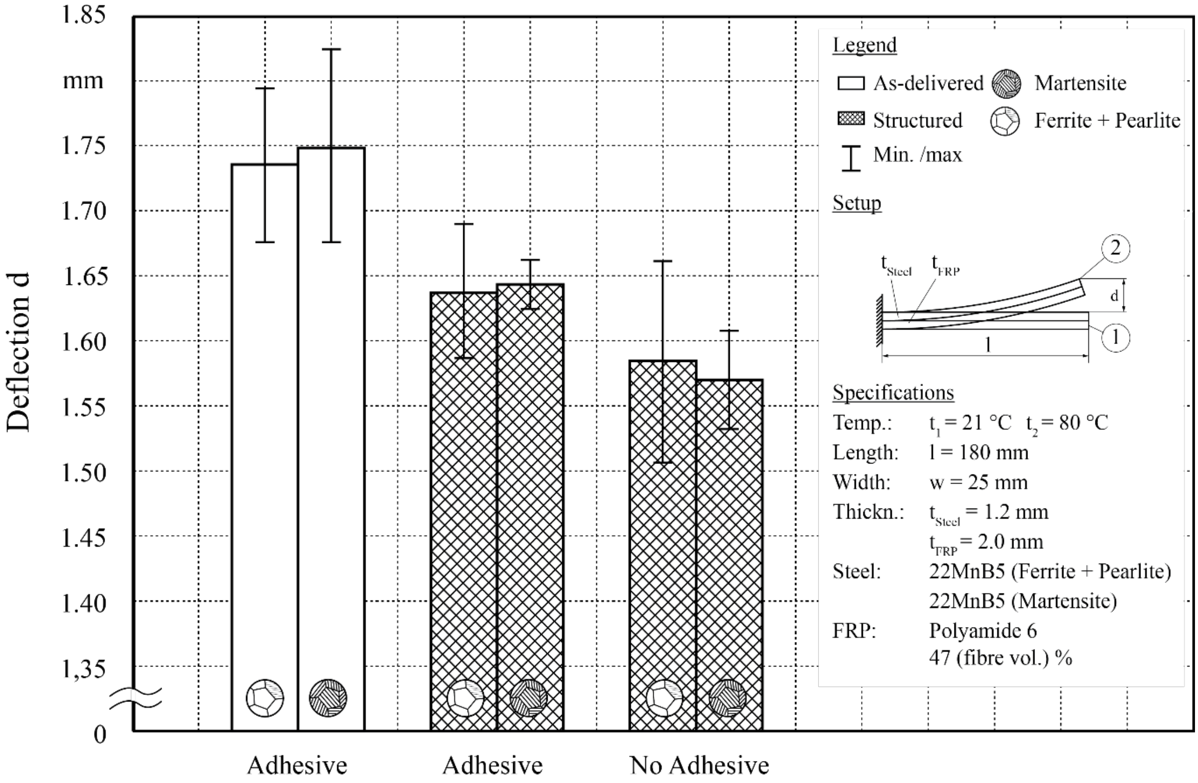


Figure 6: Deflection of specimens

4. SUMMARY AND OUTLOOK

The thermal behavior of hybrid components consisting of metal und FRP with different temperature expansion coefficient can be influenced by different joining methods. In this paper, the thermal behaviour in means of deflection of adhesive and structured bonded polymer metal hybrids of hot stamped steel and FRP was investigated by realizing flat hybrid specimens. With GOM ARAMIS optical measurement technology maximum deflection of free lowest area was detected and analyzed according to bonding mechanism.

Hybrid specimens with adhesive-only bonding are showing maximum deflection. A reduction of deflection can be achieved by structuring metal component and applying adhesive. A minimum deflection is realized by structured-only specimens. An influence on microstructure whether hot stamped or in as-delivered condition of boron-manganese steel is not observed.

In further investigations, the ageing influence after some temperature cycles will be investigated. The structure density can be improved in further studies by optimization of amount and geometry of structures to realize a smoother force transfer. Moreover, a numerical simulation of the deflection by respecting the surface structures for the hybrid design will be set up.

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