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Removal of oxides and brittle coating constituents at the surface of coated hot-forming 22MnB5 steel for a laser welding process with aluminum alloys

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ABSTRACT

The surface of a press-hardened steel 22MnB5 coated with Al-base (AlSi10Fe3) and Zn-base (ZnNi10) was conditioned by a pulse laser and by sandblasting to remove undesirable oxides and brittle phases. Oxides formed on coating surfaces counteract the wettability of welding filler during a welding or brazing process. Furthermore, welding and brazing joints of 22MnB5 coated with aluminum alloys failed along the brittle intermetallic phases in the coating under a low mechanical load. Treated 22MnB5 surfaces were analyzed microscopically, and the phase compositions were investigated by synchrotron diffraction measurements. It was found that brittle phases could be locally removed by laser ablation; however, high laser energies led to remelting and oxidation of the coating surface. In contrast, sandblasting homogenously removed oxides and brittle intermetallic phases. Surface-treated 22MnB5 steel sheets were joined to AA6016 aluminum sheets by laser welding, and the strength of the weldment was determined by tensile tests. The measured mechanical strength of the aluminum/steel joints was 210–230 MPa. Failure of the weldments under tensile loading occurred within the aluminum sheet, away from the steel surface/welding filler interface if brittle coating components and oxides were removed homogenously.

1. Introduction

High-strength steel 22MnB5 in the press-hardened condition is used in automotive bodies to comply with the safety requirements (high strength and stiffness) in safety-relevant structures. Aluminum materials can decrease the weight of cars in areas where lower mechanical properties can be tolerated. To utilize the advantages of both materials, suitable joining technologies are required in areas where both materials are used (e.g. underbody of the automotive bodywork). Most of the published investigations about thermal joining of steel/aluminum compounds focused on uncoated or galvanized mild steel sheets. For example, steel and aluminum sheets were joined by shock welding [1], friction welding [2], or laser welding [3]. Especially laser welding was found to be a suitable joining technology for different dissimilar welding operations [3–6]. However, less literature is available about thermal joining (welding/brazing) of coated, high-strength steel 22MnB5 to aluminum alloys. In the fusion welding process of steel and aluminum, generally only the aluminum alloy is melted due to its lower melting temperature. The steel surface remains solid and is wetted with the melted aluminum, which can thus be described as a welding (aluminum) — brazing (steel surface) process [7,8]. Thus, the achievable strength of coated 22MnB5/aluminum joints depends on the properties of the steel coating and the adhesion of liquid welding filler on the coated 22MnB5 surface.

Sheets of 22MnB5 steel are usually formed and hardened in a press-hardening process, in which a material strength of up to 1800 MPa can be achieved in complex formed body structures [9]. During press hardening, the steel sheets are austenitized at 880–950 °C and then transported into a tool where they are formed and quenched in one step [10]. To prevent strong oxidation of the steel sheets during austenitization, a protective Zn-, or Al-base coating is deposited on the steel surface prior to the press-hardening process [11]. During austenitization, distinctive diffusion processes occur at the interface between the steel substrate and the coating, leading to the formation of brittle intermetallic Al_xFe_y phases ($Al_{13}Fe_4$, Al_5Fe_2, Al_2Fe, AlFe) [12] or Zn_xFe_y phases (Fe_3Zn_{10}) [13] in the coating. In addition, Al-rich or Zn-rich oxides of type M_2O_3 and MO are formed on the coating surface [8]. In the Al-rich coating, the phase of type Al_5Fe_2 possesses the highest volume fraction in the press-hardened coating and exhibits a low fracture toughness of 1 MPa $m^{0.5}$ [14]. The formation of brittle intermetallic phases promotes crack initiation and propagation during forming in the press-hardening tools so that the coating microstructure possesses a network of cracks. The brittle Al coating counteracts the braze- and weldability of coated 22MnB5 owing to crack growth along the brittle intermetallic Al_xFe_y phases [15]. For this reason, brittle intermetallic

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Al_xFe_y phases can be transformed into more ductile phases by adaption of the press-hardening parameters to simultaneously increase the fracture toughness of the coating and decrease the crack density [12,16]. As an alternative that does not require adaption of the process parameters, the aim of this study is to remove brittle intermetallic phases by means of a pulse laser or sandblasting.

In Zn-base coatings, no cracks are formed in the press-hardening process [11]. During welding or brazing with cold-rolled and not additionally heat-treated Zn-coated mild steel sheets, the coating is completely melted and the liquid filler achieves good adhesion to the surface [8,17,18]. In contrast, during press-hardening, the Zn coating completely transforms into α-Fe and Fe_3Zn_{10} [13]. Consequently, the former Zn-base coating is not melted in a brazing process. The melted filler has to be brazed on the oxidized surface of the Zn-base coating on the press-hardened steel. For this reason, the oxides on the Zn coating should be removed to improve the adhesion of a filler in a welding or brazing process.

In this study, the surface of Al-base (AlSi10Fe3)- and Zn-base (ZnNi10)-coated and industrially press-hardened 22MnB5 steel was conditioned with a pulse laser and sandblasting to remove undesirable oxides and brittle phases, which should improve the adhesion of a filler on the coating surface. The treated Al-base- and Zn-base-coated 22MnB5 steel sheets were subsequently joined to aluminum alloy AA6016 by laser welding/brazing. Removing brittle coating components and oxides from the coating surfaces should lead to a good bonding strength between the coated steel and the filler, which was evaluated by tensile tests.

2. Experimental

2.1. Materials and microstructural analysis

AlSi10Fe3- and ZnNi10-coated sheets of 22MnB5 steel with a size of 50 × 120 mm and a thickness of 1.5 mm were investigated in this study. The AlSi10Fe3 layer (thickness: 25–35 μm) was deposited on the 22MnB5 by hot dipping at a temperature of 675 °C. The ZnNi10 coating (thickness: 24–30 μm) was galvanically deposited on the steel surface. The chemical composition of 22MnB5 steel was measured by optical emission spark spectroscopy and is given in Table 1. In addition, the chemical composition of the AlSi10Fe3 and ZnNi10 coatings was determined in the solidified state by energy dispersive x-ray spectroscopy (EDS) measurements.

The coated 22MnB5 sheets were welded with naturally aged (T4) AA6016 aluminum with a thickness of 1.5 mm (see Section 2.4). In addition, fillers of AlSi3Mn (Al-base coating) and ZnAl15 (Zn-base coating) with a wire diameter of 1.2 mm were used. The chemical composition of the AA6016 aluminum alloy and the fillers is also given in Table 1.

Microstructural examinations of the cross-sections were performed by optical light microscopy (OM), and examinations of the coating surfaces were performed by scanning electron microscopy (SEM). For this purpose, the cross-section of each sample was ground with 54 and 18 μm abrasives and then polished with a 3 μm diamond suspension and finally with a ¼ μm SiO_2 suspension. The chemical composition and oxide content on the coating surface was analyzed by EDS measurements using an acceleration voltage of 20 keV and a working distance of 8.5 mm. EDS measurements enabled to compare the oxygen content at the coating surfaces in the treated and initial condition and thereby discuss the removal of oxides.

2.2. Surface treatment

Surface treatment by laser ablation was carried out with the Nd:YAG laser Spectron SL900 and an Arges Racoon 16 scanner system equipped with f-theta lens (Fig. 1). This pulse laser source provided a maximum mean power of 16 W with a wavelength of 1064 nm. In these experiments, we used a spot diameter of 16 μm in the focal plane, a pulse duration of 100 ns, and a beam propagation velocity of 160 mm/s. The pulse frequency was set to 10 kHz, and the mean laser power was varied between 5 and 13 W. Argon was used as shielding gas.

Sandblasting was performed manually using a Hessler Strahlboss 140 device with a nozzle diameter of 10 mm, an angle of incidence of 60°, and a distance of 100 mm to the coating surface. Silicon oxide (SiO_2: 90–355 μm) was used as the abrasive. The sandblasting time was 10 s per steel sheet (50 × 120 mm) and the air pressure was set to 3 bar.

2.3. Phase analysis

The phase composition of the treated coating surface was analyzed with synchrotron diffraction measurements (λ = 0.45919 Å) at the electron storage ring facility Delta at TU Dortmund (Germany). The synchrotron radiation beam was focused parallel to the specimen and into the treated coating, which was further tilted by an angle of 5°. Debye–Scherrer circle segments (140–155°) were conditioned and integrated with the program Fit2D (ESRF). Phase analysis was performed using the ICDD-JCDPS database PDF-2.

2.4. Welding setup

Welding experiments were performed to determine the influence of the surface treatment on the bonding behavior of the coated 22MnB5 steel in a welding/brazing process with aluminum. Thereby, the steel surface remained solid and was wetted with the melted aluminum. Surface-treated 22MnB5 metal sheets (50 × 120 mm) were joined with AA6016 aluminum alloy (50 × 150 mm) in an overlap configuration with AA6016 in the upper position (Fig. 2). Welding was performed using a Nd:YAG laser beam (Trumpf HL4006D — maximum power: 4 kW) and a power supply for inductive preheating (maximum power output of 10 kW). The wire feed angle was adjusted to 25° to the sheet plane. The wire feed of the filler was directed contrary to the welding direction. FontArgen F400 NH flux was applied to the treated

Table 1
Chemical composition of the materials measured by emission spark spectrometry and energy dispersive x-ray spectrometry.

Chem. composition [mass%]	C	Si	Al	Mn	Mg	Ni	B	Fe	Zn
Substrate									
22MnB5	0.234	0.289	0.034	1.258	–	–	0.002	bal.	–
AlSi10Fe coating	–	10.230	Bal.	–	–	–	–	2.160	–
ZnNi10 coating	–	–	–	–	–	10,780	–	2.080	Bal.
AA6016	–	1.047	Bal.	0.135	0.463	–	–	0.249	–
Filler									
AlSi3Mn[1]	–	3.300	Bal.	1.100	0.010	–	–	0.190	–
ZnAl15[2]	–	0.002	14.620	---	---	---	---	0.004	Bal.

[1] Provided by Drahtwerke Elisental.
[2] Provided by Grillo.