Applied Surface Science 316 (2014) 595–603

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Cracking and interfacial debonding of the Al–Si coating in hot stamping of pre-coated boron steel

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ARTICLE INFO

Article history:
Received 29 April 2014
Received in revised form 27 July 2014
Accepted 8 August 2014
Available online 18 August 2014

Keywords:
Hot stamping
Anti-oxidation
Al–Si coating
Cracking
Interfacial debonding

ABSTRACT

This study is focused on the mechanisms of cracks initiation, propagation and interfacial debonding of the Al–Si coating in hot stamping of the pre-coated boron steel. The investigation was performed isothermally at three deformation temperatures (700, 750, 800 °C) at a strain rate of 0.1/s. Cracking and interfacial debonding of the coating were observed with optical and scanning electron microscope, to reveal the damage evolution under applied tensile strains. Microstructures and phase inside the coating before and after austenitization were determined by energy dispersive spectroscopy and X-ray diffraction. The results indicate that austenitization led to micro-cracks and Kirkendall voids initiation inside the Al–Si coating because of thermal loading, and the cracks were arrested by α-Fe diffusion layer. When the coating on substrate system was submitted to the uniaxial tensile test, the surface coating exhibited multiple cracking normal to the tensile direction. The Kirkendall voids seemed to promote the macro-crack growth through the diffusion layer. The macro-cracks followed a Mode I path, leading to the coating deteriorates to cracked segments. The macro-cracks then continued to propagate following a Mode II path that along the diffusion layer/substrate interface because of shear stress transferred from the deformed substrate, resulting in the interfacial debonding of the coating segments. The crack density firstly increased with the increasing tensile strain and then reached saturation. Decreasing deformation temperature caused an increase in the crack density visibly. Furthermore, the coating cracking correlated to the Fe–Al intermetallic compounds in it.

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1. Introduction

Hot stamping of boron steel sheets is rapidly increasing in automotive industry, due to the needs for higher passive safety, energy conservation and emission reduction. In the hot stamping process, the boron steels are heated to austenitizing temperature (850–950 °C), holding for 3–10 min, and then rapidly transferred to a die where the forming and subsequent quenching take place simultaneously [1]. An increase of the tensile strength of up to 1500 MPa is obtained due to full martensite transformation in the material [2]. However, under austenitization conditions, oxide scale formation occurs immediately when the bare steel is in contact with air in the furnace or during transport and forming stages [3,4]. In order to avoid that undesired surface oxidation and decarburization, as well as to improve the corrosion resistance and paintability after forming, most sheet blanks are pre-coated with a protective layer.

Different types of coatings have been developed for hot stamping steels to improve the anti-oxidation and in-service corrosion resistance of the hot-stamped parts. Zn and Zn-alloy coatings for hot stamping sheet steel grades are developed, because they offer not only barrier protection but Zn-alloy coatings also provide the additional benefit of cathodic protection [5]. However, the galvanized, i.e., hot dip pure Zn coated, hot stamping sheets suffers from the liquid-metal-induced embrittlement (LMIE) because of simultaneous application of stress and the presence of a liquid Zn surface layer during the forming process [6]. When a tensile stress is applied, liquid Zn could penetrate along grain boundaries in the steel matrix at temperatures above the Liquid + α-Fe(Zn) → Γ_1 peritectic transformation temperature of 782 °C. Several methods were suggested to avoid the LMIE of the Zn-coated hot stamping steel. An increase of the annealing time prior to hot stamping was an effective way to prevent LMIE by the elimination of the liquid Zn phase [6], but it led to a reduction in productivity. The

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http://dx.doi.org/10.1016/j.apsusc.2014.08.043
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indirect hot stamping method was suggested to avoid the LMIE of the Zn-coated hot stamping steel, that is 95% of cold deformation followed by the austenitization step + 5% of hot deformation to complete the calibration [7]. As most of the deformation was completed before heating, no LMIE was observed during press forming at high temperature. This indirect process causes a production cost much higher for a component formed by direct process. Nevertheless very few automotive components showing very complex geometries cannot be directly hot stamped. Kondratiuk et al. [8] reported a Zn-alloy coating with the addition of 11 wt.% Ni. The Ni increases the melting temperature of the Zn–Ni intermetallics to a temperature higher than 880 °C, thereby avoiding LMIE. The use of the indirect hot stamping method of a Zn–Ni coating has the drawbacks of high cost and low productivity yet.

The Al–10 wt.% Si coating is a widespread protection applied for hot stamping steels [9–11]. The incorporation of Si in the coating favors the development of a flat substrate/coating interface and promotes better adhesion [12], and the Si-rich coating has excellent resistance to both corrosion and elevated temperature oxidation [13,14]. Windmann et al. [10,11] characterized the evolution of phase, microstructure and surface roughness of the Al–Si coating layer in hot stamping process of boron steel. The steel diffusion process from the coating/substrate interface area to the coating surface was thermally activated. As a result of the diffusion processes, Al-rich Fe–Al intermetallics in the coating transformed to more Fe-rich ones. The surface roughness could be influenced by the temperature path during austenitizing and a higher heating rate resulted in a lower surface roughness [9]. Azushima et al. [15] investigated the friction behavior of the Al–Si coated boron steels under dry and lubricated conditions. It was confirmed that the use of a lubricant was highly effective for the hot stamping of aluminum coated 22MnB5 steel. Hardell and Prakash [16] studied the high temperature friction and wear on different tool steels sliding against the Al–Si coated boron steel. The flow behavior of the aluminum coated boron steels was reported in Ref. [17]. Suehiro et al. [18] assessed the properties of Al–10%Si coated steel. It was found that the coated steel showed good paintability even without phosphatized treatment. After painting, they showed good corrosion resistance in JASO-CCT as galvanized steel did. The pre-coated steel showed good spot weldability due to the stable surface layer at high temperature. Lara et al. [19] identified that even when the quality of sheet edges in the cutting process was good enough and no large defects were present, the fatigue resistance of the press hardened 22MnB5 steels was still limited by the coating integrity.

However, there is little attention has been put on the cracking and interfacial debonding of the Al–Si coating in hot stamping of the pre-coated born steel. Following austenitization, the pre-heated boron steel is pressed into desired shapes by means of hot stamping operation, and the most common deformation processes are bending, stretching and deep drawing [20]. For such applications, the Al–Si coated sheets are exposed to large deformations during the production processes, giving rise to coating cracks because of the lower forming limits of the Al–Si layer compared to the base material, especially, under tensile stress [21–23]. The opening caused by the cracked coating will provide passage for air and moisture that in turn leads to adverse oxidation reactions and corrosion of the substrate. It is of vital importance for the Al–Si coating layer to maintain its own integrity, in the application to effectively prevent the boron steel from oxidation and decarburization during hot stamping, as well as from corrosion during service. Therefore, cracking and interfacial debonding of the Al–Si coating in hot stamping process need to be clarified in detail. In the present study, uniaxial hot tensile tests of the Al–Si coated boron steel were performed under different deformation temperatures and applied tensile strains. The intent is to critically use all available information in order to assess cracking mechanisms and failure of the studied coatings. Characterization of the cracking and decohesion behavior of the coating layer was carried out under optical and scanning electron microscope. Based on the results of this work, the cracking failure of the Al–Si coating was described. In addition, the Al–Si coated boron steel is regarded as a brittle thin coating attached to an elastic-perfectly plastic metal substrate in the whole paper.

2. Experimental procedures

2.1. Materials

The tested boron steel has a thickness of 1.8 mm. The chemical composition of the substrate steel is shown in Table 1. The coating was hot-dipped on the substrate in a molten bath containing Al–10 wt.% Si. The overall thickness of the coating layer was 80.8 g/m^2.

2.2. Isothermal tensile tests

Various experimental methods such as the tensile test [24], three-point [25] or four-point bend test [22], peel test [26], scratch test [27], and increasingly nano-indentation test [28] have been used to evaluate the coating fracture stress and interfacial strength between the coating and the substrate. However, all these methods are mostly implemented at room temperature, there are fewer methods to observe the cracking behavior of coating at higher temperature in situ, in particular for the Al–Si coating under hot stamping conditions (600–800 °C) [2,29]. It is risky to directly observe the cracking and interfacial debonding of the Al–Si coating by using in situ SEM [21] or atomic force microscope [24] because of the elevated temperature. Therefore, the test is interrupted, an indirect method is adopted which is described as follow. Although this approximation is not a realistic representation of the actual conditions, in the fracture analysis it would be a successive process. The main feature that differentiates this study from the others investigations is that this article focuses on the cracking characterization of the Al–Si coating under hot stamping conditions.

2.2.1. Applied hot tensile strain

The hot stamping process was simulated in a Gleeble 3500 thermo-mechanical process simulator (Dynamic Systems Inc., Poestenkill, NY), and a set of uniaxial tensile tests were performed isothermally to evaluate the effect of deformation temperature and applied strain on the cracking behavior of the Al–Si coating. The specimen temperature was monitored by a K-type thermocouple welded to the center of the specimen surface. The specimen elongation was recorded using a high-temperature axial extensometer. Dimension properties of the tensile test specimen are shown in Fig. 1. The thermal-mechanical test procedure is illustrated in Fig. 2. Each specimen was heated to 920 °C with a heating rate of 10 °C/s, and austenitized for 5 min. Then the specimens were cooled down to 800, 750 and 700 °C at a rate of 30 °C/s, and this temperature was maintained for 3 s to attain a uniform temperature region. Finally the specimens were isothermally deformed to different strain conditions (shown in Table 2) with a strain rate of 0.1/s, and then immediately quenched to room temperature with compressed air. After the tensile tests, the specimens strained at the same temperature with different deformations were assigned in one group. From the observations of the surface modifications in the same

Table 1
Chemical composition of the steel substrate in wt.%.

C	Si	Mn	Cr	Al	Ti	B	Ni	Nb	V
0.22	0.23	1.2	0.16	0.04	0.03	0.002	0.012	0.013	0.004

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