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Influence of surface modification on galling resistance of DC53 tool steel against galvanized advanced high strength steel sheet

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ABSTRACT

The presence of galling is always detrimental when sheet metal forming advanced high strength steel (AHSS). Galling tends to reduce tool life, degrade the quality of components, and increase scrap rate of production. To prevent or postpone the initiation of galling and thereby extend the service life of DC53 tool steel forming tools, surface modification techniques like nitriding treatment and thermal diffusion (TD) carbide treatment can be utilized. A custom-designed sheet strip tribo-tester that includes bending deformation was used to perform tribological tests on tool steels having surface treatments. Comparisons were made of the friction coefficient, surface roughness and critical total sliding distance of individually treated and conventionally quenched/tempered DC53 tool steel dies against galvanized DP600 sheet. The initiation and evolution of galling and other wear mechanisms were subsequently analyzed and compared. Results indicated significant improvement in galling resistance for dies with surface modification. The improvement in galling resistance for the nitrided and TD coated DC53 tool steels, respectively, was attributed mainly to (i) the constitution of complex Fe_3N, Fe_4N phases in compound layer, and (ii) the good anti-adhesive capability of VC coating with high hardness in TD layer.

1. Introduction

Advantage of the high strength-to-weight ratio of advanced high strength steel (AHSS) was effectively utilized in the design of automotive structural parts in the past few decades. The use of AHSS for these structural parts significantly reduces the weight of automobiles and optimizes the design of the other mechanical components, which may subsequently result in energy saving, pollution reduction, and preservation of our sustainably green environment. One of the major problems in sheet metal forming (SMF) industry is the transfer and accumulation of sheet material to and on tool surface, which is a form of severe adhesive wear – galling. According to [1], galling wear is generally associated with either material transfer, plastic flow, or the combination of both. Comparing to its original counterpart, a galled surface is usually characterized by the existence of localized protrusions and relatively higher level of roughening. As galling is one of the major detrimental factors to degrade surface quality of the formed products and shorten the tool life, a great deal of research effort relevant to galling has thus been performed in automotive industry and research institutions.

Available literature shows significant research efforts specifically aiming at reducing galling in the processes of forming AHSS. Common approach to minimize galling and to extend die service life is (i) using superior tool material for the dies [2–4], or (ii) modifying the die surface by Physical Vapor Depositing (PVD) coatings of TiN, CrN, (Ti, Al)N and TiNC [5]. For example, Pelcastre et al. [6] studied the behaviors of galling resistance of the dies coated (i) with AlCrN, TiAN and DLC, respectively, by physical vapor deposition process and (ii) with plasma nitriding treatment. Comparison of their results with those of the untreated dies suggested that PVD dies appeared to give poorest galling resistance while plasma-nitrided dies gave evidence of reducing the galling wear significantly. Podgornik et al. [7] studied the galling resistance of dies to be either plasma-nitrided or PACVD coated with TiN/TiB_2 after heat treated in vacuum environment. The study inferred that galling resistance of the plasma nitride die was significantly improved in comparison to that of its TiN/TiB_2 coated counterpart. Using finite element method and some other simulating techniques, Kim et al. [8] were able to verify and optimize the influential parameters (like die material, surface coating and lubricants, etc.) in the process of stamp-forming of advanced high strength hot-dip galvanized sheet. The study illustrated the feasibility to improve galling resistance by suitably combining these parameters. Lin et al. [9] investigated wear resistance behaviors of different automobile die steels. Their study suggested that use of

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chromium plating die could effectively improve surface quality by lowering surface roughness, which recursively enhances wear resistance. Arai [10–11] developed the process of thermal diffusion (TD) carbide treatment, which has subsequently been widely used to improve the wear resistance of tools for sheet metal forming. Sen and Sen [12] studied the wear and friction behaviors of AISI 52100 steel and alumina against AISI 1040 steel disk coated with niobium carbide using thermo-reactive diffusion technique. Their results suggested that the well adhered niobium carbide coating gave beneficial effect on the tribological behavior of AISI steels. The analysis by Alejandro et al. [13] verified better corrosion resistance of the steel coated with niobium carbide than its uncoated counterpart.

However, the mechanisms relevant to the effect of (i) nitriding treatment and (ii) TD treatments on the galling resistance of forming tools are still not well understood. Currently, the lacking of experimental data and proofs on (i) the initiation of galling and (ii) the dynamic evolution of surface morphology of nitrided and TD treated tools sliding against galvanized AHSS jeopardizes the correlation in deriving their viable relationship. The study in this paper aims at shedding some light on these mechanisms in hope that the correlation of (i) the effect of nitriding treatment on galling resistance and (ii) the effect of TD treatment on galling characteristics becomes possible.

This paper used two different surface modification techniques, nitriding treatment and thermal diffusion carbide treatment, respectively, to alter the surface properties of cold work DC53 die steel. The individually treated DC53 die steels were slid against sheet materials which were also coupled with tensile deformation as being mounted onto a custom-designed tribo-tester. The sliding coupled with tensile deformation meant to simulation the stretching of sheet metal and their rubbing with tool in SMF. The tribological behaviors of the treated surfaces of DC53 die steel were subsequently evaluated for better understanding their galling initiation and corresponding wear properties. To enhance such understanding, analysis and comparison of their results with those of the die tool treated by traditional quenching/tempering technique were also performed. Systematic study by varying the thickness, hardness and composition phase of the coating on the modified surface of DC53 die steel facilitated the revelation of their corresponding influence on galling resistance of the treated surface under a condition of friction coupling deformation.

2. Experiments

2.1. Materials and treatment

Surface of DC53 cold work tool steel specimens (with chemical composition as tabulated in Table 1) were firstly machined to their design as shown in Fig. 1(a), and then treated to accomplish different levels of surface modification by either plasma nitriding treatment or thermal diffusion (TD) carbide treatment. Such treated tool steel specimens were then used as the specimens of targeted pressure head for investigating their individual performances in resisting galling initiation. Results were then compared to those of DC53 cold work tool steel to be traditional quenched and tempered. The corresponding mating sheet specimens were the hot-dip galvanized dual-phase AHSS DP600 steel having tensile strength approximately 600 MPa and chemical compositions as tabulated in Table 1. The hot-dipped zinc layer on the as-received DP600 sheet substrate was approximately 10 μm thick and electrical discharge machined to the dimensions as illustrated in Fig. 1(b). Fig. 2 shows the treatment conditions of the conventional process to quench and temper the DC53 tool steel to a hardness of about 61 HRC.

The procedures for nitriding the DC53 tool steel pressure head specimens sequentially involved with: (i) firstly quenching the pressure head at a temperature above 1040 °C, followed by tempering at a temperature of 525 °C for 2 h; (ii) placing the so quenched and tempered pressure head (forming die) in a nitriding furnace vacuumed to 55 ± 5 Pa; (iii) fluxing hydrogen into the furnace to glow-clean the die for about 15 min, followed by a period of purging with nitrogen; (iv) maintaining the furnace pressure at 150 Pa by suitably adjusting the flow ratio of hydrogen and nitrogen to 3:2 for the execution of nitriding; and (v) obtaining the desirable nitrided pressure head by cooling down the furnace which had been heated to maintain at 520 °C and the environmental condition, as specified in (iv) above, for 5 h.

The TD treatment of pressure head was conducted according to the following sequence: (i) firstly placing the sample in a molten salt consisted of borax and V_2O_5, V and Al powder, and B_4C, etc.; (ii) maintaining the temperature of the molten salt within 970 ± 10 °C and immerging the sample in (i) in the salt for 5 h; (iii) removing the sample from the immerging bath and allowed to air-cool to room temperature; and (iv) cleaning the molten salts remained on the surface off the pressure head, which was then quenched and tempered conventionally.

2.2. Testing equipment

A custom-designed sheet/strip tribo-tester (Fig. 3) was used to investigate wear test so as to explore and compare their tribological behaviors and ability to resist galling of the individually treated and/or untreated DC53 tool steel pressure heads. A TR200 portable surface roughness tester was used to measure: (i) the surface roughness (R_{y0}) of the as-received strip specimens (approximately to be 1.1 μm); and (ii) the surface roughness (R_{yi}) of the slid trace of individual test-specimens. A HITACHI SU-1500 Scanning Electron Microscope (SEM) was used to analyze surface morphology of the specimens before and after sliding. A MH-3 microhardness tester was utilized to measure the hardness of the nitrided layer and TD coating on the pressure heads. Furthermore, Energy Dispersive Spectrometer (EDS) equipped in the HITACHI SU-1500 Scanning Electron Microscope (SEM) and NIKON VHX-600 Digital Stereomicroscope measurement system were used to scan and analyze the surface morphology of strip specimens and the die, respectively. Phase compositions of nitrided layer and TD coating were scanned and identified by the CuKα radiation mode of a 40 kV, 200 mA D-MAX-2550 X-ray diffractometer, with scanning undertaken at 2θ scanning step of 8° and in a scanning range within $20° < 2\theta < 100°$.

Table1
The alloy element content (wt%).

Material	C	Cr	Ni	Si	Mn	P	S	Mo	V
DP600	0.0769	0.012	0.0102	0.442	1.55	0.0139	< 0.005	< 0.005	0.0047
DC53	0.96	8.12	\	0.95	0.38	0.02	0.005	2.07	0.17