INVESTIGATING THE EVOLUTION OF PROGRESSIVE DIE WEAR ON UNCOATED DP1180 STEEL IN PRODUCTION ENVIRONMENT

W Wu¹, D J Zhou², D J Adamski³, D Young⁴ and Y W Wang¹,*
1. Applications & Advanced Engineering, AK Steel Corporation, Dearborn, MI 48120, USA
2. Advance Stamping Manufacture Engineering, FCA US LLC, Auburn Hills, MI 48326, USA
3. Advanced Technology and Welding, General Motors Company, Warren, MI 48090, USA
4. Stamping Engineering Ford Motor Company, Dearborn, MI 48187, USA

Corresponding author’s e-mail: Yu-Wei.Wang@aksteel.com

Abstract. A study of die wear was performed using an uncoated dual phase, 1,180 MPa ultimate tensile strength steel (DP1180) in a progressive die. The objectives of the current study are to evaluate the die durability of various tooling materials and coatings for forming operations on uncoated DP1180 steel and update OEM’s die standards based on the experimental results in the real production environment. In total, 100,800 hits were performed in manufacturing production conditions, where 33 die inserts with the combination of 10 die materials and 9 coatings were investigated. The die inserts were evaluated for surface wear using scanning electron microscopy and characterized in terms of die material and/or coating defects, failure mode, failure initiation and propagation. Surface roughness of the formed parts was characterized using a WYKO NT110 machine. The analytical analysis of the die inserts and formed parts, combined with the failure mode and service life, provide a basis for die material and coating selection for forming AHSS components. The conclusions of this study will guide the selection of die material and coatings for high-volume production of AHSS components.

Keywords: Wear; Forming; AHSS; DP1180; Simulation; Production; Roughness.

1. Introduction
In order to meet the requirement of weight reduction and in the same time maintain and even improve the crash performance, the demand for advanced high strength steels (AHSS) and ultra-high strength steels (UHSS) are developed rapidly in automobile industry worldwide. The structure component manufactured by AHSSs provides the optimal performance due to their excellent combined strength and ductility. However, the die wear problem becomes more and more severe, because the hardness of the sheet metals become much higher and traditional die materials and surface treatments (coatings) are not sufficient for AHSSs stamping [1-4]. It leads to the significant cost increase due to the die
maintenance and interruption in manufacturing. In the sheet metal stamping industry, there is a pressing demand to understand die wear behavior in next generation AHSSs forming. The special die materials and coating are worth the efforts to develop for forming AHSSs in large volume production.

In the present research, the die wear properties were evaluated in real production environment for in total 33 die inserts with the combination of 10 die materials and 9 coatings when flanging uncoated DP1180 steels. The computer simulation was conducted to simulate the strain distribution and sliding energy density during the forming. The scanning electron microscopy (SEM) was adopted to measure the wear area in the inserts after forming. The energy-dispersive X-ray spectroscopy (EDS) mapping was provided to distinguish the elements distribution around the fracture surface. The final panel surface roughness was examined by Wyko NT1100. The objectives of the current study are to evaluate the die durability of various tooling materials and coatings for flange operations on uncoated DP1180 steel and update OEM tooling standards based on the experimental results. The current study provides the guidance for the die material and coating selections in large volume production for next generation AHSSs.

2. Experimental Procedures

2.1. Progressive-die setup

The die wear experiment was conducted in real production condition. The schematics of upper and lower progressive die are shown in Fig. 1(a) and (b), respectively. It is worth to mention that the hole piercing with different shape and geometry was also investigated during the experiment, beside the flange. The current study only focuses on the flange operations to assess the die wear. In progressive-die, in total 14 stations were included. The details for each station are illustrated in Fig. 1(c). The
flange die insert is displayed in Fig. 1(d). The die insert located in upper prog-die. The contact points on each side of the insert are marked in Fig. 1(d). The schematic of final formed parts is illustrated in Fig. 1(e). The sample labeling of 1-12 in Fig. 1(e) corresponds to inserts # 1-12. The left and right fingers are marked on Fig. 1(f) as letter “L” and “R”, which will be used throughout the present paper. The project was separated in two phases, 2015 and 2016. In 2015 project, in total 18 die inserts with combination of 8 die materials and 7 coatings were evaluated up to 20,000 hits. In 2016 project, in total 16 die inserts with combination of 8 die materials and 5 coatings were tested until 85,800 hits. No lubricant was applied during forming. One formed panel was preserved every 500 hits to investigate the die wear evolution for each die insert in the present study.

2.2. Materials
The uncoated DP1180 steel was selected in the present research. Because of the high strength and no zinc coating applied on the surface of steel, a brutal sheet metal forming condition was engineered to encourage die wear during stamping. It makes this steel a good candidate to evaluate the die wear properties. The gauge of the as-received blanks was 1.17 ± 0.04 mm. The stress-strain curve and tensile properties of the uncoated DP1180 steel along longitudinal (L), transverse (T), and diagonal (D) are shown in Fig. 2. The yield strength and ultimate tensile strength of the uncoated DP 1180 steel were approximately 920 and 1197 MPa, respectively. The uniform and total elongations were about 5.3 % and 9.9 %, respectively. The phase volume fraction of martensite and ferrite in the as-received material was 70% and 30%, respectively.

2.3. Forming simulations
The computer simulation was performed using LS-DYNA to simulate the sliding energy density and effective strain distribution for 2.8 and 5 mm radii contact point, as displayed in Fig. 4(a)-(c), respectively. It was noticed that the sliding energy density was much higher for the die inserts with 2.8 mm radii at contact points than the 5 mm radii. Moreover, the effective strain concentration was more severe for the 2.8 mm radii die inserts. It manifests that the die wear could be significantly reduced by optimizing the die design. However, the major objective in the present research was the die durability evaluation. A worst case scenario was artificially staged by using the aggressive die insert design coupled with uncoated sheet metal without lubrication in the current study. Therefore, the 2.8 mm
3. Results and Discussion

3.1. 2015 Project

The experiment matrix of 2015 project, including die material, coating method, die material hardness and roughness after heat-treatment, is listed in Table 1. After 15,000 hits, the die inserts #1, 2, 8, 10, 11, and 12 were replaced by #N1, N2, N8, N10, N11, and N12, respectively. In 2015 project, two critical issues were addressed, (1) Are the current die materials and coating methods for stamping 980 grade steels in the mass production still applicable for forming 1180 grade steels? (2) One step further, can the die materials of currently employed in forming 980 grade steels in production be replaced by less expensive die materials and still make parts in 1180 grade steels? The die inserts #4 and 9 were selected in the matrix, which were presently employed in production of DP980 steels. The die inserts #1, 2, 10, 11, and 12 were chosen, since the die materials were replaced by either ductile iron or low alloy cast steel.

The 2015 progressive-die wear performance is presented in Fig. 4. The safe (no scratch), rough (small scratches), and very rough (worn-out) are color coded by green, light green, and red, respectively. In production, the “safe” and “rough” are acceptable for quality check. All the results in Fig. 4 were visually checked from the panels from the part preserved every 500 hits, which actually demonstrates the die wear evolution during forming. It was found that for the first 12 die inserts, except insert #7, all of them were worn out fast. There is no major failure observed on the right side of #4 panels until 11,500 hits, while the left side was damaged at 3,000 hits. The die insert #9 was completely damaged after 1,300 hits. It indicates that the current die material and coating method for stamping 980 grade steels in production cannot be used for forming 1180 grade steels. The die inserts #1, 2, 10, 11, and 12 were worn out at very early stage of the tests at 35 hits. It manifests that these die inserts with ductile iron or low alloy cast steel as die materials should not be considered for forming...
DP1180 steel in mass production. It should be pointed out that the die insert #7 survived all 20,000 hits without scratches. It was noticed that the die insert material and coatings are the same for the die inserts #N1, N2, N10, N11, and N12. However, the performance of these die inserts was not consistent. The die insert #N1 performed the best without any worn-out for 5,000 hits, while #N2 failed at 400 or 600 hits. It suggests that the current die material and coating has a large variation of performance.

Table 1. Experiment matrix of 2015 project.

| Die Insert ID | Die Material | Coating | Hardness (Rc) | Roughness, Ra (μm) |
|---------------|--------------|---------|---------------|--------------------|
| 1             | D6510        | PVD Duplex CrN | 54-58         | 0.94               |
| 2             | CC1          | PVD Duplex CrN | 38-42         | 0.68               |
| 3             | T44          | PVD Duplex CrN | 44-46         | 0.42               |
| 4             | TD2          | PVD Duplex CrN | 55-58         | 0.35               |
| 5             | TD2          | PVD Duplex CrN | 55-57         | 0.39               |
| 6             | DC53         | PVD Duplex CrN | 55-60         | 0.42               |
| 7             | TD2          | Cool Sheet    | 55-57         | 0.26               |
| 8             | TD2          | Concept       | 55-60         | 0.42               |
| 9             | S2333        | PVD Duplex CrN | 40-45         | 0.48               |
| 10            | S0050A       | Cr Plate      | 54-58         | 0.17               |
| 11            | S0050A       | Cr Plate over Ion Nitride | 38-43 | 0.20               |
| 12            | CC1          | HVOF         | 54-58         | 0.22               |
| N1            | D2 (NEW)     | PVD Duplex CrN | 58-60         | -                  |
| N2            | D2 (NEW)     | PVD Duplex CrN | 58-60         | -                  |
| N8            | TD2 (NEW)    | Concept + Most | 58-60      | -                  |
| N10           | D2 (NEW)     | PVD Duplex CrN | 58-60         | -                  |
| N11           | D2 (NEW)     | PVD Duplex CrN | 58-60         | -                  |
| N12           | D2 (NEW)     | PVD Duplex CrN | 58-60         | -                  |

After testing, the die inserts #1-12 were examined by SEM to measure the wear area using imaging process software and EDS mapping to inspect the elements distribution around the worn-out area. An example was given in Fig. 5 for die insert # 9. The die insert # 9 after testing was displayed in Fig. 5(a). The area of the die wear was circulated by the yellow line and indicated in Fig. 5(b). The SEM picture was taken at the fracture surface, where coating was worn out in Fig. 5(c). The overlay of EDS mapping of various elements is presented in Fig. 5(d). The element distributions of Fe, O, Cr, and N are illustrated in Fig. 5(e)-(h). It was found that in the worn-out zone no coating was left, while the elements N and Cr were evenly distributed inside coating.
Figure 4 The die wear performance of 2015 project.

Figure 5 (a) The geometry of die insert #4 after experiments. (b) The worn-out area measurement by SEM. (c) The SEM picture of coating worn-out zone. (d)-(h) The element distribution around the fracture surface by EDS mapping.
3.2. 2016 Project

In 2016, the major objective was to explore the combination of die insert materials and coating methods, which are practicable for forming 1180 grade steels in production environment. The experiment matrix of 2016 project is presented in Table 2. The die insert #8 was replaced by #14 after 4,000 hits. Then, the die inserts #3, 5, and 14 were substituted by #13, 15, and 16 after 70,000 hits.

Table 2. Experiment matrix of 2016 project

| Die Insert ID | Die Material | Coating | Hardness (Re) | Roughness, Ra (μm) |
|---------------|--------------|---------|---------------|-------------------|
| 1             | S2333        | Cool sheet | 40-45         | 0.15              |
| 2             | S2333        | Cool sheet | 50-54         | 0.22              |
| 3             | Cast Caldie  | Cool sheet | 58-62         | 0.17              |
| 4             | Toolox 44    | Cool sheet |               | No heat-treatment |
| 5             | SLD-i        | Cool sheet | 58-62         | 0.24              |
| 6             | TD2          | Concept + most | 55-58   | 0.16              |
| 7             | TD2          | Cool sheet  | 55-57         | 0.17              |
| 8             | TD2          | Duplex CrN + most | 55-58 | 0.12              |
| 9             | Cast Caldie  | Concept + most | 58-62 | 0.11              |
| 10            | DC53         | Concept + most | 62-64 | 0.23              |
| 11            | TD2          | Duplex Variantic (TiAlCN) | 55-58 | 0.10              |
| 12            | SLD-i        | Concept + most | 58-62 | 0.18              |
| 13            | TD2          | Concept    | 55-58         | 0.13              |
| 14            | TD2          | Concept + most | 55-58 | 0.19              |
| 15            | S2333        | Concept + most | 40-45 | 0.08              |
| 16            | TD2          | Concept + most | 55-58 | 0.13              |

The progressive-die wear performance in 2016 project is exhibited in Fig. 6. In general, the performance of the die inserts in 2016 was significantly improved comparing with in 2015. The majority of the die inserts lasted over 20,000 hits without scratches. It should be pointed out that the die insert #7 was the same one in 2015 project. Besides die insert #7, die inserts #10 and #11 endured over 80,000 hits without failure. Die insert #9 survived over 65,000 hits without major failure. These die inserts demonstrated a great potential to be employed in forming production of next generation of AHSSs. Interestingly, one side of the die inserts #2 and #6 failed in the early stage, while the other side survived throughout the experiment. Moreover, for die insert #9, the left side of insert has some...
small scratches at 8,000 hits, but no major failure was observed throughout the tests. It exhibited the excellent resistance of the wear propagation to prevent the catastrophic failure of die during service.

2016 Die Wear Performance

![Graph showing die wear performance](image)

Figure 6 The 2016 progressive-die wear performance.

![Image showing surface roughness measurements](image)

Figure 7 The sample surface roughness measurements for die inserts #5 and #7 of the final formed part using Wyko machine.

The surface roughness of the final panel was examined using Wyko machine for all 12 parts. The surface roughness, Ra, of the as-received sample was also determined as approximately 1.83 μm. The surface roughness results of die inserts #5 and 7 were presented in Fig. 7(a) and (b), respectively. The 3D and 2D surface roughness map were displayed in Fig. 7(a). The surface roughness profile on any section lines also can be extracted from Wyko measurements, as shown in Fig. 7(a). It was found in that severe scratch marks were left on the formed part and the averaged surface roughness increased to 9.69 μm, due to the die wear from insert #5. The similar measurement was applied to final part from die insert #7 in Fig. 7(b). The averaged surface roughness of measured area was decreased to 1.19 μm
Figure 8(a)-(c) The die wear performance of 2016 project ranked by safe, rough, and safe and rough, respectively.
for insert #7 due to the roughness flattening during the forming. The sample surface roughness was actually decreased after the flanging process. It indicates that the visual check method on the formed part is reliable to evaluate the die wear evolution during forming.

In general, the die wear process can be separated into three stages, wear initiation, wear propagation, and final failure, which corresponds to safe, rough, and very rough in the die wear performance.
performance plot in Fig. 6. In order to evaluate the wear initiation and propagation resistance of various die inserts, the die wear performance of 2016 project was sorted by safe and rough, as illustrated in Fig. 8(a) and (b), respectively. The left side of die insert #7 exhibited the best wear initiation resistance among all the tested die inserts in Fig. 8(a). The die inserts #11 and right side of insert #10 survived over 80,000 hits without scratches. The left side of die insert #10 and right side of die insert #7 show a lower wear initiation resistance than the other side. Overall, die inserts #7, 10 and 11 presented an excellent crack initiation resistance over other die inserts. The wear propagation resistance is another important parameter to evaluate the die wear performance. As displayed in Fig. 8(b), the left side of the die insert #9 and right side of the die insert #7 demonstrated an extraordinary wear propagation resistance during forming. As mentioned apprehend, to a certain extend the small scratches on the formed part are acceptable in production, which correlates to the safe plus rough in the die wear performance. Therefore, the die wear performance of 2016 project is sorted by safe and rough, as exhibited in Fig. 8(c). It was obvious that the die inserts #7, 9, 10, and 11 are the decent candidates for stamping 1180 grade steels in mass production, which is the major finding in the present research.

In order to find the deciding factors to influence the die wear performance in the present research, the 2016 progressive-die wear performance ranked by die surface roughness before coating, die material hardness before coating, and actual radii after coating are presented in Figs. 9(a)-(c), respectively. It was found that no direct linkage between the progressive-die durability and die material hardness and die surface roughness was established, as shown in Fig. 9(a) and (b). It was demonstrated that the die wear performance became more promising when the contact point radii were larger than 5.9 mm in Fig. 9(c). It manifested that die wear performance was influenced by the combination of die material selection, die material hardness, die design, coating method, die surface roughness, die insert manufacturing, die alignment, and AHSSs. It has to consider all the factors to optimize the die design for improving the die durability in forming the next generation AHSSs.

| Area | Element | Weight % | Element | Weight % | Element | Weight % | Element | Weight % | Element | Weight % |
|------|---------|----------|---------|----------|---------|----------|---------|----------|---------|----------|
| 1    | C K     | 14.25    | C K     | 3.06     | C K     | 7.00     | C K     | 4.52     | C K     | 6.10     |
| 2    | Ti K    | 82.95    | N K     | 13.65    | O K     | 4.96     | N K     | 3.37     | O K     | 11.98    |
|      | Cr K    | 0.55     | O K     | 6.82     | Si K    | 0.57     | O K     | 3.07     | Si K    | 0.55     |
|      | Fe K    | 2.27     | Al K    | 0.15     | Mo K    | 1.82     | Si K    | 0.65     | S K     | 3.13     |
| 3    | Cr K    | 75.15    | Cr K    | 9.19     | Mo K    | 0.42     | Ti K    | 0.28     |         |         |
| 4    | Mn K    | 1.08     | Mn K    | 0.71     | Ti K    | 0.30     | Cr K    | 10.43    |         |         |
| 5    | Fe K    | 2.10     | Fe K    | 66.80    | Cr K    | 10.64    | Mn K    | 0.81     | Fe K    | 46.46    |
|      | C K     | 8.93     | Mn K    | 0.86     | Fe K    | 76.17    | C K     | 20.25    |         |         |

Figure 10 The SEM analysis on die insert #7 after 10,800 hits.
Similar to 2015 project, after testing the die inserts were examined using SEM to determine the wear area and elements content around the worn-out area. An example was provided in Fig. 10. It was noticed that after a small crack was formed on the die insert the coating was peeled out in the worn-out zone. The die material and interface between die material and coating became critical for the die wear propagation resistance.

4. Conclusion

The die wear properties up to 100,800 hits on a progressive-die for uncoated DP1180 steel were investigated in real production condition in 2015 and 2016 projects. In total, 33 die inserts with the combination of 10 die materials and 9 coatings were evaluated. A worst case scenario was artificially engineered by using the aggressive die insert design coupled with uncoated sheet metal without lubrication during forming in the current study to evaluate the die wear performance. The die wear performance was influenced by combination of die material selection, die material hardness, die design, coating method, die surface roughness, die insert manufacturing, die alignment, and AHSSs. It has to consider all the factors to optimize the die design for improving the die wear initiation and propagation resistance in forming the next generation AHSSs. It was found that the die material and coating method in large volume production of 980 and lower grades steels was not suitable for forming next generation AHSS, 1180 grade steels. The die materials, such as ductile iron and low alloy cast steel, should not be considered for die design in stamping 1180 grade steels. The new combinations of die material and coating methods were evaluated in the current study to explore the candidates for forming uncoated DP1180 steel. The die inserts #7, 9, 10, and 11 are the promising candidates for forming next generation AHSSs up to uncoated 1180 grade steels in the mass production. It was noticed that the die insert #7, 10, and 11 demonstrated a significant die wear initiation resistance, while die inserts #7 and 9 provided the excellent die wear propagation resistance. Besides the die material and coating methods, the interface between die material and coating plays a critical role in die wear process, which is worth the efforts in die durability research in the near future to improve the fundamental understanding on die wear behavior.

References
[1] Sandberg O, Bustad P, Carlsson B, Fallstrom, M and Johansson T 2004 Recent Advances in Manufacture & Use of Tools & Dies and Stamping of Steel Sheets.
[2] Zeghni AE and Hashmi MSJ 2004 J. Mater. Process. Tech. 155-156 1918
[3] Xia ZC and Ren F 2007 SAE Technical Paper 2007-01-1694
[4] Measuring Wear of Dies with AHSS and UHss, 2008 OFAT Report T6010-T07C

Acknowledgments
The team appreciates the support from A/SP with Rich Cover and Eric McCarty as program managers.