Materials Research Proceedings 41 (2024) 1288-1298 https://doi.org/10.21741/9781644903131-143

Analysis of wear behavior of powder metallurgy tools in shear cutting of electrical steels

KUMAR SUNDARAJAN Praveen[1,a], ŞELTE Aydın[2,b*], HOENEN Niklas[1,c], CLAUSMEYER Till[1,d] and TEKKAYA A. Erman[1,e]

[1]Institute of Forming Technology and Lightweight Components, TU Dortmund University, Baroper Str. 303, D-44227 Dortmund, Germany

[2]Uddeholms AB, SE-683 85 Hagfors, Sweden

[a]Praveen.kumar-sundarajan@thermic-energy.com, [b]Aydin.Selte@uddeholm.com, [c]niklas.hoenen@iul.tu-dortmund.de, [d]till.clausmeyer@iul.tu-dortmund.de, [e]erman.tekkaya@iul.tu-dortmund.de

Keywords: Shear Cutting, Electrical Steel, Tool Steels, Wear

Abstract. The shear-cutting process of electrical steels for electrical engines' rotors and stators influences the properties of the shear-cut edges. The properties such as geometry and mechanical and electromagnetic properties of shear-cut edges depend on the wear behavior of the tools. This study examines tool wear in three powder (PM1, PM8, PM10) metallurgical tool steels during shear cutting of electrical steel. PM1 is intended for high-performance applications owing to its unique mixture of boride and carbide precipitates. PM8 is a high alloyed Cr-Mo-V tool steel tailored for abrasive wear applications with a certain amount of ductility, and PM10 is a nitrogen alloyed tool steel specifically designed for applications where adhesive wear resistance is required. Tool wear and shear-cut edge properties were analyzed at four different intervals of punch strokes for 8% and 16% cutting clearances. The experimental study found that the 8% clearance caused excessive chipping in punch corners for all three materials, mainly PM10, which chipped in all corners at the end of 108,000 strokes. In contrast, PM1 demonstrated better chipping resistance, particularly at 16% clearances. Furthermore, PM1 showed superior resistance to edge wear for various punch strokes and clearances.

Introduction and Background

Blanking efficiently produces sheet metal parts without chip formation, relying on factors like punch-die clearance (c), sheet thickness (t), and punch radius (R_p) for accuracy [1]. The guideline VDI 2906 identifies four key edge characteristics: rollover from bending, burnishing, and angular fractures caused by sharp punches and burr formation from excessive clearance or dull tools [2]. The clearance significantly impacts tool wear and sheared edge quality; an excessive clearance causes burrs and rough fracture zones, complicating further processing.

Wear on the tool surface while blanking leads to alterations in the quality of the cut surface. The cutting-edge radius significantly influences energy consumption during blanking [3]. Wear typically occurs on the tool's outer surface, rounding the cutting edge, attributed to adhesion, abrasion, fatigue, and tribochemical wear processes [1]. According to [4], due to repeated impact loads or thermal shocks, the punch experiences some micro crushes, fragments, and breaking on the cutting edges, and mechanical or thermal fatigue during blanking creates irregular microcracks that propagate and produce chipping or macro fracture with a further increase in punch strokes.

[5] stated that electrical steels are the most commonly utilized soft magnetic materials. Non-oriented electrical steel is vital for motor components like rotors and stators. Although blanking is the favored method due to its efficiency and cost-effectiveness, it introduces high stress and strain near the sheared edge. [6] conducted a silicon steel blanking experiment, revealing gradual cutting-

edge wear at 0% clearance, increased plastic deformation zone and cutting-edge rounding with an 8% clearance. [7] studied tool wear in 22MnB5 boron steel blanking, noting minimal wear in S390 material, manufactured through powder metallurgic processes, compared to K340, which is cold work tool steel manufactured from electro slag remelting. Tool wear directly impacts sheared edge quality. Studies by [8] link tool wear to crucial burr length assessment for product quality.

[9] found high stroke counts (40,000 to 60,000) significantly increase burrs due to intense punch strokes. [10] discovered that clearance (5-20%) affects sheared edges, altering zones and reducing tool life. Inadequate clearance causes secondary shear, demanding more energy [11]. [6] noted microhardness testing analyzes work hardening in sheared edges; punch wear widens blanking gaps, raising shear stress changes in tool geometry impact microhardness, reducing Shear-Affected Zones (SAZ) with smaller clearances. [12] demonstrated intensified work hardening near edges due to tool wear.

Powder Metallurgy (PM) High-Speed Steels offer an alternative to conventionally produced tool steels, showcasing unique attributes like heightened hardness and toughness, distinguishing them from traditional tool steels. While extensive research has centered on analyzing tool wear on electrical sheets, there remains a notable gap in exploring powder metallurgical (PM) tools in the blanking process of electrical steels. This study thoroughly examines tool wear analysis using three distinct PM tool steels for varying clearances. Furthermore, it examines the properties of sheared edges resulting from different punch strokes.

Procedure

A TruPunch 5000 was used for experimental blanking with a 1000 mm x 1000 mm blank. A total of 108,000 strokes are performed using a 10 mm x 10 mm punch and two dies (10.16 mm and 10.32 mm), as shown in *Fig. 1*.

No lubricant or BHF was used. The analysis was conducted after 9,000, 45,000, 81,000, and 108,000 strokes.

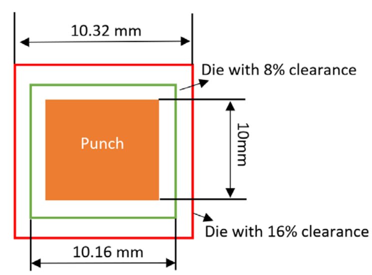

Figure 1: Schematic diagram of square punch with different die dimensions.

Tool Steel

This work uses three powder metallurgical tool steel, namely, PM1 (X50MoCoCr17-4), PM8 (X230VCrMo8-5), and PM10 (X130VMoN10-2). PM8 is abrasive-resistant with a lower hard phase content than PM1, while PM10 has enhanced anti-galling properties and it contains 1.8% of Ni. PM1 is an abrasive-resistant material with higher compressive strength. Chemical composition and properties are given in *Tables 1* and 2.

Table 1: Chemical composition of three punch materials.

Grade	C,%	Si,%	Mn,%	Cr,%	Mo,%	**V,%**
PM1	0.5	1.0	0.3	4.2	17.3	**0.25**
PM8	2.3	0.4	0.4	4.8	3.6	**8**
PM10	1.3	0.5	0.4	0.4	1.8	**10**

Table 2: Properties of three punch materials.

Grade	Compressive strength (MPa)	Conductivity at 200°C (W/m°C)	Hardness (HRC)
PM1	3600	-	68-69
PM8	2800	25	63-64
PM10	3000	25	63-65

Electrical Steel

Tool wear in PM1, PM8, and PM10 was analyzed when blanking against non-grain-oriented electrical steel of 1 mm thickness. This material is commonly employed in blanking operations. The electrical steel contains 1.25% of the mass content Si. The yield and ultimate tensile strength are 250 MPa and 370 MPa, respectively.

Tool Wear Measurement

The Keyence VR5000 profilometer, with 2 µm accuracy, quantifies punch tool wear. A 3D-printed fixture has been designed to ensure precise placement and capturing of corner and edge wear. Imaging is done at 80x magnification after 9,000, 45,000, 81,000, and 108,000 strokes. Corner chipping depth and width are measured using 10 equidistant lines spaced 30 µm apart to quantify the wear. Average values for corners with extensive chipping and maximum values for those with minimal wear enable effective comparisons across clearances and punch materials. A significant variation of wear is observed between different punch sides, which leads to the omission of an error plot, which causes higher error deviation. The quantification of tool wear in the punch involves measuring the change in its edge radius, with an initial radius of 15 µm. This process employs a profilometer to scan all four sides of the punch using 10 horizontal measurement lines spaced 1050 µm apart. Analyzing the edge profile for each line determines the edge radius. Notably, an increase in strokes correlates with an increase in the radius.

Sheared Properties Measurement

The blank is evaluated for sheared properties at the initial state and the beginning of 45,000, 81,000, and 108,000 strokes on all sides. The red marking is done at the initial point of the sheet to distinguish the different sides after blanking (*Fig. 2a*). The collected samples are embedded and polished to achieve a fine surface finish to measure sheared properties and microhardness.

A microscope with a magnification of 100x according to VDI 2906 is used to assess parameters like rollover (h_r), burnish (h_b), fracture (h_f), and burr height (*Fig. 2b*). Sheared properties are evaluated on all sides, and the average is calculated for each stroke.

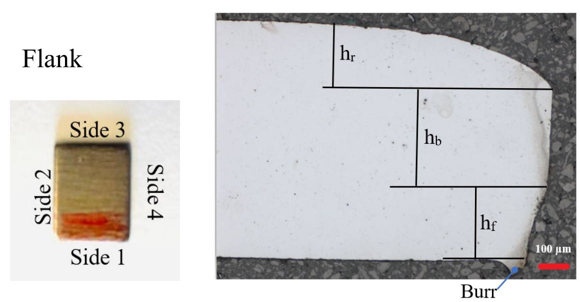

Figure 2 a): Marking on the sides of the sheared blank, b): Measurement of sheared properties according to VDI guidelines 2906.

Result and Discussions

Wear Analysis

PM8

PM8 punch is analyzed for 8% and 16% clearances to determine chipping depth, width, and edge radius changes after 9,000, 45,000, 81,000, and 108,000 strokes. Wear increases with stroke count, with more explicit chipping observed at 108,000 strokes compared to 9,000 strokes. Corner chipping is more prominent than edge chipping. For PM8 with 8% clearance, corners 1 and 2 exhibit predominant chipping, while corners 3 and 4 show minor or no chipping. Chipping starts at 45,000 strokes and gradually widens. Corner 2 has the maximum chipping depth and width after 108,000 strokes, while corner 4 shows minimal. chipping. Chipping depth and width in corner 4 after 108,000 strokes.

Fig. 3 compares corner 2, with maximum chipping, to corner 4, where there is no considerable chipping after 9,000 and 108,000 strokes, respectively. SEM images reveal cracks at punch edges (Fig. 4a), indicating an increased chipping with more strokes. Wear is mainly abrasive, with minimal galling. Fig. 4b shows a significant crack above the chipped corner that will expand with more strokes. Compared to 8% clearance, 16% clearance exhibits minimal chipping on all corners but significant wear on side 3 of the punch.

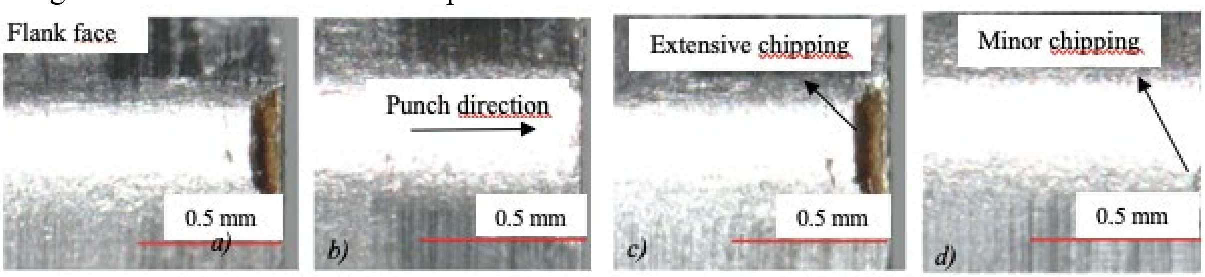

Figure 3: PM8 punch for 8 % clearance for a): Corner 2 after 45,000 strokes, b): Corner 4 after 45,000 strokes, c): Corner 2 after 108,000 strokes, d): Corner 4 after 108,000 strokes.

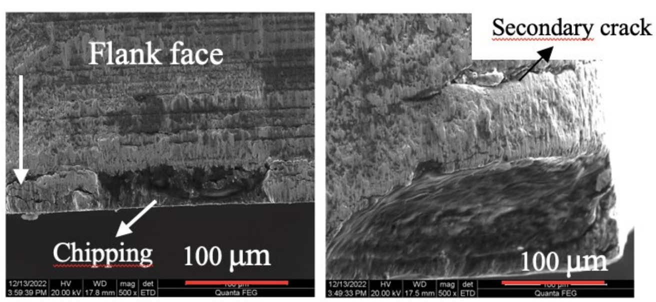

Figure 4: SEM images of PM8 for 8% clearance at the end of 108,000 strokes at the a): punch edge and b): chipped corner.

Corner 4 shows the most wear, reaching 57 µm depth and 127 µm width after 108,000 strokes. Corners 4 and 2 wear more in 45,000 strokes at 8% clearance than in 81,000 strokes. *Fig. 5* compares corners 2 and 4 at 16% clearance, with corner 2 showing the least wear (14 µm depth, 53 µm width) even after 108,000 strokes. No chipping is observed on the punch corners compared to 8%. Wear gradually increases with more strokes, with a 56.30% depth increase from 9,000 to 108,000 strokes. The width increases by 168% from 9,000 to 45,000 strokes and only 6.78% from 45,000 to 108,000 strokes, primarily at the corner tip.

Compared to 8% clearance, 16% clearance exhibits minimal chipping on all corners but significant wear on side 3 of the punch. Corner 4 shows the most wear, reaching 57 µm depth and 127 µm width after 108,000 strokes. Corners 4 and 2 wear more in 45,000 strokes at 8% clearance than in 81,000 strokes. *Fig. 6* compares the chipping depth for PM8 for the clearance values of 8% and 16%, respectively. Up to 9,000 strokes, 16% have slightly more chipping, but from 45,000 to 108,000 strokes, 8% dominate due to earlier chipping onset. and 431% for 16%, while chipping width increases by 265.93% and 323.82% for 8% and 16%, respectively.

Chipping depth increases by 1811.76% for 8%. Chipping depth remains consistent from 45,000

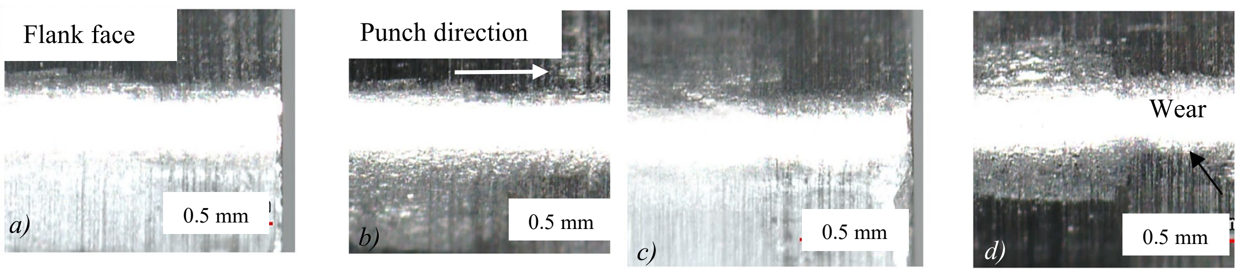

Figure 5: PM8 for 16 % clearance for a): Corner 2 after 45,000 strokes, b): corner 4 after 45,000 strokes, c): corner 2 after 108,000 strokes, d): corner 4 after 108,000 strokes.

to 108,000 strokes, with a slight 10 µm width increase, indicating wear progression with more strokes. Punch tool wear is quantified by monitoring edge radius changes for different clearances and strokes. Unlike corner chipping, edges show minimal variation. *Fig. 7a* and *Fig. 7c* compare side 1 for 8% clearance at 9,000 and 108,000 strokes, and Figure 7 b) and d) for side 4. After 9,000 strokes, sides 1 and 4 have edge values of 21.97 µm and 20.47 µm, respectively. The edge radius linearly increases with strokes, reaching 31.44 µm and 36.277 µm for sides 1 and 4 at 108,000 strokes. The average edge radius stays near 21 µm at 9,000 strokes, increasing by 10.68% to 45,000 strokes and 51.79% to 108,000 strokes, remaining consistent after 81,000 strokes. For 16% clearance, Side 3 experiences significant edge wear from 45,000 to 108,000 strokes (*Fig. 8*).

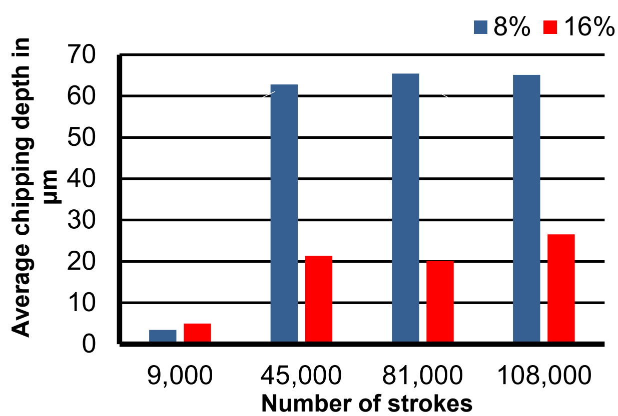

Figure 6: Comparison for PM8 between 8% and 16% clearance for chipping depth.

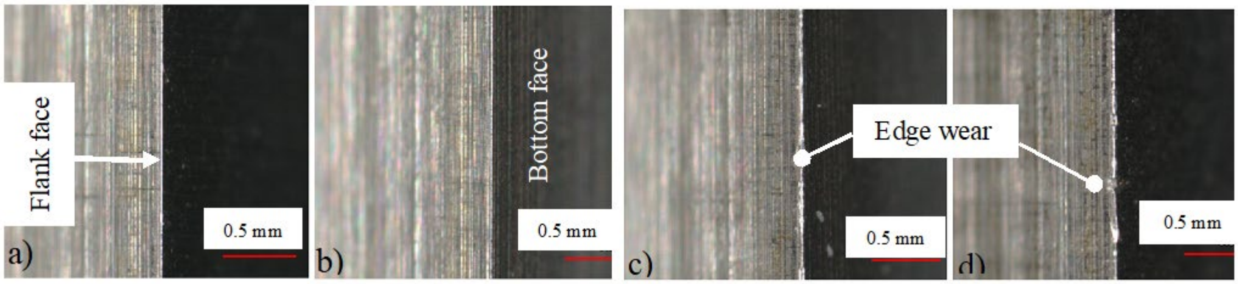

Figure 7: PM8 for 8 % clearance for a): side 1 after 9,000 strokes, b): side 4 after 9,000 strokes, c): side 1 after 108,000 strokes, d): side 4 after 108,000 strokes.

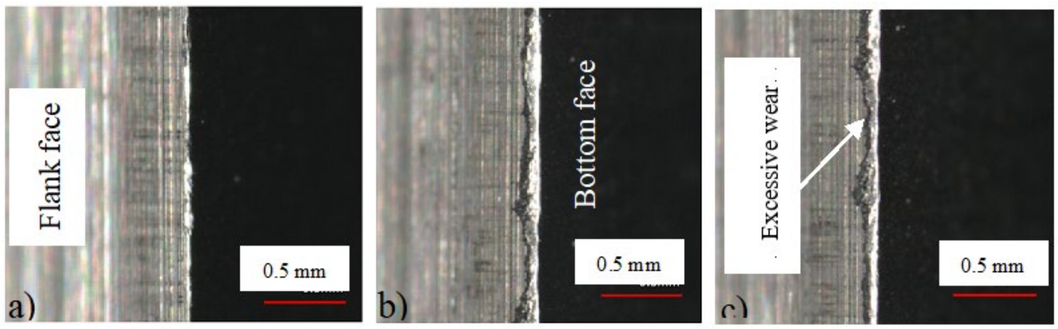

Figure 8: Punch side 3 of PM8 for 16 % clearance after a): 9,000 strokes, b): 45,000 strokes, c): 108,000 strokes.

At 9,000 strokes, minimal wear keeps the corner edge intact, but wear blunts the corner, increasing its radius with more strokes. *Fig. 9* displays the average edge radius for all sides, with Side 3's excessive wear causing significant variation. The average edge radius increases by 46% from 9,000 to 45,000 strokes and by 115% to 108,000 strokes, reaching a peak of around 56 µm.

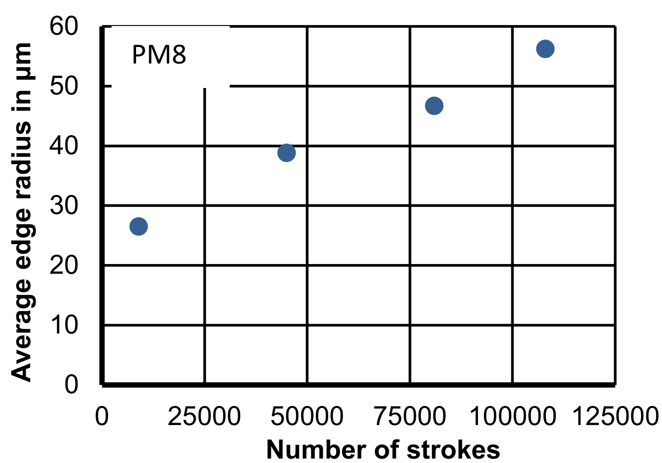

Figure 9: Average edge radius of PM8 for 16% clearance for different numbers of strokes.

PM10

PM10 is examined for chipping and corner wear at various clearances and stroke counts. At 8% clearance, extensive chipping is evident across all corners of the punch. Corner 4 experiences comparatively less chipping than corners 1 and 2. Corner 1 shows substantial chipping at 108,000 strokes, with an average chipping depth and width of 1009.5 µm and 275.21 µm, respectively. Chipping initiates at 45,000 strokes, gradually increasing to 81,000 strokes before peaking at 108,000 strokes. After 45,000 and 81,000 strokes, the chipping depth is approximately 52.83 µm and 77.59 µm, while the chipping width remains around 68 µm. A visible crack appears after 81,000 strokes, indicating further width extension. Unlike PM8, PM10 experiences significant chipping at all corners for an 8% clearance, with corners 1 and 2 particularly impacted. PM10, unlike PM8, exhibits chipping at a 16% clearance. The maximum chipping occurs at corners 1 and 2, while corners 3 and 4 remain minimally affected. Chipping width is crucial, showing a significant increase, indicating the expanded chipping area on the punch surface. For a 16% clearance, the average chipping depth peaks at 110.02 µm after 45,000 strokes, a 3348% increase from 9,000 strokes, remaining constant at 108,000 strokes. Average chipping width increases by 350% between 9,000 and 45,000 strokes, gradually expanding with stroke count. Both chipping depth and width experience substantial increases of 3254% and 436% from 9,000 to 108,000 strokes.

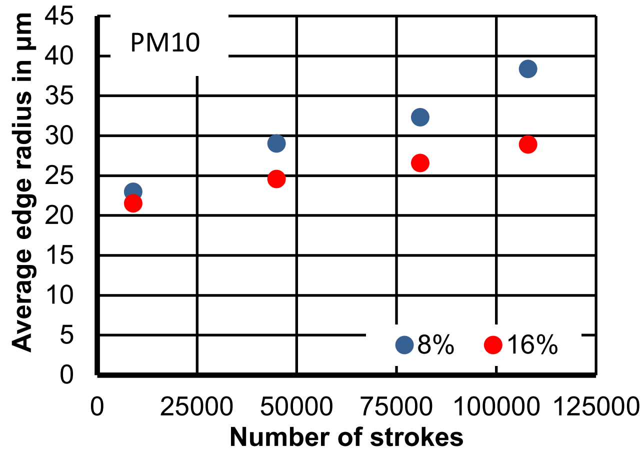

Figure 10: Comparison of average edge radius for PM10 material for two different clearances across different punch strokes.

Regarding edge wear, PM10 behaves consistently across all punch sides, unlike PM8, which displays variation. Wear is slightly higher, with 8% clearance compared to 16%. At 8% clearance, side 2 exhibits higher wear at 108,000 strokes with an edge radius of 42 µm, while other sides average around 37 µm. Similarly, at 16% clearance, side 2 shows less wear with an edge radius under 22 µm, around 10 µm less than the other sides. *Fig. 10* illustrates the average edge radius for 8% and 16% clearances, with 8% consistently outperforming 16%.

PM1

PM1, like PM8 and PM10, was examined for chipping and edge radius changes with increasing strokes. Chipping was minimal until 108,000 strokes, primarily occurring at corner 2 with maximum depth and width of 19 µm and 58 µm after 9,000 strokes. Widespread chipping began at 45,000 strokes, with a depth and width of 528 µm and 160 µm. Chipping depth remained consistent, but width increased to around 172 µm at 108,000 strokes.

Other corners had minor wear, increasing the chipping width slightly. Corners 1 and 4 had average chipping widths of 32 µm and 21 µm, respectively. PM1 outperformed other materials in wear resistance. *Fig. 11* compares average edge radius values for 8% and 16% for two clearances. Notably, the 8% clearance exhibits a linear increase in edge radius with stroke count, while the 16% clearance maintains a stable value until 81,000 strokes before rising to approximately 29 µm at 108,000 strokes. The 8% and 16% clearances differ by around 12 µm at 81,000 strokes and about 6 µm at 45,000 and 108,000 strokes. Minimal variations exist between punch sides, with a maximum difference of 4-5 µm. Side 3 influences the edge radius more at 45,000 strokes, and side 1 exhibits less wear. This trend is consistent for both clearances, with side 4 dominating the edge radius at 8% clearance. Overall, the average edge radius increases by 42% and 46% between 9,000 and 108,000 strokes for 8% and 16% clearances.

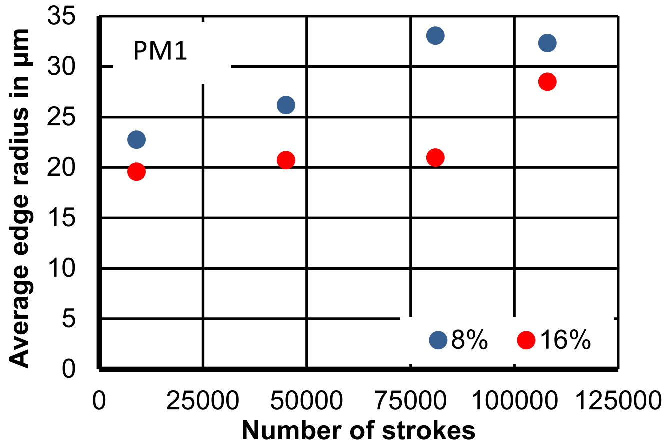

Figure 11: Comparison of average edge radius for PM1 material for two clearances across different punch strokes.

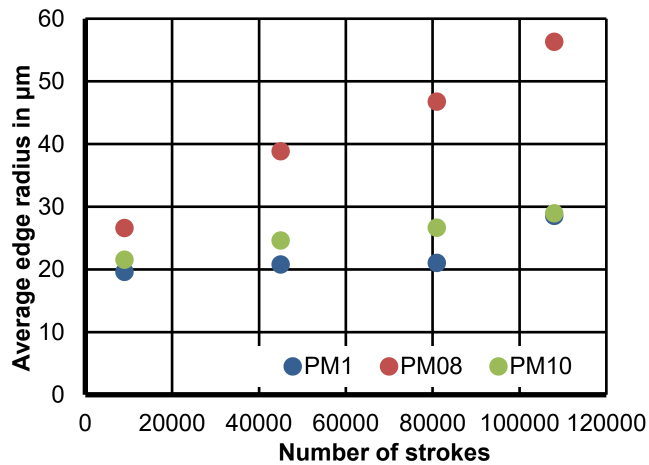

Figure 12: Edge radius comparison for 16% clearance between different punch materials across various strokes.

In terms of edge radius, side 3 increased from 18 µm to 28 µm (16% clearance) or 33 µm (8% clearance) after 9,000 strokes, with slightly more wear at 8% clearance. PM8 demonstrates minimal chipping at an 8% clearance, with a depth of approximately 65 µm after 108,000 strokes. Initially, PM10 surpasses PM1, but by 108,000 strokes, PM10 experiences extensive chipping. At a 16% clearance, PM8 and PM1 exhibit minimal wear, with PM1 showing superior chipping and wear resistance among the materials. Regarding edge wear, PM1 demonstrates superior wear resistance over PM8 and PM10 (*Fig. 12*). After 9,000 strokes, their edge radius measures 21 µm, increasing to 33 µm, 38 µm, and 32 µm after 108,000 strokes. At 8% clearance, PM8 shows 6 µm more wear than PM1 and PM10. However, at 16% clearance, both PM1 and PM10 exhibit minimal wear with a final edge radius of 28 µm, while PM8's side 3 experiences extensive wear, increasing the edge radius to 56 µm after 108,000 strokes.

Sheared Edge Analysis

PM8

The PM8 sheared edge properties were investigated with 8% and 16% clearance values, focusing on burr height as a crucial indicator of blank quality. For PM8 with an 8% clearance, burr height remained below 2% of thickness until 108,000 strokes. Sheared characteristics had a limited impact on stroke numbers compared to varied clearances [8]. **Fig. 13** displays the average values of rollover (h_r), burnish zone (h_b), fracture zone (h_f), and burr height for PM8 with 8% clearance across different stroke counts. Rollover increased by roughly 3% of sheet thickness over 108,000 strokes.

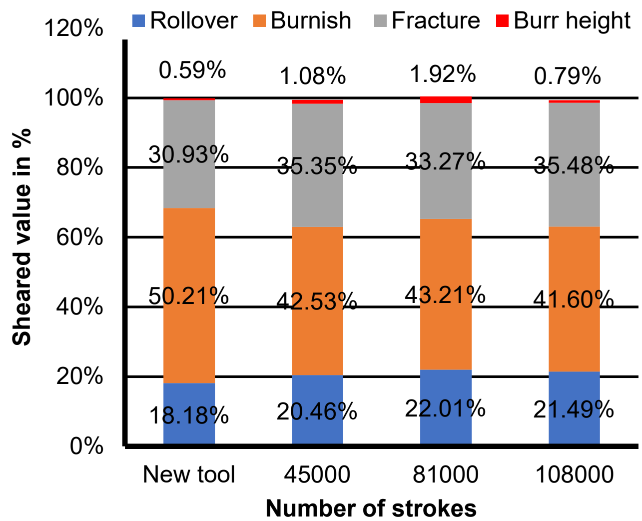

Figure 13: Sheared edge properties of PM8 for 8% clearance for different strokes.

In contrast, with 16% clearance, burr height exceeded 4% of sheet thickness and reached nearly 8% at 45,000 strokes. The increase in h_r was substantial, around 13%, from the initial state to 108,000 strokes for 16% clearance. Similarly, h_b decreased with more strokes, from 42% to 32.33% at 108,000 strokes.

PM10

PM10 exhibits more stable sheared properties than PM8 with varying stroke numbers. The rollover region remains consistent at approximately 22% of sheet thickness up to 108,000 strokes. This pattern holds for both burnish and fracture zones, at around 42% and 36%, respectively. Burr height varies slightly as strokes increase, rising from 1% to 2.5% for 8% clearance, likely due to chipping. In contrast, the 16% clearance maintains nearly constant burr height across strokes, with only slight changes at 45,000 strokes, as illustrated in *Fig. 14.*

PM1

The material PM1 exhibits more significant burr formation at 8% clearance compared to PM8 and PM10. Throughout all punch strokes, a notable burr forms, averaging about 1.5% of the sheet thickness. The fracture zone expands from 33% to around 39% of the sheet thickness at 108,000 strokes, while the burnish zone remains at approximately 40%. Initially, at 42%, the burnish zone reduces to around 39%. At 108,000 strokes, deviation increases notably, reaching 8.31% for burnish and 6.33% for the fracture zone. Burr formation is evident only at 8% clearance in PM1, absent in other materials. At 16% clearance, burr height further increases to over 5% of the sheet thickness. PM1 shows a higher deviation between its sides than other materials, impacting properties like h_b and h_r. *Fig. 15* illustrates PM1's predominant burr formation at 16% clearance compared to 8%, with an average difference of around 4% across all strokes, displaying minimal variation in burr height.

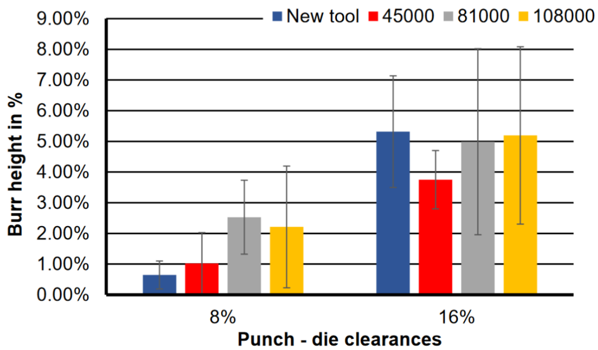

Figure 14: Burr height comparison of PM10 material for 8% and 16% clearance across different punch strokes.

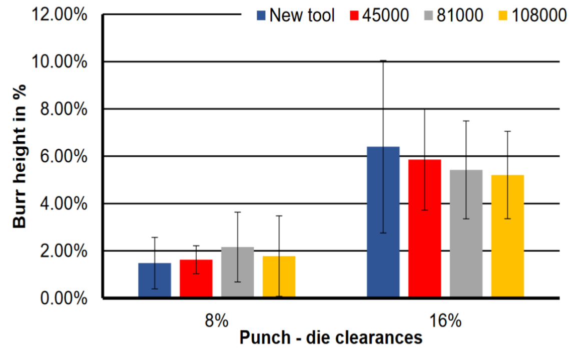

Figure 15: Burr height comparison of PM1 material for 8% and 16% clearance across different punch strokes.

Conclusion

This study investigated electrical steel blanking with PM1, PM8, and PM10 punch materials, yielding the following formal findings:

1. At an 8% clearance, all materials experienced chipping, with PM1 demonstrating superior chipping resistance. PM10 exhibited chipping at all corners, while PM8 displayed variable chipping effects.
2. At a 16% clearance, PM1 and PM8 showed no chipping, whereas PM8 exhibited minor corner wear, and PM10 chipped at corners 1 and 2.
3. Tool wear, assessed through edge radius, was most pronounced in PM10, followed by PM8 and PM1 at 8% clearance. However, PM8 outperformed the others at 16% clearance.
4. The Sheared edge analysis found varying burr heights for different materials and clearances. At 8% clearance, all punch materials had burr heights below 2.5% of sheet thickness, with PM1 slightly higher. At 16% clearance, all materials exceeded 5% burr height, with PM8 having the most due to side 3 wear. Side 4 had higher burr at 16% clearance, increasing standard deviation compared to 8%

The analysis of tool wear and sheared properties shows that different corners of the punch and blank sides behave differently for both clearance values. Chipping at the punch corners is more predominant in 8% clearance than in 16%. Both corners at the front face are prone to chipping compared to the other corners. In terms of blank, side 4 has a higher burr and side 1 has a comparatively lesser burr blank side could be due to the misalignment between the punch and die, which causes unequal clearances on four sides.

Acknowledgment and disclaimers

NH, TC and AET appreciate funding provided to TU Dortmund by Uddeholms AB for this study. PS is thankful for the funding of his M.Sc. thesis related to the work. The authors used the software Grammarly for language polishing.

References

[1] K. Lange (1986) Handbook of metal forming. McGraw-Hill, New York

[2] S. Golovashchenko, W. Zhou, S. Nasheralahkami, N. Wang, 2017. Trimming and Sheared Edge Stretchability of Light Weight Sheet Metal Blanks. Procedia Eng 207, 1552–1557. https://doi.org/10.1016/j.proeng.2017.10.1077

[3] W. Klingenberg, & T.W. de Boer, (2008). Condition-based maintenance in punching/blanking of sheet metal. International Journal of Machine Tools and Manufacture, 48(5), 589–598. https://doi.org/10.1016/J.IJMACHTOOLS.2007.08.013

[4] S. Luo, Effect of the geometry and the surface treatment of punching tools on the tool life and wear conditions in the piercing of thick steel plate. Journal of Materials Processing Technology, (1999), 122-133, 88(1-3). https://doi.org/10.1016/S0924-0136(98)00375-6

[5] S. Fortunati, S. Cicalè, J. Schneider, A. Franke, R. Kawalla, 2016. Developments in the Field of Electrical Steels over the Last Years.

[6] J. Mucha, 2010. An experimental analysis of effects of various material tool's wear on burr during generator sheets blanking. The International Journal of Advanced Manufacturing Technology 50, 495–507. https://doi.org/10.1007/s00170-010- 2554-1

[7] S. Vogt, F. Neumayer, I. Serkyov, G. Jesner, R. Kelsch, M. Geile, A. Sommer, R. Golle, W. Volk, 2017. Experimental evaluation of tool wear throughout a continuous stroke blanking process of quenched 22MnB5 ultra-high-strength steel. J Phys Conf Ser 896, 012057. https://doi.org/10.1088/1742-6596/896/1/012057

[8] H. Makich, L. Carpentier, G. Monteil, X. Roizard, J. Chambert, P. Picart, 2008. Metrology of the burr amount - correlation with blanking operation parameters (blanked material – wear of the punch). International Journal of Material Forming 1, 1243–1246. https://doi.org/10.1007/s12289-008-0167-0

[9] J. Mucha, J. Tutak, 2019. Analysis of the Influence of Blanking Clearance on the Wear of the Punch, the Change of the Burr Size, and the Geometry of the Hook Blanked in the Hardened Steel Sheet. Materials 12, 1261. https://doi.org/10.3390/ma12081261

[10] R. Wiedenmann, P. Sartkulvanich, and T. Altan, "Finite element analysis on the effect of sheared edge quality in blanking upon hole expansion of advanced high strength steel," International Deep Drawing Research Group (IDDRG) Conference, 2009, Golden, CO, USA.

[11] D. Ammar, 2019. PhD thesis. Characterization of blanking induced magneto-mechanical cut edge defects in non-oriented electrical steel. The University of Sheffield

[12] H.A. Weiss, N. Leuning, S. Steentjes, K. Hameyer, T. Andorfer, S. Jenner, W. Volk, 2017. Influence of shear cutting parameters on the electromagnetic properties of non-oriented electrical steel sheets. J Magn Magn Mater 421, 250–259. https://doi.org/10.1016/j.jmmm.2016.08.002