

EFFECT OF CARBURISATION PROCESS ON THE WEAR OF STEEL

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DECLARATION

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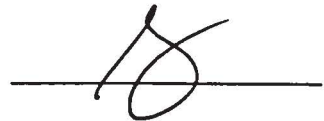
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ABSTRACT

Electro-carburisation process based on liquid carburisation process had been carried out to investigate the effect of the carburization process on the resulting hardness, microstructure change, and the sliding wear resistance of mild steel under dry and lubrication conditions. The carburisation process was conducted in carbonate salts mixtures of Na_2CO_3 -NaCl. The electro-carburisation process was first performed and followed by post-carburisation cleaning where subsequent analysis such as hardness test, metallographic observation, EDX/SEM and XRD were then carried out in order to investigate the effect of the carburisation process on the mild steel. Carburisation process resulted in a remarkedable increase in the hardness leading to an enhancement of adhesive and abrasive wear resistance, as well as load carrying capacity. Increasing the duration of the carburisation process from 1 hour to 3 hours resulted in higher peak hardness (727 HV/795 HV), greater case depth (50-100 μm /660 μm), higher amount of carbide in the grain boundaries and larger retained austenite grains. The surface of the carburised steel was dominated by retained austenite. Towards the core, the amount of retained austenite reduced while the amount of martensite increased. The austenite microstructure in the steel carburised for 1 hour exhibited higher cracking and fracture resistance as compared to the steel carburised for 3 hours. The low cracking and fracture resistance of the steel carburised for 3 hours could be due to its large grain size and high amount of cementite in the grain boundaries as the fatigue strength reduced with an increase in the grain size and the presence cementite could act as fatigue crack initiators. The superior wear resistance of the martensite, as compared to the austenite, could be attributed to its high cracking and adhesive wear resistance owing to its high hardness and tendency to form oxide. The friction was governed by the wear mechanism and the type of microstructure at the worn scar sliding on the carbide ball. It was found that surface fracture and sliding on martensite resulted in higher friction coefficient. The superior wear resistance and load carrying capacity of the carburised steel was also evident under oil lubrication condition. Compared to the austenite, the martensite showed higher tendency to react with the carbon in the oil under extreme boundary lubrication which in turn resulted in a significant drop in the friction coefficient after the running in process.

ABSTRAK

EFFECT OF CARBURISATION PROCESS ON THE WEAR OF STEEL (KESAN PROSES PENGKARBONAN KE ATAS KEHAUSAN KELULI)

Proses 'electro-carburisation' berdasarkan proses pengkarbonan cecair telah dijalankan untuk mengkaji kesan daripada proses pengkarbonan pada kekerasan yang terhasil, perubahan mikrostruktur, dan rintangan haus gelongsor keluli lembut di bawah keadaan kering dan pelinciran. Proses pengkarbonan telah dijalankan dengan menggunakan campuran garam karbonat $\text{Na}_2\text{CO}_3\text{-NaCl}$. Proses 'elektro-carburisation' dilakukan terlebih dahulu diikuti dengan pembersihan ke atas spesimen yang telah menjalani proses pengkarbonan. Analisis berikutnya seperti ujian kekerasan, pemerhatian 'metallographic', EDX / SEM dan XRD kemudiannya dijalankan untuk menyiasat kesan proses pengkarbonan pada keluli karbon rendah. Proses pengkarbonan menyebabkan peningkatan kekerasan yang ketara yang membawa kepada peningkatan rintangan kehausan las dan perekat serta beban bawaan yang lebih tinggi. Meningkatkan masa proses pengkarbonan dari 1 jam hingga 3 jam menghasilkan kekerasan puncak yang lebih tinggi (727 HV / 795 HV), salutan yang lebih mendalam (50-100 μm / 660 μm), jumlah karbida yang lebih tinggi di sempadan bijian dan bijirin austenit yang lebih besar. Permukaan keluli yang menjalani proses pengkarbonan dikuasai oleh austenit tersimpan. Ke arah teras, jumlah austenit tersimpan semakin berkurangan manakala jumlah martensit meningkat. Mikrostruktur austenit dalam keluli yang telah dikarbonkan selama 1 jam mempamerkan rintangan keretakan dan patah yang lebih tinggi berbanding dengan keluli yang telah dikarbonkan selama 3 jam. Rintangan keretakan dan patah yang rendah oleh keluli yang dikarbonkan untuk 3 jam berkemungkinan disebabkan oleh saiz butiran yang besar dan jumlah sementit yang tinggi di sempadan bijian menyebabkan kekuatan lesu berkurangan yang mana peningkatan dalam saiz butiran dan kehadiran sementit boleh bertindak sebagai pemula retak-lesu. Rintangan haus martensit yang lebih tinggi berbanding austenit boleh dikaitkan dengan rintangan keretakan dan perekat yang lebih tinggi disebabkan oleh kekerasan yang tinggi dan kecenderungan untuk membentuk oksida. Geseran telah dikawal oleh mekanisme kehausan dan jenis mikrostruktur yang terdapat di parut kehausan di mana bola karbida menggelongsor di atasnya. Didapati bahawa keretakan permukaan dan menggelongsor di atas martensit menyebabkan pekali geseran yang lebih tinggi. Kapasiti rintangan haus yang lebih tinggi dan beban bawaan keluli yang dikarbonkan juga dapat dilihat di bawah kehadiran minyak pelincir. Berbanding dengan austenit, martensit menunjukkan kecenderungan lebih tinggi untuk bertindak balas dengan karbon dalam minyak di bawah pelinciran sempadan melampau yang seterusnya mengakibatkan penurunan ketara dalam pekali geseran selepas berjalan dalam proses.

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LIST OF ABBREVIATIONS

| | |
|-------------------------------------|--|
| ASTM | - American society for testing and materials |
| BCC | - Body centred cubic |
| BCT | - Body centred tetragonal |
| CCT | - Continuous cooling transformation |
| C1 | - 1 hour carburised |
| C3 | - 3 hour carburised |
| CO | - Carbon monoxide |
| CO₂ | - Carbon dioxide |
| COF | - Coefficient of friction |
| DPH | - Diamond pyramid hardness |
| EDX/EDS | - Energy-dispersive X-ray spectroscopy |
| EHL | - Elasto hydrodynamic |
| FCC | - Face centred cubic |
| HD | - Hydrodynamic |
| HRC | - Rockwell hardness |
| HTTP | - High temperature transformation product |
| HV | - Vickers hardness |
| H₂O | - Water |
| ICDD | - International Centre for Diffraction Data |
| IT | - Isothermal transformation |
| KCl | - Potassium chloride |
| LTCSS | - Low temperature colossal supersaturation |
| M1 | - 1 hour martensite |
| M3 | - 3 hour martensite |
| Na₂CO₃ | - Sodium carbonate |
| NaCl | - Sodium chloride |
| NC | - Non carburised |
| SEM | - Scanning electron microscope |
| XRD | - X-ray diffraction |
| ZDDP | - Zinc-dialkyl-dithiophosphate |

LIST OF SYMBOLS

| | |
|---------------------------------|---------------------|
| % | - percentage |
| +ve | - positive |
| -ve | - negative |
| A | - ampere |
| C | - carbon |
| Cr | - Chromium |
| Cu | - Copper |
| E | - electron |
| Fe | - iron |
| H | - height |
| Hr | - hour |
| In | - inches |
| ml | - millilitre |
| mm | - millimetr |
| Mn | - Manganese |
| Mo | - Molybdenum |
| η | - viscosity |
| N | - Newton |
| Na | - Sodium |
| Ni | - Nickel |
| O | - Oxygen |
| R_a | - Average roughness |
| Si | - Silicone |
| Ti | - Titanium |
| V | - volt |
| V | - Velocity |
| μm | - micrometer |
| ° | - degrees |
| °C | - Degrees celcius |

LIST OF EQUATIONS

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REFERENCES

- Abdul Azis, S. A., Jauhari, I., & Ahamad, N. W. (2012). Improving Surface Properties And Wear Behaviors Of Duplex Stainless Steel Via Pressure Carburizing. *Surface & Coatings Technology*, **210**: pp 142-150.
- Abouei, V., Saghafian, H., & Kheirandish, S. (2007). Effect Of Microstructure On The Oxidative Wear Behaviour Of Plain Carbon Steel. *Wear*, **262**: pp 1225-1231.
- Ahmed, N. S., & M. Nassar, A. (2013). Lubrication and Lubricants. In J. Gegner, *Tribology - Fundamentals and Advancements* (pp. 55-76). InTech.
- Aondona, L. (2013). Variation Of Effective Case Depth With Holding Time Of Mild Steel Using Various Carburising Compounds. *International Journal of Metal and Steel Research Technology*, PP: 12 -18.
- B Zhu, G. K. (2004). Frictional Behaviour And Wear Performance Of Nitrocarburised Coating Sliding Against Aisi 1019 Steel. *Material Forums Vol 27*, 54-61.
- Bayer, R. G. (2004). *Mechanical Wear Fundamentals And Testing*. New York: Marcel Dekker.
- Bensely, A., Prabhakaran, A., Lal, M., & Nagarajan, G. (2006). Enhancing The Wear Resistance Of Case Carburised Steel (EN 353) By Cryogenic Treatment. *Cryogenics*, **45**: 747-754.
- Bera, B. (2013). Adhesional Friction Theory of Micromechanical Surface Contact. *IOSR Journal of Engineering*, **3**: 38-44.
- Bermúdez, M.D. (2009). Influence Of Sliding Frequency On Reciprocating Wear Of Mold Steel With Different Microstructures. *Wear*, 1784–1790.
- Bhusan, B. (2013). *Introduction to tribology*. Ohio, USA: Wiley.
- Blau, P. J. (1997). Fifty Year Of Research On The Wear Of Metals. *Tribology International*, 321-331.
- Brandes, E., & Brook, G. (1992). *Smithells Metal Reference Handbook 7th Edition*. Oxford: Butterworth-Heinemann.

- Buitkus, T. J. (1967). *Patent No. 3,331,708*. U.S.
- Cao,Y. (2003). Colossal Carbon Supersaturation In Austenitic Stainless Steel Scarburized At Low Temperature. *Acta Materilia* , **51**: 4171–4181.
- Callister, W. D. (2007). *Material Science And Engineering : An Introduction*. New York: John wiley & sons.
- Chatterjee, S., & Bhadeshia, H. K. (2006). TRIP-Assisted Steels: Cracking Of High-Carbon Martensite. *Materials Science and Technology* , VOL **22** NO 6 ; 645-649.
- Chen,G.X., Z. Z. (2001). Study On Transition Between Fretting And Reciprocating Sliding Wear. *Wear* , 665-672.
- Davim, J. P. (2010). *Surface Integrity In Machining*. Springer.
- Davis, J. (2002). *Surface Hardening Of Steels: Understanding The Basics*. ASM International.
- El- Ela, M. K., Ezzat, F. M., El-Gawwad, K., & Salem, M. (2013). Effect Of Lubricant Contaminants On Tribologicalcharacteristics During Boundary Lubrication Of Reciprocating Sliding. *Minia Journal of Engineering and Technology* , **32** : 90-102.
- Errichello, R. (2012). *Morphology Of Microptting*. Geartechnology.
- Gahr, K. Z. (1998). Wear By Hard Particle. *Tribology International* , **10**:587-596.
- Giordani,T. , T. R. (2013). Mechanical And Metallurgical Evaluation Of Carburized, Conventionally And Intensively Quenched Steels. *Journal of Materials Engineering and Performance* .
- Goldstein, J., & Moren, A. (1978). Diffusion Modeling Of The Carburization Process. *Metallurgical Transactions A* , Volume **9**, Issue 11 , pp 1515-1525.
- Hirst,W. & Archard, J. F. (1956). The Wear Of Metals Under Unlubricated Conditions. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical* (pp. vol **236**: pp. 397-410). The Royal Society.
- Hisakado, T. (1974). Effect Of Surface Roughness On Contact Between Solid Surfaces. *wear* , 217-234.

Hiyama, S. (1975). *Patent No. 3,876,512*. U.S.A.

Holzhauser, W., & Calabrese, S. J. (1968). Steel Hardness Effects in Boundary Lubricated Sliding: An In-Situ SEM Study. *ASME/STLE Tribology Conference in Baltimore, Maryland, October 16-19, 1968*. Maryland, USA.

Hosseini, S. R. (2012). Simulation Of Case Depth Of Cementation Steels According To Fick's Laws. *Journal of iron and steel research, international* , 71-78.

Hurricks, P. (1970). The Mechanism of fretting-A review. *wear* .

Izciler, M., & Tabur, M. (2006). Abrasive Wear Behavior Of Different Case Depth Gas Carburized AISI 8620 Gear Steel. *Wear* , 90-98.

J. Adamczyk, A. G. (2007). Heat Treatment And Mechanical Properties Of Low Carbon Steel With Dual Phase Microstructure. *Achievements in Materials and Manufacturing Engineering* .

Jones, W., Britt, K., & Newell, I. (1985). *Patent No. European Patent No 0147011*. Europe.

Kim, H.-J., & Kweon, Y.-G. (1996). The Effect Of Retained Austenite On Dry Sliding Wear Behaviour Of Carburised Steel. *Wear* , 8-15.

Krauss, G. (1999). Martensite In Steel: Strength And Structure. *Materials Science and Engineering A* , 40-57.

Krauss, G. (1995, 7). Microstructure And Performance Of Carburised Steel Part II: Austenite. *Advance Material And Processes* , pp. 48U-48Y.

L Ceschini, C. C. (2013). Influence Of The Countermaterial On The Dry Sliding Friction And Wear Behaviour Of Low Temperature Carburised AISI316L Steel. *Tribology International* , 36-43.

Liew, W. (2006). Effect Of Relative Humidity On The Unlubricated Wear Of Metals. *Wear* , **260**: 720-727.

Mehrer, H. (2007). *Diffusion In Solid : Fundamentals, Methods, Materials, Diffusion-Controlled Process*. Munster: Springer.

- Michael J Schneider, T. T. (2013). *ASM Handbook Volume 4A*. ASM: ASM International.
- Moniz, B. (2007). *Metallurgy*. American Technical Publisher.
- Moore, M. (1970). A Preliminary Investigation Of Frictional Heating During Abrasive Wear. *Wear* , 51-58.
- Mustafa Ulutan, O. N. (2010). Effect Of Different Surface Treatment Method On The Frinction And Wear Behaviour Of AISI 4140 Steel. *Journal of Material Science Technology* , 251-257.
- Nakanishi T, (1980). *Influences Of Diffence In Hardness And Roughness Of Surface Durability*. JSME.
- Nishiyama, Z. (2012). Introduction To Martensite And Martensitic Transformation. In Z. Nishiyama, *Martensitic Transformation*. Elsevier.
- Nunes, R. M. (1991). *ASM Handbook Vol 4 : Heat Treating*. ASM International.
- Nwoke, V., E.E, N., & Odo, J. O. (2014). Effect Of Process Variables On The Mechanical Properties Of Surface Hardened Mild Steel Quenched In Different Media. *International Journal Of Scientific &Technology Research*
- Pandaa,Rashmi Ranjan A. M. (2014). Mechanical and Wear Properties of Carburized Low Carbon Steel Samples. *International Journal of Multidisciplinary and Current Research* .
- Parrish, G. (1999). *Carburising Microstructure and Properties*. ASM International.
- Paul, A. (1990). *Chemistry of glasses*. New York: Chapman and Hall.
- Place, W. P. (1951). *Atlas Of Isothermal Transformation Diagram*. Pittssburgh: United States Steel Corporation.
- Qu,J., J. J. (2006). An Efficient Method For Accurately Detemining Wear Volumes Of Sliders With Non-Flat Wear Scars And Compound Curvatures. *Wear* , 848-855.
- Qu, J., Meyer, H. M., Blau, P. J., & Bruce, G. B. (2011). Low-Temperature Colossal Carbon Supersaturation Enables Anti-Wear Boundary Film Formation For Austenitic Stainless Steels In Oil-Lubricated Environment. *Wear* , 17-33.

- Quinn, T. (1983). Review Of Oxidational Wear Part I: The Origins Of Oxidational. *Tribology International* , 257-271.
- Rabinowicz, M. A. (1965). Effect Of Abrasive Particle Size On Wear. *Wear* , 381-390.
- Rao, P. (1998). *Manufacturing Technology*. Tata McGraw Hill.
- Rosenberg, S. J. (1931). The Resistance To Wear Of Carbon Steel. *Bureau Of Standards Journal Of Research* .
- Rosenberg, T. G. (1960). *Heat Treatment and Properties of Iron and Steel*. Washington: National Bureau of Standards Monograph 18.
- S. Morito, H. T. (2003). The Morphology And Crystallography Of Lath Martensite In Fe-C Alloys. *Acta Materialia* , 1789–1799.
- SAE-J423. (1998). Methods Of Measuring Case Depth. SAE International.
- Sagaradze, L. M. (1966). Influence Of Decarburisation On The Properties Of Case Hardened Steel. *Metal Science and Heat Treatment* , **8**: pp 560-563 .
- Samuel, L. E. (1999). *Light Microscopy Of Carbon Steel*. ASM International.
- Scherge, M., Shakhvorostov, D., & Pöhlmann, K. (2003). Fundamental Wear Mechanism Of Metals. *Wear* , **255**: pp 395–400.
- Schneider, M. J., Company, T. T., & Chatterjee, M. S. (2013). Introduction To Surface Hardening Of Steels. In J. Dossett, & G. Totten, *ASM Handbook, Volume 4A, Steel Heat Treating Fundamentals and Processes* (pp. 389-398). ASM International.
- Schulz-Beenen, A. (1997). Martensite In Steel: Its Significance, Recent Developement And Trends. *Journal Physics IV France* .
- Sebald, R., & Heller, T. (2009). Development Trends In Advanced High-Strength Steels. *ThyssenKrupp techforum* , pp. **1**; 22-27.
- Siambun, N.J., Liew, ,Y.W., & Chen, G. Z. (2012). The Effect of Cooling Rate in Molten Salt Electro-Carburisation Process. *Advanced Materials Research* , pp 264-267.

- Siambun, N. J. (2011). *Electrolysis Of Molten Carbonate Salt And Its Application*. The University of Nottingham: PHD Thesis.
- Siepak, J. (1982). The Influence Of Contact Stress On The Wear Of A Carburised Steel Case With High Content Of Retained Austenite. *Wear* , 301-305.
- Stachowiak, A. W. (2005). *Engineering Tribology*. Butterworth Heinemann.
- Stolarski, T.A. (1979). Adhesive Wear Of Lubricated Contacts. *Tribology International* , 169-179.
- Stott, F. (1998). The Role Of Oxidation In The Wear Of Alloys. *Tribology International* , 31 : pp 61-71.
- Suh, N. P. (1973). The Delamination Theory Of Wear. *Wear* , **25**: pp111-124.
- Suh, N. P., & Sridharan, P. (1975). Relationship Between The Coefficient Of Friction And Wear Of Metal. *Wear* , **34** : 291-299.
- Tomkins, G. J. (1983). *Molten salts volume 5 part 2*. new jersey.
- Totten G.E., M. N. (2002). Failures Related To Heat Treating Operation. In *ASM Handbook Volume 11, Failure Analysis and Prevention* (pp. 192 - 223 (32)). ASM International.
- Totten, L. D. (2004, August). Eliminate Quench Cracking With Uniform Agitation. *Heat Treating Progress* .
- Truhan, J. J., Qu, J., & Blau, P. J. (2005). The Effect Of Lubricating Oil Condition On The Friction And Wear Of Piston Ring And Cylinder Liner Materials In A Reciprocating Bench Test. *Wear* , **259**: pp1048-1055.
- Vander Voort, G. M. (2009). Microstructural Characterisation Of Carburised Steel.
- William C. Jones, K. R. (1986). *Patent No. 4,591,397*. USA.
- Williams, J. A. (2005). Wear And Wear Particles—Some Fundamentals. *Tribology International* , 863-870.

- Wise, J.P. & Matlock G. K. (2000). Microstructure and Fatigue Resistance of Carburised Steel. *ASM Heat Treating Society Conference Proceeding*. St Louis: ASM International.
- Xianglong Yu, Z. J. (2013). Tribological Properties Of Magnetite Precipitate From Oxide Scale In Hot-Rolled Microalloyed Steel. *Wear*, 302: 1286–1294.
- Yu, M.T. (1988). The Effect Of Microstructure On The Mechanical Behaviour Of A Low Carbon, Low Alloy Steel. *International Journal Fatigue*, 249-255.
- Zhang, P., Zhang, F., Yan, Z., Wang, T., & Qian, L. (2011). Wear Property Of Low-Temperature Bainite In The Surface Layer Of A Carburized Low Carbon Steel. *Wear*, 697–704.
- Zmitrowicz, A. (2006). Wear Patterns And Law Of Wear - A Review. *Journal Of Theoretical And Applied Mechanics*, 219-253.
- Zou, Q., Huang, P., & When, S. (1996). Abrasive Wear Model For Lubricated Sliding Contacts. *Wear*, **196**: 72-76.