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Enhancing Durability of Hot Work Tool Steel by Duplex Treatments: A Review

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Abstract - **The abrasive wear unitedly with thermo-mechanical fatigue and plastic deformation is a critical factor of the process of failure of forging dies during the forging of components with close tolerances and not subject to further mechanical treatment. The failure rate of forging dies are also greatly influenced by the variety of the shapes of the forging and the precision with which these are made. The effective way to improve the durability of forging dies is a modification of surface properties by the constitution of layers or coatings having appropriate properties. Among huge available techniques; Plasma nitriding along with suitable coating formed by physical vapor deposition (PVD) technique; commonly known as Duplex/Hybrid treatment; is widely used, allows control of surface microstructure, enhance wear resistance, corrosion resistance and fatigue resistance. This had been noted that Duplex Treatment can increase the wear resistance of the tool/die up to 30%. The tribological behaviours of duplex treated dies in hot forging are reviewed and presented here. Some commonly used surface treatments as well as coatings in hot forging dies are given. Eventually, experimental results obtained by various researchers could be used in theory and model developments for hot forging process and die materials at high temperatures. The review also showed the great potential in further investigations in tribology.**
Keywords: **Die Failure, Duplex Treatment, Plasma Nitriding, PVD Coatings.**

I.INTRODUCTION

In some technology applications, there are a wide range of components which necessitate special surface properties, specified as utmost hardness, corrosion and wear resistance. The most effectual and cost-effective approach to improve surface properties of materials is to either create surface layers or coatings that inherently possess high level of corrosion and wear resistance or diffuse another element(s) by thermochemical reaction. In literature, the important deposition methods proposed to create and/or surface layers are physical vapour deposition (PVD), chemical vapour deposition (CVD), electroplating, flame, and laser surface treatment and thermochemical reactions such as carburising, nitriding, carbonitriding (nitro-carburising), boriding etc. after appropriate heat treatment. In spite of the large number of surface technologies available today, there are nevertheless industrial applications where none of these technologies on its own could offer a viable solution. For example, in hot forging dies/tools which come into contact with the melt suffer many types of damages: Wear (Abrasive and Adhesive), Plastic Deformation and Thermal Fatigue (heat cheeking), Cracking result in premature tool failure; require combination of various properties altogether, where one particular technology may not work alone, thereby combination of diffusion and deposition technologies will provide a set of highly demanding properties.

A solution to increasing the wear resistance of surfaces, especially those in the high stress processing environment, is duplex treatment. Properly planned hybrid methods of surface treatment permitting the production of “nitrided layer/ PVD coating” layered composites are an effectual technological solution for the increase in the sturdiness of dies for hot forgings [1]. It has already been accounted that duplex coatings, consisting of plasma nitriding of hot work tool steel substrates and successive deposition of hard coatings by PVD, can extend both wear and contact fatigue resistance and also the load bear capability of hot work steel substrates.

To the best of our knowledge, there exists no paper that elaborates depth understanding of *Duplex Treatment*. In the present work, various methods adopted by different researchers have been explored.

Rest of the paper is organized as follows: Section 2 presents description of failure analysis of hot forging dies used in forging industry. The brief discussion of experimental setup for duplex treatment with optimized parameters is given in section 3. Section 4 gives the experimental results and its discussion. Finally the paper is concluded with their future enhancement in section 5.

II. FAILURE OF HOT FORGING DIES

During the hot forging process, the dies undergo a blow of three most important factors causing their failure: the regularly changeable mechanical loading, rigorous thermal loads, as well as intensive friction and erosion. In hot forging process the temperature of the material may rises up to 1000°C to 1200°C; lowers the yield point causes easy deformation into desired shape. Due to repetitive loading during the hot forging process, the forging die attain high temperature from the forged material and then cool down by water based lubricants, the forging die surface may attain the temperature from 600° C to 900°C [2]. Due to continuous, repeated changes in the temperature of the surface of die causes thermal and structural stresses, very opportune conditions to generate a grid of cracks appear. This type of demolition of the forging die is called the thermal fatigue [3]. All type of structural defects on to surface and inside the material of die enhances tendency of formation of stress concentrations [4]. Alternate, reversible enactment of external mechanical loading, playing on the forging die during the walk of production, results in exhaustion phenomenon recognized as mechanical fatigue of the material [5]. The cracks formed during the thermal fatigue boost the mechanical fatigue phenomena; the combined nature of thermal and mechanical fatigue give rise to thermo-mechanical failure. Amongst these, wear is the predominating factor in hot forging process. Lange,1997 reported that wear is the dominated failure mechanism for forging dies, being accountable for approximately 70% of failures, another 25% are due to mechanical fatigue, and the remaining 5% are due to plastic deformation and thermal-mechanical fatigue[6, 7]. These wear and other die failure related problems can be minimized/controlled mainly by following three approaches (Figure 1):

- *Approach 1*: By using high cost wear resistant metals/alloys better than the existing low cost ones.
- *Approach 2:* By heat treating the die components to obtain right combination of mechanical properties.
- *Approach 3*: By applying certain modifications to the surfaces of the existing hot work die materials to improve the wear resistance.

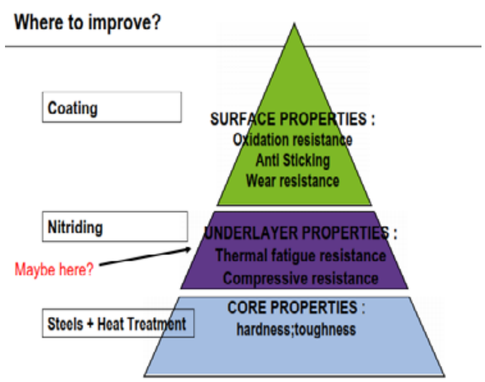

Fig. 1. Options to Enhance Die Life

Based upon the literature available number of researchers had contributed in each option to enhance die life however surface treatment is the most successful method to improve die life due to as wear is a surface phenomenon mostly occurs at the contact surfaces, also it does not change the whole chemistry of die as the heat treatment process; provide better wear resistant properties at elevated temperature too. Therefore the effectual way to improve the robustness of forging dies is a modification of surface properties by the establishment of layers or coatings having appropriate properties [8]. This approach is acceptable by the fact that all the processes of the forging die demolition, i.e. the thermo-mechanical fatigue, plastic deformation, abrasive wear, and erosion, are situated just in the surface layer of the die [9] .The latest research trends bend towards surface treatment processes due to proven results. Large number of researchers had proposed notable advancements in the die life enhancement of hot forging process by surface treatment.

III. DUPLEX TREATMENT

Duplex treatment is a two action treatment process which involves thermal surface treatment (Nitriding) of a substrate in order to increase its load bearing capacity, followed by deposition of a hard wear resistant coating by either method primarily by PVD. This can be either achieved in a single step in a vacuum chamber, or in two separate operations. The formation of surface modified layer in the subsurface zone takes place during the first step while most suitable PVD coating is deposited on top of this layer during the second step.

Duplex surface treatments were used for improving die life under the heavy thermal and mechanical loads and at conditions of tribological aspect namely wear. Although conventional surface treatments such as thermal treatment, thermo-chemical treatment and anti-wear monolayer/multilayer’s (TiN, TiCN) coatings have achieved prolonged lifetime of tools, they do not lead to the desired increase in the tool life due to the substrate being unable to withstand the mechanical loads and the plastic deformation of the substrate causing the breakage of thin coatings. This goal can be achieved only by the application of a duplex surface treatment which involves the substrate hardening pre-treat and PVD anti-wear coatings. The number of research groups had investigated a lot; however the results few of them are summarized as follows and Annexure 1 in chronological order.

The first attempt of applying the duplex surface treatment was carried out in the 1980s. However, concentrated work concerning the development of this method for tool life enhancement was undertaken only at the beginning of the 1990s [10]. Among the duplex treatments, plasma nitriding of the alloy steel substrate followed by the PVD coating method is the most extensively used in industry [11].

The duplex treatment combining plasma nitriding and ceramic hard coating can extensively improve the wear performance and lifetime of tool steel due to the promoted load-carrying-capacity [12] [13]. The properties obtained of combined surface structure were exceptional. The most key parameter, the coating-to substrate critical load for adhesion exceeded the maximum level. However, the adhesion at the coating/substrate interface can be powerfully affected by the presence of a compound layer, which can be created during the plasma nitriding step.

The hard coating of TiN, after nitriding, grants a very hard, wear, heat and chemical resistant surface layer. Thus properties obtained by the combination of nitriding with hard-coating allow function sharing between the core material, the hardened case and the surface [15]. First results were obtained with TiN coating, deposited on Z28CDV5 steel substrate, nitrided with a compound layer.

Relative life time improvement was more than 150% against a TiN coated die. Due to the fact that duplex treatment improves the corrosion resistance of hot working steels impressively, it is expected that the duplex treatment with CrN coating will bring additional possibilities to improve die life [16].

The hard coatings used can hinder thermal fatigue. The mechanism was not disclosed yet but it is likely to involve both delaying crack nucleation and crack growth due to the coating high hot hardness and high residual compressive stress. This effect, combined with the high hardness of the coatings which reduces wear, may put in to die life raise in hot work. A nitrided layer between TiN and the tool steel may improve low cycle fatigue resistance even further [17]. The best results have been obtained with a double-layer PVD CrN /ZrN coating on a pre-nitrided substrate (AISI H11). The effect of plasma nitriding and NIPRE treatments is positive too, but the progress to the corrosion resistance is lower than that obtained by PVD [18].

Coatings of PVD layer on a pre-clad substrate (AISI H13) proved extremely successful in improving tribological performance of the composite layer. A load of 40 N has been withstood by all deposited coatings, indicates the effectiveness of clad layer in enhancing the load bearing capacity of thin PVD coatings. The authors recommended PVD coatings on pre-clad layers should be pursued as viable surface engineering solution for applications such as hot forming tools and dies [19]. Enhanced grip of the covering is another favorable position of the procedure. The grip of TiN covering by PACVD on nitrided AISI H13 passes on was considered by [20]. The applied DUPLEX treatment low pressure pulsed plasma nitriding with a diffusion layer of 85-mm and 4-mm-thick BALINIT FUTURA coating as a top protective layer undoubtedly improved the tool life of hot forging dies and resulted in reproducible quality of forged parts in comparison to the use of dies with a FUTURA coating only, and especially to the traditional technology.

The replacement of the AISI H11 tool steel by tool steel with 3.5% Mo, produced an increase in the number of forgings of 30-40% with both gas and plasma nitrided dies. DUPLEX treatment of such Mo dies could additionally improve the final result in hot forging of steel parts. The dies made of ASP 30 tool steel was improved by 500% with a standard TiN coating had been reported [21].

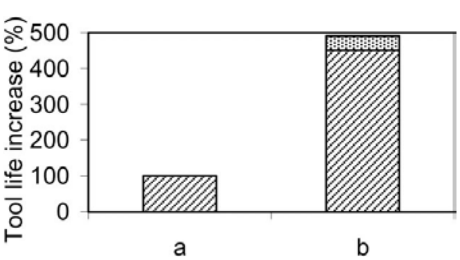

Fig 2. Punching die tool life in hot forging manufacturing of steel components: a) ASP30 originally designed die; b) punching die improved with a PVD 3-mm-thick TiN coating [21].

The roughness of frontal working surface increased strongly with the number of forgings for a heat treated tool and increased slowly for a plasma nitrided tool, while it remained more or less unchanged for a duplex treated tool Ref. Fig.3. The roughness of work pieces also increased with the number of forgings much faster for a heat treated tool than for plasma nitrided tools, while it remained unchanged for a duplex treated tool [22].

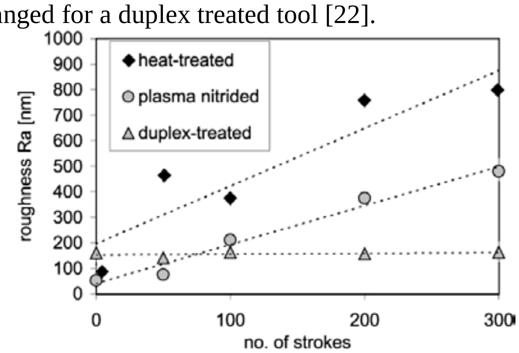

Fig 3. Roughness of frontal surface of tool before and after 50, 100, 200 and 300 forgings [22]

The coatings were found to adhere better when the nitrided dies were polished prior to coating. Some studies [23] investigated the use of multilayer coatings such as Titanium Aluminium Nitride [(Ti, Al) N] along with the use of an "adhesion" layer. Fig. 8 shows a schematic of such a deposited layer.

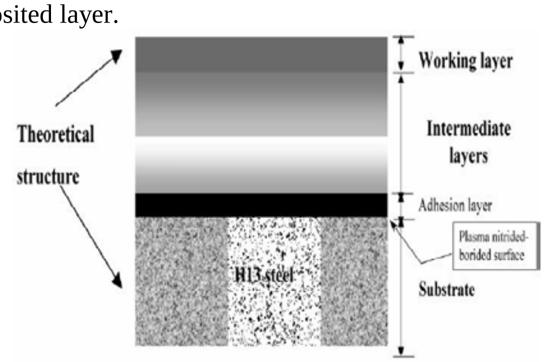

Fig 4: Schematic Representation of a Multilayer Coating On AISI H13 Die Steel [23]

However in few cases the problem of adherence of coating was solved by [24] by inserting an intermediate treatment consisting of cooling down the samples in vacuum and carrying out an Ar plasma-etching step; provides good adhesion strength by successfully avoiding compound layer destabilisation. It also elucidates a systematic approach to produce duplex coatings which are compound-layer-free, by removing this iron nitride layer through an Ar sputtering mechanism. The same adhesion strength was measured for duplex TiN coatings with nitrided cases consisting of mono-phase ε compound layer + diffusion zone and for duplex TiN coatings with nitrided cases consisting of a diffusion zone only. A. Persson (2003) investigated effect of surface treatments (Boriding, Toyota diffusion to give CrC) and physically vapour deposited (PVD) coatings of CrN, as single-layered or duplex-treated, on hot work tool steel specimens on thermal fatigue. With the exception of duplex-treatment, all variants of surface engineering show a tendency to decrease the resistance to thermal fatigue cracking as compared to the reference steel. However, the fact that the duplex-treated PVD CrN coating increased the resistance to thermal fatigue cracking as well as reduces the density of cracks as compared to the single-layered CrN coating, the potential to improve the life and performance [25]. Tribological properties of a duplex treatment consisting on plasma nitriding and PVD/TiN coating an AISI H13 hot work tool steel was studied by [26]; and observed practically an increase of the wear resistance of the tool up to 30%.

The standard heat treatment has been performed before plasma nitriding of die, which ensure the creation of diffusion layer. This was followed by deposition or PVD CrN coatings PAPVD, TiCrN, TiN/TiCN (Cr/CrN) x 3 and (CrN/TiN) x 3 coatings. *Duplex Treatment* was successfully applied to smaller die by fitting on automatic forging machines type Hatebur. In the case of processing dies, depending on the type of coating, reached the increase of life from 1.3 to 1.5 times [27]. The wear behaviour of AISI H13 predicted after single layer gas nitrided , single layered (Ti,Al)N PVD coated and duplex coated using ball on disc setup and room and elevated temperatures by [28]. At high temperatures and the same load, single-layered (Ti,Al)N PVD coatings shows the highest wear volume among the treated samples tested at this temperature, a behaviour that has been mainly attributed the limited load-carrying capacity of this system, which does not prevent the substrate from deforming plastically and to cause the brittle fracture of the PVD film. The single gas nitrided layer showed a better wear resistance of ~5 times than the single-layered (Ti,Al)N PVD coating system, whereas the duplex coating system showed no wear loss at all. Duplex surface treatment on the steel X12CrNi 18 8 surface was investigated by [29]; found the relation between chemical composition, structure and properties of duplex system. This system improved the hardness differences between the coating and substrate. It leads to better wear properties of whole system. The highest values of micro hardness has duplex system had been noted. M. Polok-Rubiniec et al.(2010) compared various PVD hard coatings deposited on plasma nitrided hot work X37CrMoV5-1 steel substrate and observed A very good adhesion of the TiN/(Ti,Al)N coating, high hardness are connected with the good results of the pin-on-disc tribological test for this coating. The biggest resistance to the wear resistance at 20°C and 500°C temperatures is characterized by the TiN/(Ti,Al)N coating, while the smallest resistance shows the CrN coating [30]. Significant improvements in the resistance to erosion and adhesion of MARAGING steel 14 10 5 achieved by plasma nitriding followed by coating the metal by a TiN layer speak in favour of the application of this combination of processes for the manufacture of moulds that have to meet the requirement of an increased wear resistance [31]. Gas nitriding followed by 3 types of PVD coatings e.g. TiAlN, AlCrN, and AlCrTiN were deposited on AISI H13 tool steel. The top PVD coatings increase the surface hardness to the value of greater than 30 GPa. The increased in the surface hardness is in the following order: DUPLEX TiAlN coating < DUPLEX AlCrN coating < DUPLEX AlCrTiN coating. The DUPLEX AlCrTiN coating showed the best adhesive property with the highest first failure critical load. Whereas the DUPLEX AlCrN coating was found to be tougher with higher crack propagation resistance. DUPLEX TiAlN coating showed high degree of chipping along the edge of scratch tracks with lower value of full delamination load [32].

Jakub HORNÍK et.al, (2012) experimentally applied a duplex CrN coatings by PVD sputtering on tool steel Orvar Supreme (19 554) and Vanadis 23 (19 830) clearly showed improved properties by duplex coatings. The greatest improvement noted in the duplex coating adhesion; in particular the improvement of 260 % and 179 % for Orvar Supreme and Vanadis 23 [33]. Andrei SURZHENKOV et.al, (2012) compared different duplex coatings; The 1.6–1.7 times higher impact wear resistance was demonstrated by the PVD I generation TiN coating in comparison with the other studied coatings due to the highest modulus of elasticity. The PVD III generation FiVIc® coating showed the1.2– 8.9 better wear resistance in comparison with the other studied coatings due to the lowest coefficient of friction [34]. M. Válová et. al., (2012) experimentally observed that duplex treatment is a useful way to increase the die service life and that the most suitable coating is the PVD coating TiN. This coating in combination with a nitrided substrate, had a low friction coefficient and a small wear while the coating hardness, the most favourable is the coating TiN, in terms of nanohardness depth profile. Current thin abrasion-resistant surface layers and coatings bring remarkable extension of service life and reliability to machine parts and dies [35]. Steel samples (31CrMoV9) were nitrated and subsequently treated by PVD process by M. Kolaríková and J. Suchánek (2012); deposited different types of coatings (TiN,CrN, TiAlN and multilayer 3 × (CrN-TiN)) with thickness 1 and 3 µm. The most favourable coating was CrN and the multilayer coating 3 × (TiN – CrN) in terms of micro hardness. The friction coefficient is low and the coating exhibits better service life. Duplex treatment is a useful way to increase the die service life and that the most suitable coating is the PVD coating TiN. This coating in combination with a nitrided base material had a low friction coefficient and a small wear [36]. The maintenance testing was performed on the forging dies employed for production of various parts in the automotive industry. The best durability was obtained for the duplex treated dies used for the forging of rolling bearing tracks. In comparison with the durability of the dies subjected solely to the gas nitriding, nearly an increase of 600% in the durability was noticed.[37]. The adhesion tests of the samples (AISI H13) reveal the better cohesive and adhesive properties of the CrN coatings deposited onto the nitrided hot work steel. The high hardness and low friction coefficient of the duplex treated samples come along with the good results of the ball-on-disc test for this coating system. As compared with CrN monolayer, duplex coatings are a more promising and efficient surface treatment for hot work tools applications. The use of these duplex coatings could lead to an increase of the life time of hot work steel and to a reduction of maintenance and production costs [38].

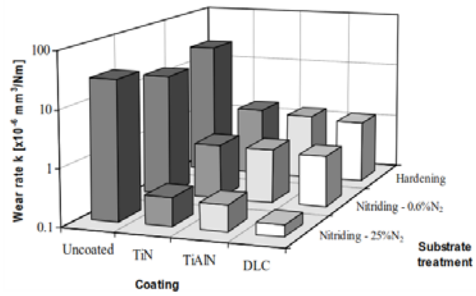

Fig. 5 Wear rate of duplex coating systems in sliding test [39]

AISI H13 steel was treated with oxynitriding, CrN coating, and CrN coated with oxynitriding to find the molten loss for melting A380 aluminium alloy and wear resistance by [40]. The minimum melting loss appeared in duplex surface treatments of CrN coated with oxynitriding after a 3 h erosive test. Weight loss was only 0.8%; however the untreated specimen was 3.2%. The lowest coefficient of friction also observed in the duplex surface treatment of CrN coated with oxynitriding. The average value of frictional coefficient was 0.28 [40]. Jacek Sawicki et al. (2013) experimentally applied four different types of surface treatments on hot work tool steel DIN 1.2343; namely FineLPN vacuum Nitriding, SULFONIT (sulfonitriding), Duplex technology (FineLPN nitriding+PVD/TiN), and Duplex technology (SULFONIT sulfonitriding +PVD), with low friction MoS_2 (Ti,W) coating composed of molybdenum disulfide with the addition of titanium and tungsten was deposited on sulfonitrided and nitrided diffusion layers. The increase in the service life of dies obtained; thanks to the duplex technology followed from the lower coefficients of friction between the material and the hardened surface layers [41]. The potentials of newly developed vanadium doped chromium nitride (CrVN) and boron containing titanium nitride(Ti-B-N) coating systems were investigated by [42] on basic hot work steel AISI H11 deposited through PVD (Physical Vapour Deposition) and PECVD (Plasma Enhanced Chemical Vapour Deposition) after plasma nitriding respectively. Vanadium-doped chromium nitride layers have a high wear reduction potential for hot forging dies [42]. The durability of forging tools with hybrid layer type nitrided layer / PVD coating used in a process of continuous manual forging is 3 – 4 times longer than that of dies subjected only to ion nitriding. The wear of the punch covered with CrN coating was found to be less that of the TiAlN coated one [43]. The pin-on-disk analysis of duplex, plasma nitriding and PVD (TiN-TiAlN-CrAlN), treated steel pins sliding against a two phase brass between room temperature to 700 °C have been evaluated by [44]. The coefficient of friction first increases, stabilises due to formation of oxide layer, removal of coating lead to further rise and formation of Cr_2O as a solid lubricant reduces the friction coefficient with elevation of temperature [44]. Tribological induced wear like abrasion and adhesion, and reduction of the crack sensitivity of the base material is possible. In order to provide the surface areas with local performed treatments, a covering with paste in combination with a multistep plasma treatment is effective to reduce locally dominating wear mechanisms [45].

The results reveal that tribological properties which depend upon hardness and wear resistance of hot work steel had been greatly enhanced with the help of Duplex Treatment.

IV. CONCLUSION

The first step in improving the tribological properties (wear resistance) of forging tools is the increasing both hardness and toughness. Hardness achieved through heat treatment while the toughness of die surface improved through nitriding process. The depositions of a hard coating, although improving the abrasive wear resistance, overstress the effect of the surface roughness. The proper selection and optimal parameters of substrate thermo-chemical treatment are crucial for the proper performance of the coated tools. The highest potential for improving the performance of hot-forging dies is shown by the combination of a plasma-nitrided tool-steel substrate coated with a multilayer nano-composite coating; a viable and cost effective method, Duplex Treatment. However, before the coating the substrate needs to be polished and increased substrate hardness combined with sufficient fracture toughness through selective heat treatment.

REFERENCES

[1] J.Smolik and A. Mazurkiewicz, "Comparative analysis of wear mechanism of different types of forging dies," *Archives of Materials Science and Engineering,* vol. 49, pp. 40-45, 2011.

[2] P. Panjan, I. Urankar , B. Navinsek , M. Terceljb, R. Turkb, M. Cekadaa, V. Leskovsekc, " Improvement of hot forging tools with duplex treatment," *Surface and Coating Technology,* pp. 151-152, 2002.

[3] H-J Christ, A Jung, H J Maier and R Teteruk, "Thermomechanical fatigue – Damage mechanisms and mechanism-based life prediction methods," *Sadhana* vol. 28, pp. 147-165, 2003.

[4] K. H. Lee, J.S. Sun, H.P. Lee,, "Effect of geometry and fillet radius on die stresses in stamping processes," *Journal of Materials Processing Technology,* vol. 104, p. 254, 2000.

[5] G. A. Bretti and M. Monti, "Thermo-mechanical fatigue life assessment of hot forging die steel," *Blackwell Publishing ltd. ,fatigue fracture mat. structure,* vol. 28, pp. 1025-1038, 2005.

[6] K. Lange, "Modern metal forming technology for industrial production," *J. Mater. Process. Technol. ,* pp. 2-13, 1997.

[7] Hallstrom. J. Stahlberg U., "A comparison between two wear models," *j. Materials Processing Technology,* pp. 223-229, 1999.

[8] F. Deschaux-Beaume, F. Schimdt., N. Frety, J.C. Boyer , C. Levaillant. (1998). Failure prediction for ceramic dies in the hot-forging process using FEM simulation. *Journal of Materials Processing Technology, 75*, 100-110.

[9] Sailesh Babu, Dilmar Ribeiro, Rajiv Shivpuri, "Material and Surface Engineering For Precision Forging Dies," 1999.

[10] Münz Wolf-Dieter, Lembe Mirkka., Lewis D. Brian, Smith lain, "*Microstructure, Composition and Performance of PVD Coatings Designed for Successful Dry High Speed Milling.* Paper presented at the 15'" International Plansee Seminar, , Plansee Holding AG, Reutte

[11] Zlatanović M., ""Combined Plasma Nitriding/PVD Processes Treatment and Surface Engineering Conference and Exibition in Europe," Amsterdam, 1991, pp. 655-666.

[12] M. Vanstappen, J. D'haen, C. Quaeyhaegens, And L. Stals, "Interface Study of Physical Vapor-Deposition TIN Coatings On Plasma-Nitrided Steels" 1993.

[13] K. Höck, H.-J. Spies, B. Larisch, G. Leonhardt, and B. Buecken, "Wear resistance of prenitrided hardcoated steels for tools and machine components," *Surface and Coatings Technology,* vol. 88, pp. 44-49, 1997.

[14] Mehmet CAPA, M. Tamer., Turgut GulMEZ, Cengiz Tahir BODUR. (2000). Life Enhancement of Hot-Forging Dies by Plasma-Nitriding. *Turk J Engin Environ Sci, 24*, 111-117..

[15] H. Brockhaus, A. Guderjahn and I. Schruff, « *Improving the performance of forging tools–a case study.* » Paper presented at the The 6th International Tooling Conference, Karlstad University, Sweden. 2002

[16] B. Navinsek, P. Panjan, I. Milosev, "Industrial applications of CrN (PVD) coatings, deposited at high and low temperatures," *Surface and Coatings Technology* vol. 97, pp. 182-191, 1997.

[17] C.M.D. Starling and J.R.T. Branco, "Thermal fatigue of hot work tool steel with hard coatings," *Thin Solid Films,* vol. 308-309, pp. 436-442, 1997.

[18] A. Molinaria, M. Pellizzeria, G. Straffelinia ,M. Pirovanob, "Corrosion behaviour of a surface-treated AISI H11 hot work tool steel in molten aluminium alloy," *Surface and Coatings Technology* vol. 126, pp. 31-38, 2000.

[19] S. W. Huang, "Tribological performance and microstructure of physical vapour deposition coatings, laser clad WC/Ni layers and duplex coatings," Doctor of Philosophy, University of Wollongong, 2000.

[20] S. Ma, Y. Li, and K.Xu, "The composite of nitrided steel of H13 and TiN coatings by plasma duplex treatment and effect of pre nitriding," *Surface and coatings technology,* vol. 137, pp. 116-121, 2001.

[21] Boris Navinsek, Peter Panjan and Frank Gorenjak, "Improvement of hot forging manufacturing with PVD and DUPLEX coatings," *Surface and Coatings Technology,* vol. 137, pp. 255-264, 2001.

[22] P. Panjan, I. Urankar, B. Navinsek , M. Terceljb, R. Turkb, M. Cekadaa, V. Leskovsekc, "Improvement of hot forging tools with duplex treatment," *Surface and Coatings Technology 151–152 (2002) 505–509,* vol. 151-152, pp. 505-509, 2002.

[23] O. Salas, K. Kearns, S. Carrera, and J. Moore,"Tribological Behavior of Candidate Coatings for Aluminum Die Casting Dies," *Surface and Coating Technology,* vol. 172, pp. 117-127, 2003.

[24] Junia Cristina Avelar-Batistaa, Cristina Godoyb, Rafael D. Mancosub, Janaína Morais , A. Matthewsc, "Plasma Nitriding And Papvd Hard Coating: A Critical Overview of Duplex Coating Processing," *JORNADAS SAM/ CONAMET/ SIMPOSIO MATERIA 2003,* vol. 6, pp. 600-604, 2003.

[25] A. Persson, "On Tool Failure in Die Casting," Upasala university, 2003.

[26] A. R. Franco Jr, C. E. Pindo, A.P. Tschiptschin, "Influence of The Plasma Pre-Nitriding Surface Treatment On Wear And Adhesion Of PVD/TIN Coating For The Hot Work Tool Steel AISI H13," presented at the 7TH TOOLING CONFERENCE, 2005.

[27] J. Suchánek, "Increasing life ofdies by duplex coating.," *Acta Metallurgica Slovaca - Roč. 11, special issue 2,* pp. 178-182, 2005.

[28] R. Rodrıguez-Baracaldo, J.A. Benito, E.S. Puchi-Cabrerad, M.H. Staia, "High temperature wear resistance of (TiAl)N PVD coating on untreated and gas nitrided AISI H13 steel with different heat treatments," *Wear* vol. 262, pp. 380–389, 2007.

[29] Zednek Joska and Jaromir Kadlec, "Plasma Nitrided And PVD TIN Coated X12CRNI 18 8 Steel Surface," in *Trends in the development of machinery and associated technology,* Hammamet, Tunlsia, 2009, pp. 741-744.

[30] M. Polok-Rubiniec, L. A. Dobrzanksi, M. Adamiak, "Comparison of the PVD coatings deposited onto plasma nitrited steel," *Journal of Achievements in Materials and Manufacturing Engineering,* vol. 42, pp. 172-180, 2010.

[31] Franjo Cajner, Darko Landek, Vojteh Leskovek, "Surface Modifications Of Maraging Steels Used In The Manufacture Of Moulds And Dies," *Materials and technology,* vol. 44, pp. 85-91, 2010.

[32] P. Dawan and K. Tuchinda, "Experimental Study of Wear Performance of Tool Steel Undergone DUPLEX Surface Treatments for Hot Forging Applications," *AIJSTPME* vol. 4, pp. 53-61, 2011.

[33] Jakub HORNÍK, Jan Runisek, Martin RUND, Pavlína HÁJKOVÁ, Evgeniy ANISIMOV,David TONDL, "Evaluation Of Properties Of CRN PVD Coating For Functionally Graded Materials," *METAL,* pp. 23-28, 2012.

[34] Andrei SURZHENKOV, Priit PÕDRA, , Fjodor SERGEJEV, , Mart SAARNA, Eron ADOBERG, , Valdek MIKLI, , Mart VILJUS, , Priit KULU, "Comparative Study of the PVD Coatings on the Plasma Nitrided Steel," *Materials Science (Medžiagotyra),* pp. 40-44, 2012.

[35] M. Válová, "Characteristics Of Duplex Coated Steels," 2012.

[36] M. Kolaříková, "Tribological Characteristics Of Plasma Nitrided And PVD Coated CR-MO-V Steels," *Scientia Agric. Bohem.,* vol. 43, pp. 58-63, 2012.

[37] J. A. Smolik, "Hybrid Surface Treatment Technology For Increase Of Hot Forging Dies," *Archives Of Metallurgy And Materials,* vol. 57, pp. 657-664, 2012.

[38] Bejarano Gaitan Gilberto, Gomes Botero Meryory, Mauricio Arroyave Franco, "Deposition And Characterization Of Duplex Treated Coating System Applied On Hot Work Steel AISI H13," *REV. Latin Am. Metal Mat.,* vol. 32, pp. 218-224, 2012.

[39] B. Podgornik, "Tribology Of Hard Coatings And Importance Of Substrate Preparation," *Sustainable Technologies of Metallic Materials,* pp. 71-98, 2014.

[40] Shih-Hsien Chang, Kuo Tsung Huang, Yung Hsiang Wang, "Effects of Thermal Erosion and Wear Resistance on AISI H13 Tool Steel by Various Surface Treatments," *Materials Transactions,* , vol. 53, pp. 745-751, 2012.

[41] Jacek Sawicki, Marek Gorecki, Lukasz Kaczmarek, Zbigniew Gawronski, Konrad Dyboski, Robert Pietrasik and Wojciech Pawlak, "Increasing the Durability of Pressure Dies by Modern Surface Treatment Methods," *Chiang Mai J. Sci,* vol. 40, pp. 886-897, 2013.

[42] Prof. Dr.-Ing. G. Braeuer, Dipl.-Ing. H. Paschke. Dipl.-Ing. M. Weber, Prof. Dr.-Ing.` B.-A. Behrens, Dipl.-Ing. T. Yilkiran, "Potential of Duplex Plasma Deposition Processes for the Improvement of Wear Resistance of Hot Forging Dies," *Key Engineering Materials,* vol. 554-557, pp. 345-358, 2013.

[43] S. Legutko, A. Meller, M. Gajek, "Investigation Of The Influence Of Hybrid Layers On The Life Time Of Hot Forging Dies," *METABK,* vol. 52, pp. 185-188, 2013.

[44] I. Ebrahizedah and F. Ashrafizade, "The Influence of Temperature on the Frictional Behavior of Duplex-Coated Die Steel Rubbing Against Forging Brass," *Journal of Materials Engineering and Performance,* 2014.

[45] H. Paschke, T. Yilkiran, L. Lippold, K. Brunotte, M. Weber,G. Braeuer , B.-A. Behrens "Adapted Surface Properties Of Hot Forging Tools Using Plasma Technology For An Effective Wear Reduction," *Wear,* vol. 330-331, pp. 429-438, 2015.