ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSC THESIS

HAYDAR POLAT

COMPARISONS OF DIFFERENT METHODS USED FOR IMPROVING LIFE OF HOT FORGING DIES

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA, 2006

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

COMPARISONS OF DIFFERENT METHODS USED FOR IMPROVING LIFE OF HOT FORGING DIES

HAYDAR POLAT

YÜKSEK LİSANS TEZİ

MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

Bu Tez, 10/07/2006 Tarihinde Aşağıdaki Juri Üyeleri Tarafından Oybirliği/Oyçokluğu İle Kabul Edilmiştir

İmza :	İmza:	İmza:
Prof.Dr.Melih BAYRAMOĞLU	Prof.Dr. Necdet GEREN	Yrd.Doç.Dr.Ali KOKANGÜL
DANIŞMAN	ÜYE	ÜYE

Bu Tez Enstitümüz Makina Mühendisliği Anabilim Dalında Hazırlanmıştır

Kod No :

Prof. Dr. Aziz ERTUNÇ
Enstitü Müdürü

ABSTRACT

MSc THESIS

COMPARISONS OF DIFFERENT METHODS USED FOR IMPROVING LIFE OF HOT FORGING DIES

Haydar POLAT

DEPARTMENT of MECHANICHAL ENGINEERING

INSTITUTE of NATURAL and APPLIED SCIENCES

UNIVERSITY of ÇUKUROVA

Supervisor : Prof. Dr. Melih BAYRAMOĞLU

Year : 2006, **Page**: 104

Jury : Prof. Dr. Melih BAYRAMOĞLU

Prof. Dr. Necdet GEREN

Assist.Prof. Dr. Ali KOKANGÜL

In this work, many of the methods used for improving life of hot forging dies were investigated in the forging department ÇIMSATAŞ. For this aim, the surface treatments such as one layer surface coating AlTiN, a special multilayer coating called TOKTEK (two layer coating), nitriding, and the weld overlay coating of the contact surface of the hot forging dies were studied with same hot forging dies under same conditions and the results were compared with the as received die material. The as received material was hardened and tempered DIN 1.2344 (ORVAR 2M) steel with the final hardness of 44 – 46 HRC.

After the experiments, it was found out that all of these methods improve life of hot forging dies in various amounts and the best result was obtained by weld overlay of the contact surface of the dies with CASTOLIN N9080.

Key Words: hot forging, die life, nitriding, weld overlay coating

ÖZ

YÜKSEK LİSANS TEZİ

SICAK DÖVME KALIPLARINDA KALIP ÖMRÜNÜ İYİLEŞTİRMEK İÇİN KULLANILAN FARKLI YÖNTEMLERİN KARŞILŞTIRILMASI

Haydar POLAT

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Prof. Dr. Melih BAYRAMOĞLU
Yıl : 2006, **Sayfa**: 104
Jüri **: Prof. Dr. Melih BAYRAMOĞLU**
Prof. Dr. Necdet GEREN
Yrd.Doç. Dr. Ali KOKANGÜL

Bu çalışmada, ÇİMSATAŞ firmasına bağlı Dövmehanede sıcak dövme kalıplarının ömürlerinin iyileştirilmesinde kullanılan çok sayıda yöntem üzerinde çalışılmıştır. Bu amaçla yüzey işlemlerinden tek katmanlı AlTiN yüzey kaplama, özel bir çok katmanlı kaplama yöntemi olan TOKTEK (çift katmanlı yüzey kaplama) kaplama ve nitrürasyon, sıcak dövme kalıplarının temas yüzeylerinin kaynak elektrotları ile kaplanması yöntemleri aynı kalıp üzerinde aynı koşullar altında denenmiş ve elde edilen sonuçlar satın alındığı gibi kullanılan kalıp malzemesinden yapılan kalıp ile karşılaştırılmıştır. Satın alınan malzeme tavlanmış ve temperlenmiş, sertliği 44 – 46 HRC olan DIN 1.2344 (ORVAR 2M) malzemedir.

Yapılan deneyler sonucunda bütün bu yöntemlerin kalıp ömrünü farklı miktarlarda iyileştirdiği görülmüş ve en iyi sonuç CASTOLIN N9080 elektrod ile temas yüzeyinin kaynak kaplandığı durumda elde edilmiştir.

Anahtar Kelimeler: sıcak dövme, kalıp ömrü, nitrürasyon, kaynak kaplama

ACKNOWLEDGEMENTS

I am very grateful to my supervisor Prof. Dr. Melih BAYRAMOĞLU for his guidance, inspiration and encouragement during all my thesis studies including the selection of this theme.

I would like to thank to the management of ÇİMSATAŞ for their support in this study and especially to my Assistant General Manager responsible from Production for his encouragement.

And finally special thanks to my wife Ayşegül, my daughters Deniz and Derya, my parents, my sisters Sebahat TORUN and Gün BİNZET, and their husbands Fuat TORUN and Rıza BİNZET for their endless support.

CONTENT PAGE

NOMENCLATURE

(C_{die})	The cost of the raw die material
(C_{saw})	The cost of sawing of the die materials
(C_{mach})	The cost of turning and milling of the dies
($C_{S.treat}$)	The cost of surface treatment
(C_{press})	The cost of the break of the forging press due to die polishing
(C_{res})	Cost of resinking and reproduction with the same dies until the life of the surface treatment has been finished.
(PF_{tot})	Total forged parts
($C_{prof+lab}$)	The profit, including the cost of pre - paid direct and indirect labor, that can be made from the production, that could be made in the time of break due to die polishing and die exchange of the forging press
(CD_{ini})	The total initial cost of the dies
(C_{ph})	Cost of one hour of press break
(C_{labh})	Cost of one hour of direct and indirect labor
k	Number of press breaks
($CD_{parts\ forged}$)	Die cost Per part

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Forging is the plastic working of metals by means of localized compressive forces exerted by manual or power hammers. A variety of forging processes have been developed that make it economically possible both to forge a single piece by using open die and to mass-produce thousands of identical parts by using shaped dies. The use of shaped dies increases production rate and provides parts which are very closely duplicate of all others. However, the cost of shaped dies used in hot forging processes are generally high so that long die life is necessary in order to reduce the unit cost of the product.

The main component of the total cost is the die cost which is closely related to the die life, which can be defined as the amount of products, that can be produced with the same die. The die cost is of about 30% of the total cost for a closed die forging process. So an increase of 100 % in the die life can reduce the total cost of about 15%.

In general, there are many factors affecting the die life. The life of a hot working tool steel is affected by the wear behavior of the tool steel (Sallit et all., 2002; Barrau, et all. 2003; Bahrami et all., 2004), heat treatment applied to the die steel (Dobrzanski et all., 2004; Zhang et all., 2004; Li et all., 2000; Bahrami et all., 2004) condition of the die surface, (Sallit et all., 2002; the condition of the work metal at forging,the shape of the die cavitiy (Vieilledent and Fourment, 2001), the alignment of the upper and lower dies, the stress distribution on the die surface generated during each blow and surface treatments like nitriding (Çapa et all, 1999; Funatani, 2004; Pessin et all, 2000) coating (Starling and Branco, 1997; Pellizari et all, 2001; Navinsek, et all, 2001; Panjan et all, 2002; Dobranzski et all, 2004; Lee and Kim, 2002) and weld overlay (Grenestedt, 2003; Tucker, 2004).

Changing one of these factors almost always changes the influence of another, and the effects are not constant throughout the life of the die. Researches carried out on extending die life have been concentrated on treatment of die surfaces. These treatments are applied to the dies due to the properties they provide to the main material. Typically, these include minimizing corrosion, reducing frictional energy losses, reducing wear, acting as a diffusion barrier, or providing thermal insulation. Surface modification however, is largely done when the main concern is damage to the surface of the die. The potential causes of such damage in most engineering applications are due to chemical, thermal and mechanical reasons.

The newer surface engineering techniques along with the traditional ones have a profound influence on several engineering properties. The thickness of engineered surface can vary from several millimeters for weld overlays to a few nanometers for physical vapor deposition (PVD) and chemical vapor deposition (CVD) coatings or ion implantation. Example of coating hardness range from 250 - 300 HV for spray coatings, 3500 HV for Titanium Nitride PVD coatings and up to 10000 HV for diamond coatings.

The Surface treatment process consists of three interrelated activities. These are :

- Optimisation of the surface/substrate properties and performance in terms of corrosion, adhesion, wear and other physico-mechanical traits.
- Coatings technology including the traditional techniques of painting, electroplating, weld surfacing, plasma and hypervelocity spraying, thermal and thermochemical treatments such as nitriding and carburising, newer combinations of laser surfacing, physical vapor deposition (PVD), chemical vapour deposition (CVD), ion implantation and ion mixing.
- Characterisation and evaluation of surfaces and interfaces in terms of composition and morphology and their mechanical, electrical and optical properties.

Surface engineering processes can be classified into two main groups namely, surface preparation processes that help clean and prepare the component surfaces and surface treatment processes that give the desired properties to the material. Surface preparation is an integral part of any coating deposition process. Surface preparation aids in easier and better treatment through removal of unwanted impurities, reduces interfacial surface tension, removes scaling as well as condition the surface for better adhesion bonding. Adequate care and detailing can ensure durable treatment that will improve die life. Inadequate surface preparation is often the single greatest cause for failure of surface treatments.

Treating surfaces can be done in a variety of ways and techniques depending on the end result desired. Modifying without altering the substrate's chemistry is one of the techniques. In this case the existing metallurgy of the component surface is changed within the surface regions either by thermal or mechanical means to increase hardness. Changing the surface layers by altering the alloy chemistry is another technique Here, new elements are diffused into the surface usually at elevated temperatures so that the outer layers are changed in a composition and properties compared to those of the bulk. Adding layers of material to the surface is also a technique applied in surface treatment. This category incorporates a wide variety of coating processes where a material different from the bulk is laid on the base substrate. Unlike the first two categories, there will exist a clear boundary at the substrate/coating interface and the adhesion of the coating is the major issue.

There are different methods used in surface coating technology. A few of them which are proven and commercially practised are surface hardening treatments like carburising, carbon nitriding, induction hardening, nitriding (gas/ion) nitro carburising etc. improve surface hardness, providing case hardening so that the material withstands heavy loads and improves fatigue resistance. Common applications include cam shafts, crank shafts, rocker arms, cylinder liners, punches and dies, steel etc. Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) are further methods. Very hard coating such as TiN, TiAlN, TiC, TiCN, and Alumina are applied on the die surfaces to enhance die life. The coating imparts 30% to 500% improvement in life.

In this study, different surface coating techniques were applied to the die surface in order to reduce the wear at the die surface, and so, to increase the die life. The experimented surface coating techniques were nitriding, single layer AlTiN surface coating, multi layer TOKTEK surface coating and weld overlay surface coating. The coated surfaces were investigated in real forging process, and the results obtained for the polishing life and die service life were compared. With the fact that the most important issue is the cost for a forging company, and that the die cost per part is one of the most important portions of the total cost, a comparison is also made for the die cost per part for all of the experimented coating techniques. It has been found out, that each of the coating techniques increases the die service life, and reduces the die cost per part. The amount of the increase in die service life, and the decrease in the die cost per part depends on the type of the coating.

2. PREVIOUS STUDIES

2.1 Forging Processes

Forging is a metal forming process that transforms a simple shape of a workpiece to a predetermined complex shape through the application of compressive forces. Generally, the final forging components have complex intricate shapes. In this case, the simple workpiece is deformed through a number of intermediate shapes of dies to avoid problems such as fold over, cracks, and improper die fill. (URL 1).

Forging involves the controlled plastic deformation of metals into useful shapes Deformation may be accomplished by means of pressure, impact blows, or a combination. In order to reduce the flow stress, forging is usually accomplished at an elevated temperature. Forging refines the microstructure of a metal and can improve its mechanica properties, especially in preferred directions. Forging can also be used for other purposes, such as to consolidate powder preforms by welding grains, eliminate porosity in castings, break up long inclusions in forgings, and demolish the dendritic structure resulting from Lee et all (1999).

Forging changes the size and shape, but not the volume, of a part. The change is made by force applied to the material so that it stretches beyond the yield point. The force must be strong enough to make the material deform. It must not be so strong, however, that it destroys the material. The yield point is reached when the material will reform into a new shape. The point at which the material would be destroyed is called the fracture point.

In forging, a block of metal is deformed under impact or pressure to form the desired shape. Cold forging, in which the metal is not heated, is generally limited to relatively soft metals. Most metals are hot forged; for example, steel is forged at temperatures between 1150 ^{o}C to 1260 ^{o}C. These temperatures cause deformation, in which the grains of the metal elongate and assume a fibrous structure of increased strength along the direction of flow.

Normally this results in metallurgical soundness and improved mechanical properties. Strength, toughness, and general durability depend upon the way the grain is placed. Forgings are somewhat stronger and more ductile along the grain structure than across it. The feature of greatest importance is that along the grain structure there is a greater ability to resist shock, wear, and impact than across the grain. Material properties also depend on the heat-treating process after forging. Slow cooling in air may normalize workpieces, or they can be quenched in oil and then tempered or reheated to achieve the desired mechanical properties and to relieve any internal stresses. Good forging practice makes it possible to control the flow pattern resulting in maximum strength of the material and the least chances of fatigue failure. These characteristics of forging, as well as fewer flaws and hidden defects, make it more desirable than some other operations (i.e. casting) for products that will undergo high stresses.

In forging, the dimensional tolerances that can be held vary based on the size of the workpiece. The process is capable of producing shapes of 0.5 to >50.0 cm in thickness and 10 to <100 cm in diameter. The tolerances vary from ± 0.8 mm for small parts to ± 6 mm for large forgings. Tolerances of 0.25 mm have been held in some precision forgings, but the cost associated with such precision is only justified in exceptional cases, such as some aircraft work (URL 2).

2.2 Forging Machines

Each forging process is associated with at least one type of forging machine. Forging machines can be classified according to their principle of operation as hammers and presses where hammers can also be sub-classified as gravity drop hammers, power drop hammers, die forger hammers, counterblow hammers and open die forging hammers and presses can be sub-classified as mechanical presses, hydrolic presses screw presses and multiple ram presses (Altan, 1998).

2.2.1 Drop Hammers

Hammers and high-energy-rate forging machines deform the workpiece by the kinetic energy of the hammer ram; they are therefore classed as energy-restricted machines.

2.2.1.1 Gravity Drop Hammers

Gravity drop hammers consist of an anvil or base, supporting columns that contain the ram guides, and a device that returns the ram to its starting position. The energy that deforms the workpiece is derived from the downward drop of the ram, the height of the fall and the weight of the ram determine the force of blow.

In recent years, two significant innovations have been introduced in hammer design. The first is the electrohydraulic gravity drop hammer. In this type of hammer, the ram is lifted with oil pressure against an air cushion. The compressed air slows the upstroke of the ram and contributes to its acceleration during the downstroke blow. Therefore, the electrohydraulic drop hammer also has a minor power hammer action. The second innovation is the use of electronic blow-energy control. Such control allows the user to program the drop height of the ram for each individual blow. The electronic blow control increases the efficiency of the hammer operations and decreases the noise and vibration associated with unnecessarily strong hammer blows (Altan, 1998b).

2.2.1.2 Power Drop Hammers

In a power drop hammer, the ram is accelerated during the downstroke by air, steam or hydraulic pressure. This equipment is used almost exclusively for closed-die (impression) forging. The steam or air-powered drop hammer is the most powerful machine in general use for the production of forgings by impact pressure. In a power drop hammer, a heavy anvil block supports two frame members that accurately guide a vertically moving ram; the frame also supports a cylinder that, through a piston and piston-rod, drives the ram. In its lower face, the ram carries an upper die, which contains one part of the impression that shapes the forging. The lower die, which contains the remainder of the impression, is keyed into an anvil cap that is firmly wedged in place on the anvil. The motion of the piston is controlled by a valve, which admits steam, air or hydraulic oil to the upper or lower side of the piston. The valve, in turn, is usually controlled electronically, Most modern power-drop hammers are equipped with programmable electronic blow control that permits adjustment of the intensity of each individual blow. Power-drop hammers are rated by the weight of the striking mass, not including the upper die. Hammer ratings range from 450 to 31750 kg. (Altan, 1998b).

2.2.2 Mechanical Presses

The ability of mechanical presses to deform the work material is determined by the length of the press stroke and the available force at various stroke positions. Mechanical presses are therefore classified as stroke restricted machines.

All mechanical presses employ flywheel energy, which is transferred to the workpiece by a network of gears, cranks, eccentrics, or levers. Driven by an electric motor and controlled by means of an air clutch, mechanical presses have a full eccentric type of drive shaft that imparts a constant-length stroke to a vertically operating ram.The stroke is shorter than that of a forging hammer or a hydraulic press. Ram speed is greatest at the center of the stroke, but force is greatest at the bottom of the stroke. The capacities of these forging presses are rated on the maximum force they can apply and range from about 2.7 to 142 MN.

Compared to hammer forging, mechanical press forging results in accurate close tolerance parts. Unlike the blow of a forging hammer, a press blow is more of a squeeze than an impact and is delivered by uniform stroke length. Because the dies used with mechanical presses are subject to squeezing forces instead of impact forces, harder die materials can be used in order to extend die life (Altan, 1998a).

2.3 Classification of Forging Processes

Forging is classified as Open-die Forging, Closed Die Forging with Flash, Closed Die Forging without Flash (Flashless Forging), Coining, Forward Extrusion Forging, Backward Extrusion Forging, Isothermal Forging, Rotary Forging, Precision Forging, Metal Powder Forging, Radial Forging, and Upsetting (Altan et all, 1995).

2.3.1 Open Die Forging

Open die forgings or hand forgings are made with repeated blows in an open die, where the operator manipulates the workpiece in the die. The finished product is a rough approximation of the die. This is what a traditional blacksmith does, and is an old manufacturing process.

Open-die forgings are the least refined in shape, being made with little or no tooling. These forgings are large, relatively simple shapes that are formed between simple dies in a large hydraulic press or power hammer. Examples are ship propeller shafts, rings, gun tubes, and pressure vessels. Since the workpiece is always larger than the tool, deformation is confined to a small portion of the workpiece at any point in time. The chief deformation mode is compression, accompanied by considerable spreading in the lateral directions. (Lee et all, 1999).

Open-die forging can produce forgings from a few kilograms up to more than 150 tons. The metal is not confined laterally by impression dies during forging, this process progressively works the starting stock into the desired shape, most commonly between flat-faced dies. In practice, open-die forging comprises many process variations, permitting an extremely broad range of shapes and sizes to be produced. In fact, when design criteria dictate optimum structural integrity for a huge metal component, the sheer size capability of open-die forging makes it the clear process choice over non-forging alternatives. At the high end of the size range, open-die forgings are limited only by the size of the starting stock, namely, the largest ingot that can be cast.

Practically all forgeable ferrous and non-ferrous alloys can be open-die forged, including some exotic materials like age-hardening superalloys and corrosion-resistant refractory alloys. (URL 3)

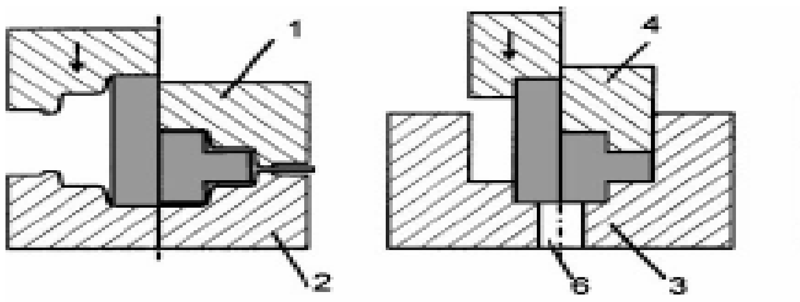
Not unlike successive forging operations in a sequence of dies, multiple open-die forging operations can be combined to produce the required shape. At the same time, these forging methods can be tailored to attain the proper amount of total deformation and optimum grain-flow structure, thereby maximizing property enhancement and ultimate performance for a particular application. Forging an integral gear blank and hub, for example, may entail multiple drawing or solid forging operations, then upsetting. Similarly, blanks for rings may be prepared by upsetting an ingot, then piercing the center, prior to forging the ring.

2.3.2 Precision Forging

Precision forging is a forging process that produces net shapes or near net shapes in as - forged condition. The term net indicates that no subsequent machining or finishing of a forged surface is required. Thus, a net shape forging requires no further work on any of the forged surfaces, although secondary operations may be required to produce minor holes, threads, and other such details.

Precision forging is especially attractive in the case of parts with complex surfaces that are difficult or costly to machine. Turning is a relatively inexpensive operation in comparison with milling, grinding, or gear cutting. Not surprisingly, many precision forging applications involve gears and similar types of parts . Given a geometry that is amenable to precision forging, tolerances of ±0.25 mm can generally be achieved.

The main differences between conventional forging and closed die forging are demonstrated in Figure. 2.1 (Doege and Bohnsack, 2000).



1. Upper die
2. Lower die
3. Die
(a)

4. Punch
5. Counterpunch
6. Ejector
(b)

Figure 2.1 Comparison between (a) conventional closed die forging and (b) flashless (precision) forging (Doege and Bohnsack, 2000).

In precision forging, it has to be considered that due to the working principle of deformation and the higher accuracy of parts, the precision die forging technology leads to larger efforts and requirements in process, tooling and forging equipment.

The process requirements are:

1) High billet accuracy, which permits to a variation of the mass between ± 0.5 and ± 1%. This can be achieved by precision shearing or sawing of the billets. The billet accuracy depends mainly on the billet material; a higher strength leads to higher billet accuracy
2) Constant tool temperature; Regarding small tolerances of the die and small gaps between relatively-moving tool components a constant tool temperature is very important for a reliable tool function as thermal expansion can lead to decreasing gap dimensions and blocking tool elements. Additionally the thermal expansion of the die influences the workpiece quality
3) Constant forging temperature; Because of the thermal shrinking of the forged part, the forging temperature correlates directly with the workpiece geometry and accuracy. Furthermore the forging temperature influences the microstructure of the final workpiece, the flow stress of the material, the deformability and - by thermal expansion - the volume of the billet

The tool requirements are as follows:

1) Exact guidance of tool elements; Especially when the die is closed by the upper punch an exact guidance of the upper punch is necessary because of the small gap between punch and die wall. The gap is usually less than 0.1 mm to avoid flash on the face of the forging.
2) Positioning of the billets inside the die; To guarantee a constant form filling of the whole die an exactly defined position of the billet inside the die is necessary
3) Reliable closing of the dies; This is the most important factor for the function of precision forging closed die tool sets because for many precision parts the die-parting line is nearby function elements so burr in these areas is not allowed. As shown in Figure 2.1 dies can be closed by additional closing elements like die parts or by punches. If dies are closed by closing elements the level of the closing pressure has to be higher than the normal pressure inside the die at the end of the deformation.

The tool requirements are overload protection, tool mounting space, ejector, and constant forging energy. (Doege and Bohnsack, 2000).

Weronski et all (2005) studied the screw spike forging based on the flashless forging and hot rolling processes. They found out that the flash and the groove on the head surface of the workpiece thread part could be eliminated by use of the new technology combining the flashless forging and hot rolling processes. The designing in this technology was based on computer simulations and this technology has several advantages like improving the finished product functional quality, increasing of productivity and obtained economic effects.

2.3.3 Closed Die Forging

In impression or closed die forging, two or more dies are moved toward each other to form a metal billet, at a suitable temperature, in a shape determined by the die impression. These processes are capable of producing components of high quality at moderate cost. (Altan et all, 1995).

The shaping of hot metal is performed completely within the walls or cavities or two dies that come together to enclose the workpiece on all sides. The impression for the forging can be entirely in either die or can be divided between the top and bottom dies.

The forging stock, generally round or square bar, is cut to length to provide the volume of metal needed to fill the die cavities, in addition to an allowance for flash and sometimes for a projection for holding the forging. The flash allowance is, in effect, a relief valve for the extreme pressure produced in closed dies. Flash also acts as a brake to slow the outward flow of metal in order to permit complete filling of the desired configuration.

With the use of closed dies, complex shapes and heavy reductions can be made in hot metal within closer dimensional tolerances than are usually feasible with open dies. Open dies are primarily used for the forging of simple shapes or for making forgings that are too large to be contained in closed dies. Closed-die forgings are usually designed to require minimal subsequent machining.

Closed-die forging is adaptable to low- volume or high-volume production. In addition to producing final, or nearly final, metal shapes, closed-die forging allows control of grain flow direction, and it often improves mechanical properties in the longitudinal direction of the workpiece.

The size of the forgings produced in closed dies can range from a few kilograms to several tons. The maximum size that can be produced is limited only by the available handling and forging equipment. Forgings weighing as much as 25400 kg have been successfully forged in closed dies, although more than 70% of the closed- die forgings produced weigh 0.9 kg or less.

In closed-die forging, a material must satisfy two basic requirements. First, the material strength (or flow stress) must be low so that die pressures are kept within the capabilities of practical die materials and constructions, and, second, the forgeability of the material must allow the required amount of deformation without failure. (ASM 1988)

2.4 Forging Material

The forging material influences the design of the forging itself as well as the details of the entire forging process. Table 2.1 lists various alloy groups and their respective forging temperature ranges in order of increasing forging difficulty.

Table 2.1 Classification of alloys in order of increasing forging difficulty (ASM,1988)

Alloy Group	Approximate Forging Temperature Range (^{o}C)
Least difficult	
Aluminum alloys	400-550
Magnesium alloys	250-350
Copper alloys	600-900
Carbon and low alloy steels	850-1150
Martensitic stainless steel	1100-1250
Maraging steels	1100-1250
Austenitic stainless steel	1100-1250
Nickel alloys	1000-1150
Titanium alloys	700-950
Iron base superalloys	1050-1180
Cobalt base superalloys	1180-1250
Niobium alloys	950-1150
Tantalum alloys	1050-1350
Molybdenum alloys	1150-1350
Nickel base superalloys	1050-1200
Tungsten alloys	1200-1300
Most difficult	

In most practical hot-forging operations, the temperature of the workpiece material is higher than that of the dies. Metal flow and die filling are largely determined by the resistance and the ability of the forging material to flow, that is, flow stress and forgeability; by the friction and cooling effects at the die/material interface; and by the complexity of the forging shape. Of the two basic material characteristics, flow stress represents the resistance of a metal to plastic deformation, and forgeability represents the ability of a metal to deform without failure, regardless of the magnitude of load and stresses required for deformation.

The concept of forgeability has been used vaguely to denote a combination of resistance to deformation and the ability to deform without fracture. Because the resistance of a metal to plastic deformation is essentially determined by the flow stress of the material at given temperature and strain rate conditions, it is more appropriate to define forgeability as the capability of the material to deform without failure, regardless of pressure and load requirements.

In general, the forgeability of metals increases with temperature. However, as temperature increases, grain growth occurs, and in some alloy systems, forgeability decreases with increasing grain size. In other alloys, forgeability is greatly influenced by the characteristics of second-phase compounds. The state of stress in a given deformation process significantly influences forgeability. In upset forging at large reductions, for example, cracking may occur at the outside fibers of the billet, where excessive barreling occurs and tensile stresses develop. In certain extrusion-type forging operations, axial tensile stresses may be present in the deformation zone and may cause center burst cracking. As a general and practical rule, it is important to provide compressive support to those portions of a less forgeable material that are normally exposed to the tensile and shear stresses.

The forgeability of metals at various deformation rates and temperatures can be evaluated by using such tests as torsion, tension, and compression tests. In all of these tests, the amount of deformation prior to failure of the specimen is an indication of forgeability at the temperature and deformation rate used during that particular test difficulty (ASM,1988).

2.5 Forging Dies

2.5.1 Die Materials for Hot Forging

Die materials used for hot forging include hot-work tool steels, some alloy steels such, and a small number of proprietary, lower-alloy materials. The hot-work tool steels can be loosely grouped according to composition (see Table 2.2). Die materials for hot forging should have good hardenability as well as resistance to wear, plastic deformation, thermal fatigue and heat checking, and mechanical fatigue. Die design is also important in ensuring adequate die life; poor design can result in premature wear or breakage.

Hot-work die steels are commonly used for hot-forging dies subjected to temperatures ranging from 315 to 650 °C. These materials contain chromium, tungsten, and in some cases, vanadium or molybdenum or both. These alloying elements induce deep hardening characteristics and resistance to abrasion and softening. These steels usually are hardened by quenching in air or molten salt baths. The chromium-base steels contain about 5% Cr (Table 2.2). High molybdenum content gives these materials resistance to softening; vanadium increases resistance to abrasion and softening. Tungsten improves toughness and hot hardness; tungsten containing steels, however, are not resistant to thermal shock and cannot be cooled intermittently with water. The tungsten-base hot-work die steels contain 9 to 18% W, 2 to 12% Cr, and sometimes small amounts of vanadium. The high tungsten content provides resistance to softening at high temperatures while maintaining adequate toughness, but it also makes water cooling of these steels impossible.

Low-alloy proprietary steels are also used frequently as die materials for hot forging. The steel 55NiCrMoV7 has good toughness and shock resistance, with good resistance to abrasion and heat checking. This steel is tempered at lower temperatures (usually 450 to 500 °C,) therefore, they are more suited for applications that do not result in high die surface temperatures, for example, die holders for hot forging or hammer die blocks (Wood, 1998a).

Table 2.2 Chemical composition of tool and die material for hot forging (Wood, 1998a)

Die Material	Chemical Composition							
	C	Mn	Si	Cr	Mo	Ni	V	Co
X32CrMoV12-28	0.35	0.80	0.80	3.00	2.10	-	-	
X38CrMoV5	0.38	0.35	1.00	5.20	1.30	-	0.45	-
X40CrMoV5 1	0.40	0.40	1.10	5.20	1.40	-	1.00	-
X38CrMoV5-3 1	0.37	0.35	0.45	5.10	2.90	-	0.55	-
55NiCrMoV7	0.55	0.80	0.25	0.90	0.35	1.65	0.10	-
32CrCoMoV12-12-28	0.32			3.00	2.80		0.50	3.00

Additional to the tool steels, given in Table 2.2, there are still developing new hot work tool steels for the aim of improving die steels. Investigations on one of the newly developed tool steel 47CrMoWVTiCeZr16-26-8 steel and of the standard X40CrMoV5-1 steel were carried out by Dobranzski et all (2001).

The tensile strength at room temperature was about 1600 MPa for 47CrMoWVTiCeZr16-26-8 steel, and about 1500 MPa for X40CrMoV5-1 steel. With the increase of the temperature to 500 ^{o}C, the tensile strength of both of these steels drop to a value of less than 200 Mpa. The plastic properties also increase with the increase of the test temperature. At room temperature, the elongation of 47CrMoWVTiCeZr16-26-8 steel, was found as the half of the standard X40CrMoV5-1 steel.

They stated that the newly developed 47CrMoWVTiCeZr16-26-8 steel can be used for hot-work small size tools which require higher strength properties at elevated temperatures than standard alloy hot-work tool steel X40CrMoV5-1.

2.5.1.1 Requirements for Die Materials

Properties of materials that are important for die materials for hot forging are:

a) Ability to Harden Uniformly. The higher the hardenability of a material, the greater the depth to which it can be hardened. Hardenability depends on the composition of the tool steel. In general, the higher the alloy content of a steel, the higher its hardenability (Wood, 1998a).

b) Wear Resistance: A significant part of the energy in forging is used to break the interfacial junctions due to friction between the tool and the workpiece. A specific disadvantage of the hot and warm die-forging process is that the tools are exposed to high thermal stresses. These stresses cause failure of the dies because of wear and thermo-mechanical fatigue. The tools then have to be exchanged after a certain time of use. It leads to considerable costs not only for the tools themselves but also for the needed set-up times and thus may cause delays in delivery of the forged parts. (Andreis et all, 1999).

The hot working steels usually used for the die-forging tools are exposed to tempering effects because of high thermal and mechanical loads. These tempering effects on their part cause a greater susceptibility to wear.

Generally, due to the forging temperature being well above 1000 ^{o}C, the temperature of the surface of the tool temporarily exceeds 500 ^{o}C and thus the tempering temperatures of conventional hot work tool steel. In such a case, the hardness of the tool is reduced and the mechanical impacts during forging operations can easily cause plastic deformation as well as abrasion of tool material. The friction and wear behavior of hot work tool steels were analized by Barrau et all. (2003). The hardnesses of the tool steels were 42 HRC and 47 HRC. The temperatures were between 20 ^{o}C and 800 ^{o}C. For the tool steel X38CrMoV5-1, they found out that the friction coefficient raises dramatically for the specimen at 42 HRC while it remains linear for the 47 HRC steel.

c) Resistance to Plastic Deformation: Each work metal being forged has a different resistance to plastic deformation and therefore, a different abrasive action against the die surfaces. The resistance of hot steel to plastic deformation increases as the carbon or alloy content increases. Other factors being constant, the higher the carbon or alloy content of the steel being forged, the shorter the life expectancy of the forging die.

On the other hand, increase in the temperture decreases the deformation resistance due to softened layer. The research carried out in this aspect showed that if thermally softened layer of about 1 mm thickness develops, the decrease in the deformation resistance should be within 20% of the deformation resistance of the bulk material. They also explain that this can be achieved by controlling the temperature of the tool surface layer and the strength of the hardened layer (Saiki et all (2001).

d) Toughness: Toughness can be defined as the ability to absorb energy without breaking. The energy absorbed before fracture is a combination of strength and ductility. The higher the strength and ductility, the higher the toughness. Ductility, as measured by reduction in area or percent elongation in a tensile test, can therefore be used as a partial index of toughness at low strain rates.

Fracture toughness and resistance to shock loading are often measured by the notched-bar Charpy test. This test measures the amount of energy absorbed in introducing and propagating fracture, or the toughness of a material at high rates of deformation (impact loading). impact strength. On the other hand, wear resistance and hot strength decrease with decreasing hardness. Thus, a compromise is made in actual practice, and the dies are tempered to near- maximum hardness levels at which they have sufficient toughness to withstand loading.

e) Resistance to Heat Checking: Heat checking is defined as the nucleation and propagation of thermal cracks. Thermal cracking is caused by thermal cycling, which is the periodical occurrence of a state of tension and compression on die surface. This explains cycling promotes the nucleation and propagation of radial cracks, which are the origin of the well-known heat checking phenomenon.

Pellizzari et all (2001) studied the thermal fatigue resistance of 38CrMoV5-1 and as a general rule they deduced that surface treated material presents reduced thermal fatigue resistance as compared to untreated steel. Among the surface-treated materials they remarked that plasma nitrided materials exhibit higher mean crack length than unnitrided ones and that PVD coated sample exhibits higher crack density than nitrided one. They also stated that plasma nitrided samples revealed typical bimodal distribution, which was different from AISI H11 and unnitrided samples. For plasma ntrided samples, the crack length values are concentrated around two mean values, whih represent the short or the long cracks.

Starling and Branco (1997) studied the thermal fatigue of hot work tool steel AISI H13 (quenched and tempered to 37 HRC hardness) coated with hard coatings TiN, CrN and duplex coatings. The test materials are heated to 720 ^{o}C and cooled them to 50 ^{o}C in water shower to investigate the thermal fatigue resistance of coated materials. Each sample was subjected to 500 cycles between these temperatures. After these test, they concluded that the coatings increase thermal fatigue resistance.

f) Fatigue Resistance: Mechanical fatigue of forging dies is affected by the magnitude of the applied loads, the average die temperature, and the condition of the die surface. Fatigue cracks usually initiate at points at which the stresses are highest, such as at cavities with sharp radii of curvature whose effects on the fatigue process are similar to notches (Figure 2.2). Other regions where cracks may initiate include holes, key ways, and deep stamp markings used to identify die sets.

Redesigning to lower the stresses is probably the best way to minimize fatigue crack initiation and growth. Redesigning may include changes in the die impression itself or modification of the flash configuration to lower the overall stresses. Surface treatments may also be beneficial in reducing fatigue-related problems. Nitriding, mechanical polishing, and shot peening are effective because they induce surface residual (compressive) stresses or eliminate notch effects, both of which delay fatigue crack initiation. On the other hand, surface treatments such as nickel, chromium, and zinc plating, which may be beneficial with respect to abrasive wear, have been found to be deleterious to fatigue properties. (Wood , 1998a).

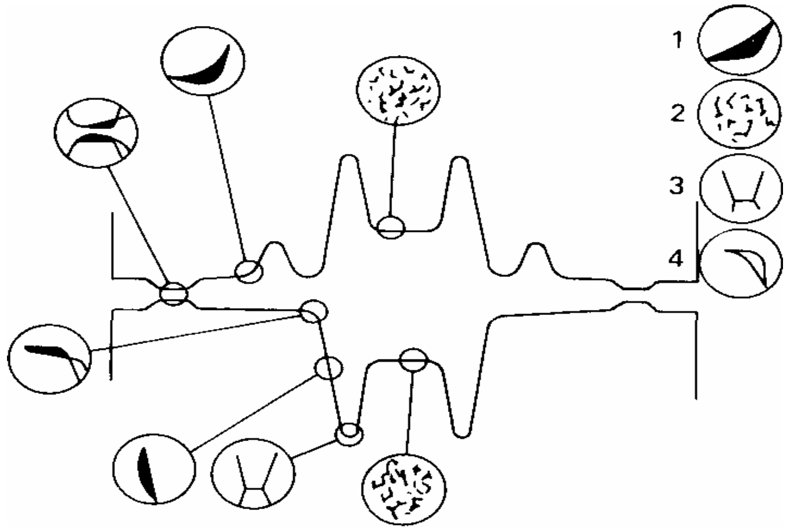


Figure 2.2 Common failure mechanisms for forging dies. 1, Abrasive wear; 2, thermal fatigue; 3, mechanical fatigue; 4, plastic deformation. (Wood, 1998a).

2.5.2 Die Life

Die life depends on several factors, including die material and hardness, work metal composition, forging temperature, condition of the work metal at forging surfaces, type of equipment used, workpiece design, the preform design, and a variety of other factors. Changing one factor almost always changes the influence of another, and the effects are not constant throughout the life of the die.

Venkatesan et all (1997) stated that the lifetimes of dies used for in the production of critical parts are very variable and are determined by the wear rate, plastic deformation, thermal fatigue and mechanical fatigue. They explained that the type of wear occurring in these dies is variously described as erosive, adhesive or abrasive wear and that wear of the die surface is caused primarily by oxide scale from the forging stock. The examinations on some worn dies showed that the abrasive wear is one of the main factor for die failure.

Some methods to estimate the die service life of dies in the hot forging process have been developed. One is a method that can predict the plastic deformation of dies; the other is for calculating abrasive tool wear (Lee et all, 2003).

Die material and hardness have a great influence on die life. A die made of well- chosen material at the proper hardness can withstand the severe strains imposed by both high pressure and heavy shock loads, and can resist abrasive wear, cracking, and heat checking (Barrau et all, 2003).

Kim et all (2005) proposed two estimating methods for predicting the die life due to wear or plastic deformation during hot forging considering the deviation of the preheating temperature of the billet. They developed an induction heating program to calculate the temperature distribution of the billet in the preheating process according to the parameters such as heating time, frequency and current density in high frequency induction heating. Then, they carried out an FE-simulation with the proposed wear and the plastic deformation models .The results they obtained showed that die life is greatly affected by the wear under the conditions that exist in a given deformation process. They concluded that the deviation of the preheating temperature of the billet leads to the reduction of the service life of hot forging dies by abrasive wear more than by plastic deformation and that these proposed methods of the die life could be used effectively for quantitative prediction of the die life in the hot forging process. These results might also be extended further for the study of optimization of the die change schedule to grind the die.

Srivastava et all (2004) investigated the cracking mechanism using laboratory experiments. They applied the thermal fatigue loading by dipping the test coupons in molten liquid aluminum bath and quenching in water at room temperature. The dip times in aluminum and water are changed to represent different conditions. Commercial FEM software is used to simulate the test conditions and to analyze the temperature and stress profile. The general thermal fatigue equations are modified to model the cracking in die-casting and predict the number of cycles and regions more susceptible to such cracking. In their study, they also represent a methodology to use a computer model to predict failure in actual dies and to make design changes like placement of cooling lines, thermal cycles, etc. to minimize cracking and increase die life.

2.5.2.1 Effect of Part Shape on Die Life

The shape and design of the workpiece often have a greater influence on die life than any other factor. For instance, records in one plant showed that in hammer forging of simple, round parts (near minimum severity), using dies made of a hot work tool steel at 341 to 375 HB, the life of five dies ranged from 6000 to 10000 forgings. In contrast, with all conditions essentially the same except that the workpiece had a series of narrow ribs about 25 mm deep (near maximum severity), the life of five dies ranged from 1000 to 2000 forgings. In thin sections of a forging, the metal cools relatively rapidly. Upon cooling, it becomes resistant to flow and causes greater wear on the die. Thin sections, therefore, should be forged in the shortest time possible. Pads or surfaces on the forging designated as tooling points, or those used for locating purposes during machining, should be as far from the parting line as practicable to increase die life. Draft angles in the die cavity and, correspondingly, draft on the part increase as more forgings are made in the die. This is because wear on the die wall is greatest at the parting line, and least on the sidewall at the bottom of the cavity. Maximum wear near the parting line is caused by metal being forced to flow into the cavity and then along the flash land. Deep, narrow depressions in a forging must be formed by high, thin sections in the die. The life of thin die sections usually is less than that of other die sections, because the thin sections may become upset after repeated use.

The workpiece tolerance has also an effect on die life. Its effect on die life can be demonstrated by assuming a constant amount of die wear for a given number of forgings, assigning different tolerances to a single hypothetical forging dimension, and then comparing the number of forgings that can be made before the tolerances are exceeded. For instance, if a dimension on a forging increased 0.025 mm during the production of 1000 forgings and the dimension had a total tolerance of 0.76 mm, die life would be no greater than 30000 forgings, assuming a uniform rate of die wear. If the tolerance on the dimension were reduced to 0.5 mm, all other factors being the same, die life would be reduced to no more than 20000 forgings. In assuming a constant rate of die wear, this calculation does not give an accurate reflection of the relation between number of forgings made and amount of die wear. In particular, experience has shown that die wear is not constant during the forging of carbon and alloy steels. The first few hundred forgings cause more wear on the die than an intermediate group of a larger number of forgings. Near the end of the die life, a small number of forgings cause a large amount of die wear. The actual effect of a change in dimensional tolerance on die life therefore depends on the slope of the curve that shows the relationship of die wear to the number of forgings made (Wood, 1998a).

2.5.2.2 Effect of Die Design on Die Life

The improvement of fatigue life of hot forging dies is of primary concern to design engineers. Fracture usually starts at the working surface of die that is subjected to repeated thermal–mechanical loading. Quite often, cracks on the surface of the die become visible after only a few thousand forging cycles. Cracks initiating in the most critical areas propagate under applied loading which can lead to a complete fracture of the die. Design of intermediate preform is generally carried out using empirical production experience. Its quality is dependent on the skills of the design engineer. Checking and correction of preform-shape are often based on construction of prototypes, or by modeling with soft model materials. Lapovok (1998) explained a new developed method of optimizing preform design which is carried out by means of a program called FORM 2D. The simulation for calculations, of the stress – strain – temperature distribution showed that the stresses in some points exceeded the yield stress, and plastic deformation occurred at the die surface. He stated that accumulation of damage at the surface, caused by accumulated plastic strain, lead to the final failure of the die. He concluded that that the geometry of the preform die had to be changed to increase the finisher die life.

The same software is also used in the study of N.Biba et all (2001) concerning the cost effective implementation of forging simulation. He also stated that die life could be increased by means of pre stressed dies.

2.5.2.3 Effect of Temperature on Die Life

Of all the work metal factors influencing die life, the temperature of the metal being forged is one of the most difficult to analyze. The surface temperature of the metal as it leaves the furnace can be determined, but unless the proper heating technique has been used, ensuring that the temperature is the same throughout the cross section, the measured temperature will not be an accurate indication of metal temperature. In addition, the time used for performing all the operations involved in forging works against maintenance of the optimum forging temperature. The metal loses heat during transfer from the heating source to the forging machine. Cooling of the metal during forging is accompanied by an increase in its resistance to plastic deformation and, correspondingly, in its abrasiveness.

The life of the finisher impression can be increased by reheating the preform before finish forging. Even though the metal may be hot enough to forge satisfactorily without reheating, forging of cooled metal in the finisher impression may cause premature flash cooling and premature wear of the flash land. When the temperature of the flash is reduced several hundred degrees and forging is continued, the cushioning effect that otherwise would be provided by freely flowing flash is either greatly reduced or lost completely. If the dies do not crack, they suffer a peeling effect on the flash land, which may cause a bulge in the die impression.

Scale is a hard, abrasive substance formed by the combining of iron and atmospheric oxygen on the surface of heated steel, particularly at the high temperatures of hot forging. The amount of scale formed varies with the grade of steel, type of furnace, and the atmosphere, or air-to-fuel ratio, in which the metal is heated. Lifting the forging and blowing the scale away after every blow or every two blows in the hammer or press helps reduce die wear due to scale. Hydraulic descaling, scraping, or using a preforming impression in which the scale is broken reduces die wear. (Wood, 1998a)

2.5.2.4 Effect of Heat Treatment of Die Materials on Die life

Research and Development activities focused on improving die life have found that the heat treatment process has a significant effect on the ability for the die materials to meet, or exceed, the performance requirements. Of particular importance is a rapid quench rate. In general, a die steel is firstly quenched and then tempered

The complex hot-work tool steel in which, due to suitable selection of alloying elements and their concentration as well as due to suitably performed thermal treatment, one can modify the structure and properties, is a group of steel that requires the effective utilization of alloying elements contained in a considerable portion of carbides.

One of the factors that decides on operation life and reliability of tool materials is structure and chemical composition of carbides undissolved during austenitizing, whose fraction and type determines saturation of matrix with alloying elements and with carbon, thus obtaining good steel properties as a result of separation of dispersion carbides during tempering. During experiment carried out for the comparison of X40CrMoV5-1 and 47CrMoWVTiCeZr16-26-8 hot work tool steels, it has been found that alloy carbides, in steel enriched with elements like Zr, Ce and Ti, differ considerably both in structure and in chemical composition from carbides in Cr–Mo–V steels, The main reason for this case is stated as the fact that this alloy carbides have influence on temperature of phase transformation, structure as well as steel properties (Dobrzanski et all, 2004). The chemical composition of these steels is given in Table 2.3.

Table 2.3 Chemical composition of 47CrMoWVTiCeZr16-26-8 and X40CrMoV5-1 tool steels (Dobrzanski et all, 2004).

Steel Denotation	Mass Concentration of Elements									
	C	Mn	Si	Cr	W	Mo	V	Ti	Ce	Zr
47CrMoWVTiCeZr16-26-8	0.47	0.13	0.27	4.04	1.97	2.60	1.10	0.26	0.10	0.06
X40CrMoV5-1	0.41	0.44	1.09	5.40	0.01	1.41	0.95	-	-	-

Another important factor that is affected by the heat treatment of the die and which is closely related with die life is wear. Wear has been defined as the material removal from solid surfaces, which may cause failure of industrial components. Many investigations about modes of wear have been carried out by many investigators over many years. The regimes of wear mechanisms and wear rate depend extensively on chemical composition, microstructure, load level and the surface properties of materials.

The modes of wear in steels are oxidative or mild. At low load levels, sever wear occurs just after the start of sliding with the formation of large, metallic wear debris resulting in a high wear rate and afterwards the wear mode changes to a steady, mild condition with fine oxidized wear debris (Goto and Amamoto, 2003)

On the other hand at high load levels, the contact temperature is increased. This temperature may be greater than 400 ^{o}C if the sliding velocity and contact pressure are sufficiently high. This high temperature condition may induce the oxidative wear of steels.

In general, martensitic phase transformation is usually used to increase the wear resistance of steels. However, a large number of components with ferrous martensitic structure fail at unexpected times and the failures of these parts are usually due to wear. Thus, the volume fraction of martensite phase not only has a dominant influence on the surface life of industrial parts, but also may have inverse effects under some conditions.

The wear resistance of quenched and hardened X40CrMoV5-1 tool steel and effects of in situ surface tempering on it have been examined. This grade is an important industrial steel which is used in hot working applications such as forging and die casting moulds. In addition a transition of wear modes from mild to oxidative is investigated. Regarding this fact, the specimens have been subjected to wear for different variables such as load, sliding distance, and tempering time under dry sliding conditions at normal room temperature (Bahrami et all , 2004)

Effect of tempering time on the hardness of X40CrMoV5-1 tool steel is shown in Figure. 2.3. Specimens that tempered twice for 90 min at 600 ^{o}C exhibit significant secondary hardening. This typical behavior of hot work tool steels is related to the various carbide precipitations that occur during tempering. The distribution of carbide particles in the matrix of quenched specimen is shown in Figure 2.4. These particles are almost vanadium carbides that are not dissolved during austenizing. The percentage of the carbides area measured by an image analyzer software is nearly equal to 6.9%. These carbides have an important role in increasing wear resistance.

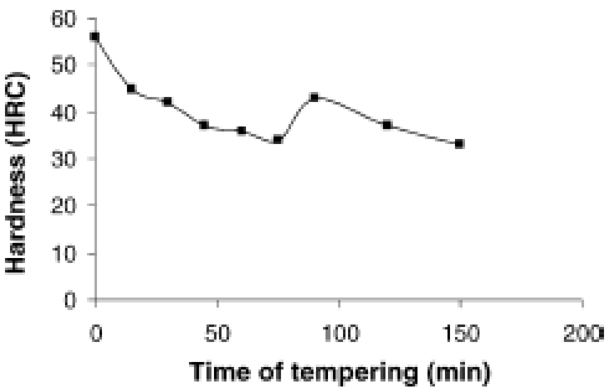


Figure 2.3 Effect of double tempering time on hardness of X40CrMoV5-1 tool steel. (Bahrami et all , 2004)

Figure 2.5 shows the weight loss or in other words the wear amount of samples after 1000 m against tempering time for 29.4 and 98N load levels. It is observed that for the 29.4N load level, quenched specimens have the lowest weight loss. But at the 98N load level, the specimens tempered 30–60 min show the lowest weight loss. As the load increases, because of high localized pressure and temperature, in situ surface tempering is occurred. This tempering, probably, transforms these specimens to the secondary hardening state that shows the highest wear resistance. Exactly for this reason the martensitic quenched structure transforms to a soft tempered structure that shows the highest weight loss. It seems that sliding under 98N load is similar to temper between 30 and 50 min which results in a considerable decrease in hardness of quenched specimens as evident in Fig. 2.3. But when the values of both load and sliding velocity are small, the rising in temperature is not enough for rubbing surface tempering and the quenched specimens have the highest wear resistance because the martensitic structure, probably, remains stable during wear.

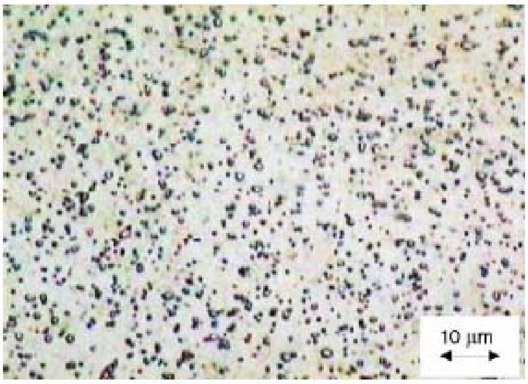


Figure 2.4 Distribution of carbide particles in the matrix of quenched specimens. (Bahrami et all , 2004)

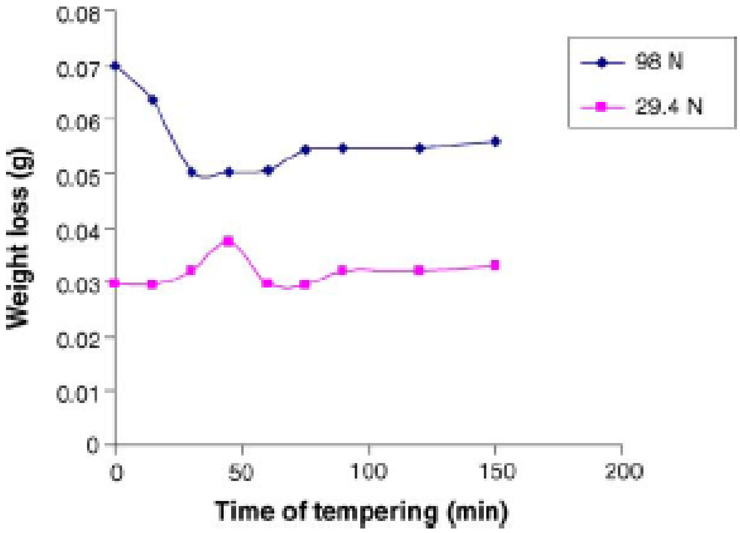


Figure 2.5. Weight loss of the specimens after 1000m with time of tempering. (Bahrami et all, 2004)

2.5.2.5 Effect of Lubrication on Die Life

In the metal forming process, lubricants are used between surfaces in the contact area and moving relative to one another to reduce the value of the friction factor or to reduce the wear of the contacted surfaces and to reduce heat-transfer from the billet to the die during the forging processes. Therefore, the frictional conditions between the dies and the billet have a great effect on metal flow, internal defects, the working stress on the tool and the forming load. Also the heat-transfer coefficient from the billet to the die, which can have different values according to the kind of lubricant, is in great importance because the temperatures developed in the process influence the lubrication conditions, the metal flow during deformation, and the quality and properties of the final product. In addition, the selection of suitable lubricant for extending the die life leads to reduce heat-transfer from the workpiece to the die (Kim et all; 2001).

The service life of a hot forging die is mostly determined by wear, thermal cracking and fatigue, and plastic deformation of the die. Many researchers have investigated the influence of various process variables and tool conditions on die service life. The surface hardness of a die decreases during the repeated operations, which induces thermal softening of hot forging tools. This thermal softening decreases the resistance to wear or plastic deformation of the die (Lee et all, 2003; H.Saiki et all, 2001).

During the hot forging process, lubrication conditions can depend on the boiling state of the water base and oil base lubricants. In the case of water-base lubricants, the boiling point of water is 100 ^{o}C, and that of oil is 236 ^{o}C for oil-base lubricants. Therefore, the lubrication condition of the hotter billet can easily change to a dry friction state, and also the die surfaces sprayed with a water-base lubricant progress gradually to a dry friction state. By contrast, die surfaces sprayed with an oil-base lubricant may be in a boundary lubrication state. On the basis of the friction factor with boundary lubrication being smaller than that of dry conditions, the friction factor of an oil-base lubricant is lower than that of a water-base lubricant, and so the die service life for an oil-base lubricant is higher than that for a water-based lubricant owing to the low friction factor, and the die service life restricted by abrasive wear was shorter than that restricted by plastic deformation. Therefore, the die service life for lubricant depends on abrasive wear rather than on plastic deformation, and consequently it was abrasive die wear that influenced the die service life of the hot forging process. (Lee et all, 2003)

2.5.3 Surface Treatments

Extremely abrasive materials such as titanium alloys, or others requiring high forging pressures, subject the dies to greater wear rates than most commonly forged ferrous materials. And complicated forging designs, because of the higher pressures required, create more wear than simple forging designs. In these situations, it may be economically justifiable to enhance the wear resistance of the tooling by some surface modification.

Some common methods of modifying the surface to improve the wear properties are weld overlays, nitriding, chemical vapor deposition (CVD) and surface coatings. These techniques produce a very high hardness material, perhaps 70 HRC or more, but only in very shallow layers, a thousandth of an inch or less in the case of nitriding or CVD. It is the thinness of the applied layer that negates the inherent brittleness, but captures the excellent abrasion resistance. Although the base die steel is relieved of the demands for abrasion resistance, the die material must have sufficient heat resistance to provide a strong substrate for the working layer. High die temperatures though have minimal effect on the modified surface, may weaken the substrate sufficiently to permit deformation to occur; a mode of failure to which the shallow surface layer is susceptible.

The disadvantage to modified surfaces is that they must be reapplied whenever die repair or resinking is performed.(Cerwin and Phillips; 1995)

2.5.3.1 Plasma – Nitriding (İon Nitriding)

In general, under high loads, temperatures and corrosive environments, the surfaces of machine parts are subjected to higher stresses than the interior regions. Unless there exists a material defect within the machine component, failure starts from the surface region. Contact surfaces of the machine components tend to wear much faster than the other regions due to contact loads and other stress inducing effects, e.g., heat and corrosion. By steel surface treatments such as nitriding and carburising, the surface hardness of the material is increased and this effect improves the wear properties of the materials.

Plasma-nitriding, also called ion-nitriding, or glow discharge nitriding is one of several advanced surface treatment processes for improving the surface properties of the materials. It is a thermo chemical process, in which the surface chemistry of the material is changed under heat. Plasma-nitriding has advantages over traditional nitriding processes such as salt bath nitriding and gas-nitriding, including lower treatment times, lower temperatures and environment friendliness (Çapa et all, 2000)

Çapa et.all. (2000) applied plasma-nitriding surface treatment process to AISI-H13 hot-work tool steel. The nitriding time varied from 2 to 16 hours in order to investigate the effects of time on the nitriding process. This material was used for making hot-forging dies. The effects of nitriding time on the hardness, diffusion layer depth and life of hot-forging dies were studied. The effect of nitriding time on hardness is shown in Figure 2.6

Plasma-nitriding treatments were found to increase the surface hardness of the materials in comparison with the as-received material, which had a hardness of 550 HV0.1. The surface hardness varies with nitriding time. About 8 -10 hours of ion-nitriding treatment increases surface hardness to a maximum of about 1300 HV0.1.

They stated that for plasma – nitriding time of 10 hours which resulted in a diffusion layer only without the white nitride layer the maximum lives of plasma-nitrided hot-forging dies increased to more than eight times of that of the as received die.

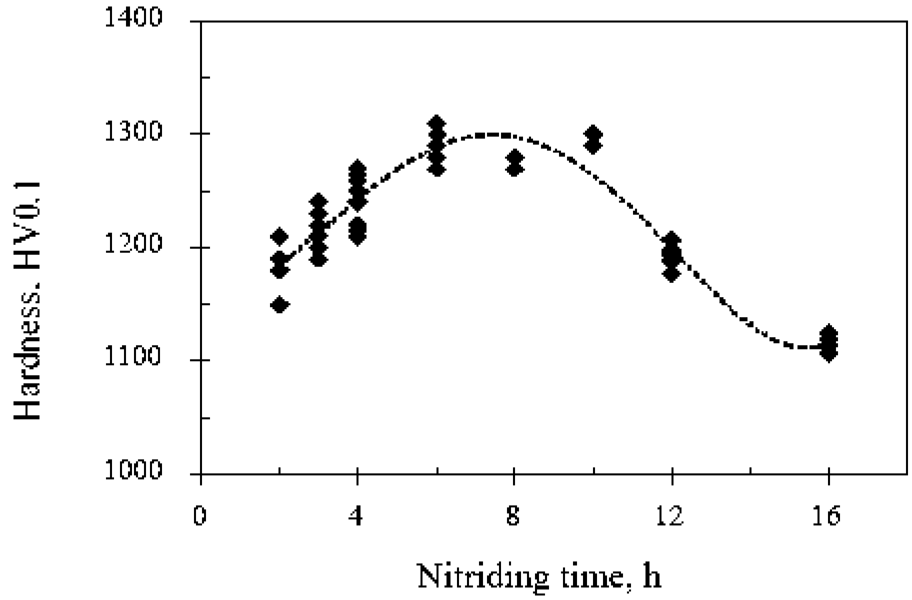


Figure 2.6 Surface hardness as a function of nitriding time (Çapa et.all., 2000)

The plasma - nitriding hardening mechanisms of low alloy steels are explained by Sun and Bell (1991). Nitrogen diffuses in the steel from the surface to the core. During the diffusion process, nitrogen partly replaces carbon in martensite, and forms metal nitrides, such as iron nitrides and chromium nitrides in the matrix and also at the grain boundaries. Redistribution of carbon occurs in the diffusion zone, and carbon is pushed back towards the core region. Near the surface, carbon concentration decreases, and towards the core region a higher concentration of carbon is observed in comparison to the overall carbon concentration.

Pant and Bleck (2005) used hard metal mono carbides like TiC, Cr3C2, WCCo and WCCoCr, alloyed in the tool's surface for backing the nitrided layer in their study. Nitrided layer cases often suffer from severe impact wear. Therefor, they carried out the impact wear tests of the duplex-coatings by a special apparatus where a fixed tungsten carbide ball periodically stroke on the specimens' surface. Results have shown that the best impact wear resistance is provided by plasmanitrided duplex-layer WCCoCr. After the laboratory experiments, some of the tested duplex-coatings were produced on simple industrial tools for screw-production to evaluated their exposure time. In these tests they obtained a 50% increase in tool life for plasma nitrided duplex-layer WCCoCr.

2.5.3.2 Gas Nitriding

The efficiency of nitriding is controlled by the nitrogen potential Np, which is affected by the conditions arising on the surface of the treated material. The final state of the surface and the chemical composition of the material considerably influence the reactivity of the surface. This primarily concerns chromium-bearing materials that have a coat of chromium oxidgas nitriding on the surface, which hinders the interaction with nitrogen-bearing gases. For this reason many researchers have used various methods for increasing the surface reactivity, such as shot blasting, oxidizing, or treatment with chlorine- or fluorine-bearing substances. Nitriding at reduced pressure with and without ionization has some use, but such processes take more time than plasma nitriding. On the contrary, enhanced-pressure nitriding promotes a certain increase in the nitrogen potential and is applied at an industrial scale. In any case, the addition of carbon increases the surface reactivity and results in the formation of carbonitride, and a carbon-bearing saturating medium can accelerate the reactions. Specialists in nitriding argue on the interrelation between the formation of the layer of chemical compounds and its properties and the presence or absence of carbon. The general term "nitriding" applied to any process of the kind should be differentiated into nitriding as such, "carbonitriding," and "nitro oxinitriding" because each of the processes is characterized by specific duration and by resulting properties (Funatani, 2004).

Smolik et all (2000) studied the influence of the TiN, CrN, (Ti,Cr)N and Ti(C,N) nitrided layer/PVD coating composites, on the durability of tools made of 35CrMoV5 (0.4%C, 0.4%Mn, 1.0%Si, 5.0%Cr, 1.3%Mo, 0.3%V) for hot plastic working. The structures were obtained by gas nitriding and PVD coating by means of the arc-vacuum method. Their investigations proved that the best durability was achieved for tools covered with the composite 'nitrided layer/CrN coating', for which the increase in durability was almost 90%. The smallest durability was noted for tools covered with the composite ‘nitrided layer/TiN coating’. The results obtained showed that a proper choice of the composite ‘nitrided layer/PVD coating’ structure may increase the durability of tools considerably for hot plastic working.

A similar study was carried out by Smolik et all (2004) with five different structures on dies made of tool steel DIN 1.2367. The structures were TiN / Ti (C,N) , (Ti,Cr) N, (CrN / TiN)x3, (Cr / CrN)x3, and CrN, and the nitriding process was executed with the use of the regulated gas nitriding method, whereas the PVD coatings were created by means of the arc-vacuum method. They observed three different mechanisms of destruction of hot forging dies covered by composites ‘nitriding layer / PAPVD coating’ : thermal fatigue cracks, plastic deformation and abrasive wear. And they stated that the thermal fatigue cracks are the most important destruction mechanism of forging dies in the hot plastic working processes and their intensity depends first of all on the nitriding layer properties. In order to increase the thermal fatigue wear resistance of forging dies the optimal structure of the nitriding layer must be created in the composite ‘nitriding layer / PAPVD coating’, i.e. without the compound layer on the surface and without the precipitations of iron nitrides on the grain boundaries. They also concluded that the properties of PAPVD coatings in composites obtained by the duplex treatment technology are significant for the abrasive wear and plastic deformation processes of forging dies. They observed that in the first process, the dominant parameter is hardness while in the second one it is the thermal conductivity. The analysis of forging tests results enabled them to recommend the (CrNyTiN)x3 multilayer coating as the most effective protective layer increasing durability of hot forging dies.

2.5.3.3 Salt Bath Nitriding

Funatani (2004), stated that as distinct from the long-used process of gas nitriding, which yields a layer of Fe2N nitrides on the surface, the Tenifer-Tufftride process, also known as “soft nitriding” , yields a tough and wear-resistant layer. It has been widely used in the automotive industry since BMW started to use salt bath nitriding for treating crankshafts and other parts. The diffusion layer lying under the layer of chemical compounds exhibited high wear and seizure properties and enhanced fatigue resistance. However, the requirements on environment protection replace the treatment of engine parts in cyanide baths by soft nitriding in a gas medium. However, salt bath nitriding was still used for treating parts fabricated from special steels, the gas nitriding of which gave unsatisfactory results.

Though less than half of the earlier used baths for “soft” nitriding based on cyanides are still in operation, there is a tendency for using cyanate baths, which solves virtually all of the environmental problems.

The development of a low temperature process is a recent advancement in salt bath technology. Low temperature treatment of aluminum extrusion dies and of other forming dies at 480 °C is acquiring a wide use and ensures enhanced wear resistance without deterioration of hardness even in repeated nitriding. In addition, low-temperature nitriding reduces the distortion of shafts and crankshafts for automotive applications. One more advantage of salt bath nitriding is the possibility of control of the chemical composition of the bath and of lowering the operating temperature by changing the chemical composition, which promises wider and more effective use of salt bath treatment including the nitriding of stainless and maraging steels. There are several kinds of salt bath compositions like Cyanide-Base Salt Baths and Cyanate-Base Salt Baths (Funatani, 2004) .

The diffusion rate in nitriding depends on the amount of alloying elements, especially chromium. It can be seen from Table 2.4 that the thickness of the diffusion layer depends on the type of the alloying elements However, the main characteristic of nitrogen diffusion in carbon steels C15 and C45 is its rate. The diffusion rates in α- and γ-phases and in ε and γ' compounds differ, but the nitrogen potential is the highest in salt bath treatment. Table 2.4 shows the Nitriding methods, materials and characteristics of diffusion layer.

Table 2.4 Nitriding Methods, Materials, and Characteristics of Diffusion Layer (Funatani, 2004)

Method	Temperature °C	Steel	Thickness of compound Layer μm	Thickness of diffusion Layer μm
Tuffride TF1	580	1015	ε;13	800
	580	1045	ε;13	780
	580	34Cr4	ε;10	480
	580	X210Cr12	--	160
Tuffride NS1	570	1015	ε;12	780
	570	SCM435	ε;8	171
Soft nitriding in Gas medium	570	SS2250	γ, ε;(?)	353
Soft nitriding in Gas medium	520	38CrMoA 1	γ, ε;(5)	78-97
	520	40CR	γ, ε;(4)	63-80
Gas nitriding	500	SAE9254	γ, ε;(5)	49
Plasma Nitriding	520 (pulsed)	722M24	12 h	72
Plasma Nitriding	560	En40B	(-)	100
	540	En19	(-)	110
	520	Nirtaps	(-)	46
	550	36CrMo	(-)	100
Low temperature salt bath nitriding	480	SKD61	ε;1,5	150
	570	SKD61	ε;4 + (CrN)	106
	480	SCM435	ε;4	141
	570	SCM435	ε;	200

Comparing the duration of the treatment as a function of diffusion rate for various variants of nitriding (see Table 2.4) shows that processes occurring in salt baths are preferred. Even at the lowest temperature (about 400°C) a salt bath provides the highest nitriding activity and minimum duration of treatment.

2.5.3.4 Nitrocarburizing

A subcritical nitrocarburizing process, in combination with a protective coating application, greatly improves the corrosion resistance of a wide range of carbon, alloy steel, and cast iron parts while also improving their wear resistance and fatigue, impact, and yield strength. The thermal treatment processes can be conducted in recirculating furnaces of "Homo" type at temperatures between 410°C and 635°C and the cycle times from 30 minutes up to 14 hours, depending upon the material being processed and the case depth desired. At the end of the nitrocarburizing cycle a controlled oxidation step in the same furnace is the usual process, providing an aesthetic protective finish. (Erie Steel Treating,Inc - Technical Bulletin, 2005)

The nitrocarburizing process was claimed to be predominantly a sulfurizing treatment. However, after a more fundamental examination, it was established that the surface conferred was an epsilon iron nitride layer containing carbon. Further development work led to revised salt bath techniques.Components treated in these salt baths developed an epsilon iron nitride surface containing approximately 1% carbon, hence the name nitrocarburizing. This process needed to be taken a step further, so pit type recirculating furnaces, which provide an even distribution of gas throughout the overall furnace and a high degree of temperature uniformity were customized to perform nitriding and the nitrocarburizing processes.In addition, the converted furnace made possible the oxidizing step and excellent size control.

When the nitrocarburizing cycle is completed, the furnace is purged for approximately two minutes with nitrogen. The purge is followed by the oxidizing treatment. Oxidizing is accomplished by a proprietary method where a carrier gas is injected directly into the furnace. The atmosphere produces black porous (Fe_3O_4) iron oxide on the surface of the parts.

When increased corrosion resistance is desired, the same processing steps are performed. Additionally, a coating tank is required for coating the parts with the polymer. The tank contains an updraft tube with an agitator for consistent coating of the parts and proper mixing of the liquid.

The process creates a triplex metallurgical case structure (See Figure 2.7 and Figure 2.8) that is composed of the following layers:

1. An outermost surface zone is composed of iron oxide (Fe_3O_4) which has a typical depth of from .0025 mm. This layer is produced during the oxidizing phase of the process by submitting the part to a proprietary atmosphere. The layer formed is porous with its color being black. This layer provides a highly porous surface

capable of retaining oils and corrosion preventatives. Due to the thinness of this layer it is only accurately measured using a scanning electron microscope.

2. The second layer under the iron oxide layer is compound zone, better known as the "white layer," which contains primarily epsilon iron and is micro porous at the surface. Its depth ranges from 0.0125 to .0375 mm and its micro porosity also acts as a carrier for the coating. Depending on the material being treated, surfaces hardness ratings of 60 to 72 Rockwell "C" are possible

3. The third layer is a nitrogen diffusion zone. Coupled with the compound zone, the total case will range from 0,075 to 1.0 mm, and it enhances tensile and fatigue strength.

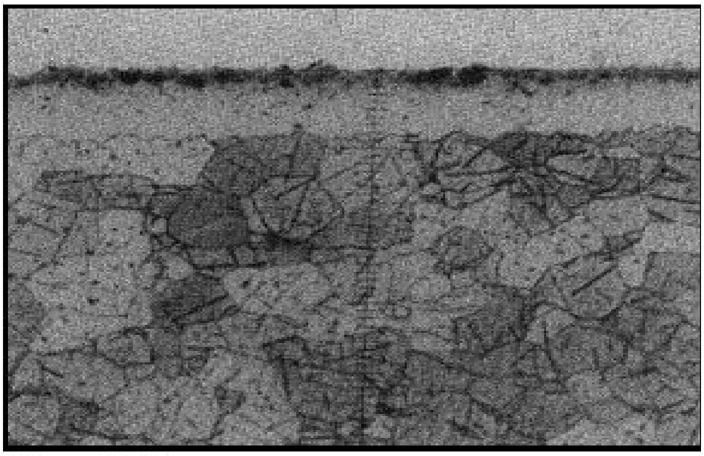


Figure 2.7 1010 low carbon steel, 0.0025 mm oxide layer,0.0125 mm compound layer, 0.25 mm diffusion zone (Erie Steel Treating,Inc - Technical Bulletin,2005)

Figure 2.8 H13 Tool steel, heat treated to 42 - 46 HRC then processed 0.0025 mm Fe_3O_4 oxide layer (Black) ,0.015 mm compound layer (white), 0.2 mm diffusion zone (black)

Chiu et all (2002) studied the surface wear characteristics of the nitrocarburized AISI H13 tool steel in quenched and tempered condition. Then the specimens were nitrocarburized for 1, 3, and 5 h. After analyzing the chemistry, microstructure, and hardness of the nitrocarburized coatings, they tested the wear behavior. They observed that white layers were predominantly composed of the ε phase iron nitrides dispersed with γ-phase, and a large amount of nitrogen and carbon trapped in the ferrite phase in the diffusion layer for ferritic structure. It was stated that nitrocarburizing treatment increased the surface roughness, hardness and the friction coefficients of the specimens and that wear contact pressures and nitrocarburized holding time also affected the friction coefficients of the nitrocarburized specimens. As result they concluded that both the ferritic and the tempered martensitic substrate specimens treated with subsequent nitrocarburizing process have shown significant improvement of the wear resistance, but wear behaviors of the specimens nitrocarburized for 1, 3, and 5 h did not vary significantly.

2.5.3.5 Single Layer and Duplex Surface Coatings

Due to the enormous quantities of products in the forging industrie and the relatively short life of the dies necessary, even small improvements in that field bring the economic effect. The PVD coatings have become the extremely important technological materials for several industrial applications; these coatings are successful in working processes at elevated temperatures. The PVD hard coatings are known for providing surfaces with enhanced tribological properties in terms of low friction and higher wear resistance (Dobrzanski et all , 2004)

It is stated that PVD TiN, TiN/ (Ti, Al)N and CrN coatings can reduce friction in tribological contacts and increase the abrasive wear resistance. In addition to the enhanced wear resistance, TiN coatings can also provide wear and oxidation resistance, especially at high temperatures (Navinsek et all, 2001; Cekada et all, 2002; Dobrzanski et all, 2004)

As reported by Dobrzanski et all.(2004) the PVD techniques make it possible to extend by 50–100% the life of tools after studied the structure and wear resistance of CrN, TiN, TiN/(Ti, A1)N PVD coatings deposited onto X37CrMoV5-l type hot work steels. The thickness of the PVD coatings in their work are presented in Table 2.5.They observed that the monolayer TiN coating and the multilayer TiN/(Ti, Al)N one demonstrate occurrence of the preferential (1 1 1) crystallographic orientation. For the adhesive and wear resistance they obtained that The CrN coatings demonstrate a very good adhesion to the substrate, next come the TiN ones, and the least advantageous adhesion was observed for the multilayer TiN/(Ti, Al)N coating. They also observed that the coating failure mechanism in all cases begins from the numerous spallings on both edges of the developed scratch. The difference was in the location of these spallings. In case of the TiN/(Ti, Al)N coating, spallings start from the lowest load (13 N). Then cracks and stretches develop at the scratch bottom, and the spalling process at the scratch edge develops further, and finally total coating delamination occurs at the scratch bottom.In their study, spalling began with the monolayer TiN coatings at the medium load value of about 20 N, and with the multilayer CrN ones at about 32 N load value.

Table 2.5 Thickness of the coatings (Dobrzanski et all. ; 2004 19)

Coating Type	Thickness (μm)	Number of Layers
CrN	7.70	1
TiN	3.16	1
(TiN / (TiAl)N)3x	3.24	6

Navinsek et all (2001) studied the applications of CrN, PN + CrN and PN + TiAlN in aluminium pressure die-casting, CrN in hot extrusion of Al and FUTURA and PN + FUTURA coating in hot forging of steel parts. They have concluded that :

1) Hard, oxidation- and corrosion-resistant CrN coating was successfully used to improve die casting of Al alloy in the mass production of components for compressors and electromotors in Slovenia. They also observed better tooling behavior by the use of a duplex treatment, while service life in production increased by 200 - 300% and the cost per injection was lowered by 15 - 40%.
2) CrN coating remarkably improved the hot extrusion dies of aluminum AC30 alloy in the production of Al rods with a diameter of 80 mm. They found out that die life increased up to 300%, die correction time was reduced and operating costs were significantly reduced. Thay believe that duplex treatment, including CrN and a TiN / TiAlN multilayered coating, will also play an important role in the improvement of hot extrusion dies in the future.
3) The duplex treatment applied undoubtedly improved the service life of hot forging dies in the manufacturing of steel components, especially in the second stroke cutting-off flash and calibration of the final size. They stated that for success in the first stroke, where the most aggressive wear appears during the forging of hot billets 1100 ^{o}C., an increase in the

plasma-nitrided diffusion depth to 150 - 200 μm and to use a 6 - 8-μm-thick FUTURA coating was needed.

Panjan et all. (2002 21) also studied the subject duplex treatment. The plasma nitrided tool steel surface provides better mechanical support for the hard coating than the original hot working tool steel, the combination of plasma nitriding and PVD hard coating may also increase the thermal fatigue resistance due to high residual stresses. High microhardness of hard coatings is not sufficient for protection of hot forging tools. The coating must also have high fracture toughness, while crack initiation and growth cause degradation and failure of hard protective coatings. One of the possible ways to achieve high hardness in combination with high fracture toughness is to use multilayered coatings. Namely, multilayered coatings have higher cracking resistance than the corresponding single layer coatings, while cracks tend to branch and deflect at the interfaces w11x. They present the results of performance tests of hot forging tools protected by duplex treatment. Heat treated and plasma nitrided tools were also tested for comparison by them.

They carried out performance tests on heat treated, plasma nitrided and duplex treated tools. They studied the wear of the tools by SEM at various points of the metallographic cross-section after forging of 300 and 1100 workpieces. They saw that the heat-treated tools were considerably damaged after 300 forgings. Specific surface effects (craters, cracks, thick oxide layer) were clearly visible. The results with plasma nitrided forging tool were much better. After 300 forgings, only a relatively thick oxide layer on the working tool surface was observed. After 1100 forgings, wear damages in the form of radial grooves and cracks were developed at the roundings of the tool where the sliding lengths were the largest. Best results were obtained with a duplex treated tool with a 90 μm plasma nitrided layer and a 3.5 μm thick Futura coating. No wear was observvcd after 300 strokes (Figure 2.9 a,b). After 1100 forgings, no damage was observed on the upper part of the tool (Figure 2.9 c), while partial delamination of hard coating in the area of the largest sliding lengths was observed (Figure 2.9 d). They concluded that Futura coating remained practically unaffected on the front side, while it was partially damaged at the roundings of the tool.

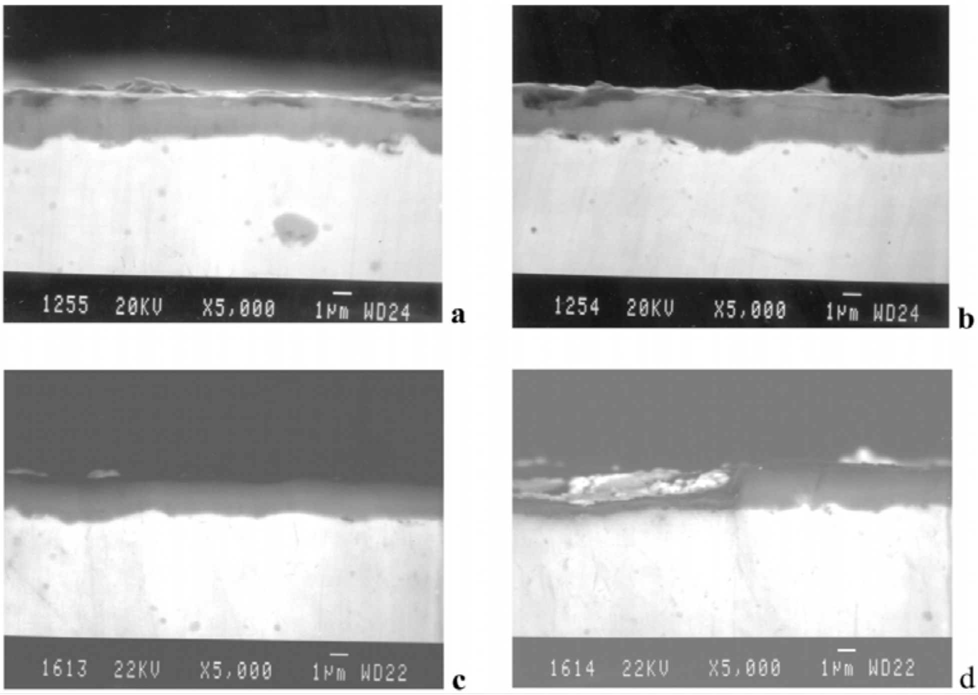


Figure 2.9. Cross-sectional SEM micrographs of duplex treated tool on the frontal surface (a,c) and at the roundings (b,d) after 300 (a,b) and 1100 (c,d) forgings (Panjan et all ;2002)

2.5.3.6 Weld Overlay Coating

The weld overlay is a coating process that applies a surface deposit that metallurgically bonds to the base material. In the past, the process was used primarily for repair and maintenance of dies and molds. Now, it is increasingly being used as an inexpensive means for depositing a hard layer on localized wear-prone die areas.

Babu et all (1999) explained that weld deposits of Alloy 625 increased forging die life by 400%. They stated that weld deposits used could be one of the following:

1) Deposits of identical material onto a die block to repair it or to allow resinking
2) Deposits of higher alloy steels (e.g., chromium hot-work steels) onto the die surface of low-alloy steels to improve the service performance of the dies (e.g., wear and heat resistance).

3) Deposits of hard or high-temperature materials (usually cobalt or nickel-based alloys) onto low-alloy or hot-work steels to improve the service performance of the dies.

The first step in any of the hardfacing processes should be the annealing of the die block into which the rough impression has been sunk. This relieves residual stresses and helps prevent cracking during welding of the surface layer. After annealing, the die block should then be reheated to a temperature of 325 to 649 °C, which is also necessary to minimize cracking due to thermal gradients set up between the surface and interior during welding. The application of the surface layer can then be performed by using a proper welding process.

Together with the solidification conditions, the amount of melted base material and base material dilution is important for wear properties. For repair of dies, the shielded metal- arc method is preferred. It allows high productivity and has the advantage of low heat input and thus minimal distortion of the die cavity.

After welding, the die block must be cooled to room temperature to prevent cracking of the welded deposit. The die impression is then finished, machined and ground. Heat treatment (austenitizing, quenching, and tempering) of the die block is performed last. Once again, differences in thermal properties between the base metal and surface deposit are critical insofar as thermal cracking is concerned.

For weld overlay, welding alloys are generally base on iron, cobalt and nickel metals. Hard phases are formed by addition of carbon (in Fe) or boron (in Ni). The preferred application methods for various alloys are: iron alloys deposited by surface weld methods, cobalt alloys by welding and powder surfacing and hard nickel alloys ing the form of powder. The volume fraction for hard phase is very important for the wear resistance in the weld deposit. Often there is no proportional dependence and the best wear resistance is not achieved by the highest hard phase concentration.

Various ferrous alloys are used to repair steel dies or to lay down deposits of better wear and heat resistance in the welded deposit. Often there is no proportional dependence and the best wear resistance in not achieved by the highest hard phase concentration. Different microstructural combinations are used to increase wear resistance of tool steel, these include transformation behavior (bainite, eutectic) and the use of carbide forming elements where chromium is used as alloying element. Austenitic and austenitic-ferritic materials are preferred for wear resistance under higher loads (Babu et all, 1999).

Hard-faced tool steels have to be heat treated before use. However, hyper-eutectic cast or carbide sinter alloys are not suitable for heat treatment and the weldment from carbide filler rods exhibit the required material properties directly after welding. In respect of the economic importance, hard facing with iron base alloys predominates in comparison with nickel and chromium alloys. This is more relevant with the increasing automation of hard surfacing and the use of robots in welding systems.

Nickel- and cobalt-base alloys are the usual choices for hard-facing of dies. Questions concerning the transformation or primary phase instability during hard surfacing process can be considered of secondary importance in hard cobalt or nickel alloys. The material properties are present after solidification from melt. Use of these alloys in hardfacing offers a considerable saving over die blocks of these alloys. In a typical hardfacing operation, one or two layer of alloy, each about 0.25 to 1.27 mm thick are deposited in the die. If a very large amount of buildup is desired or require, however, it is advisable to apply layers of stainless steel, high nickel alloy, or low-alloy filler metal first rather than many layers of hardfacing.

The influence of the cobalt matrix composition and the carbide content on the impact strength, thermal shock resistance, coefficient of linear expansion, tensile strength, ductility and hardness, as a function of temperature are used for evaluating the wear behavior of the coating. Hard cobalt alloys are processed as cast rods, electrodes, filler rods and metal powder. Another recent laboratory investigation into the elevated temperature properties of cobalt based hardfacing alloys concluded that for the Stellite group of cobalt alloys, the higher the cobalt content, the better the resistance to metal-to-metal wear in the temperature range 0 to 750 ^{o}C. For this group of alloys, wear rate decreases with increasing temperatures, in the range 850 to 1000 ^{o}C. For a given matrix chemistry, increased hard phase volume friction may be of some benefit in resisting metal-to-metal wear The cobalt-chromium and cobalt iron chromium alloys exhibit a maximum metal-to-metal wear rate around 250 ^{o}C.

The low wear rates of nickel-rich hardfacing alloys have been attributed to their oxidation kinetics and the nature of their oxide scales. Low wear rates and the formation of very shiny oxide scales, termed glazes, characterize the high temperature behavior of some nickel-chromium alloys (Babu et all,1999).

Lin and Chen (2006) studied the deposition of cobalt based alloys (Stellite 6 and Tribaloy T-900) and 410 stainless steel (SS) on mild steel substrates by a coaxial laser cladding process to create a thin surface layer with the thickness of less than 0.5 mm. In their study, they observed that laser-clad Stellite 6 and Tribaloy T-900 specimens exhibited refined dendritic microstructure and that the interdendritic eutectics consisted of either small carbides or intermetallic compounds randomly distributed in a cobalt-rich solid solution, unlike the lamellar structure as observed in conventional weld overlays. They measured the hardness values of the laser-clad layers higher than those of conventional welding deposits owing to the refined effect. They observed that the wear and corrosion resistance of Stellite-6 and T-900 specimens were considerably better compared to those of laser-clad 410 SS specimens. In addition, they stated that the T-900 specimen had substantially lower corrosion rates than the Stellite-6 specimen in hydrochloric acid solution. Experimental results indicated that wear and corrosion characteristics of the T-900 specimen were excellent; however, preheating was required to avoid cracking in the laser cladding process.

2.6 Evaluation of Literature Survey

In hot forging, the surface parts of the die are cyclically exposed to various kinds of loads, This loads are very high thermal loads (600–900 ^{o}C), mechanical loads (contact pressures of 1000 N/mm^2 or more), tribological and chemical loads. These loads result in various types of damages on the tool surface layer, which may lead to the tool failure during the forging process. On forging tools, wear is responsible for tool failure in 70%, mechanical cracking in 25%, thermal cracking in 2% and plastic deformation in 3% of failure cases. For tools coated with surface coatings, thermal and mechanical fatigue (scaling of the coated layer) are the main mechanisms responsible for tool wear. The main parameters that influence wear are: normal and tangential contact stresses (friction), relative sliding velocity, sliding lengths, contact time, temperature of the workpiece, basic temperature of the tool, scale of thickness with a mixture of oxide phases and structures, workpiece reduction (contact interface traction), lubricant (modes of lubrication), heat transfer, tool hardness and ductility (type and quantity of carbide-forming elements), etc. mentioned scale of thickness is the dominant index in establishing predictive relations between surface shear and contact pressure, temperature gradients and modes of lubrication (Tercelj et all, 2006).

With the purpose of increasing the thermal fatigue resistance, reducing the friction and wear, increasing the hardness, several studies have been carried out. Most of the studies are related with the coating of the die surface. Many researchers have studied the coatings vary from nitriding, including salth bath nitriding and plasma nitriding, PVD coating, or duplex coating including both nitriding and PVD coating. But only a few researches have been made for the weld overlay coating of hot forging dies. Because of the lack of the study for weld overlay coating, in this study, besides the above mentioned coatings, the weld overlay coating has been studied widely. Finally, it was observed that in hot forging processes, weld overlay coating may be the best solution for hard coatings of the dies.

3. MATERIAL and METHOD

3.1 Material

3.1.1 Forging Equipment

A mechanical press produced by BRET, a French company, type PM 250 has been used in this study. The press, shown in Figure 3.1, had a capacity of 2500 metric tons at 8 mm from bottom dead center (BDC). The frame of this press has a compact structure which ensures very high stiffness that reduces distortion during forging. The press is fitted with huge flywheel that provides the energy for forging. The ram is guided by 8 very long hardened bronze high precision guides, adjustable in each direction by non-reversible shims. The forging and die stamping press bolster are fitted with a mechanism for accurately adjusting the height between the bolster and the ram plate, which enables an adjustment within 12 mm. The technical specifications of the press are outlined in Table 3.1.

Figure 3.1 Two views of the mechanical press used in this work

Table 3.1 Technical properties of BRET PM 250

Capacity (ton)	2500 tons at 8 mm from BDC
Ram Stroke (mm)	300
Maximum tool shut height (mm)	900
Minimum tool shut height (mm)	888
Ram height adjustment (mm)	12
Press speed (strokes /min)	60
Distance between uprights (mm)	1340
Distance between Ram guides (mm)	1140 (left-right) – 1300 (front-rear)
Bolster Dimensions (mm)	1260 (left-right) – 1300 (front-rear)
Side opening (mm) (width of windows in upright)	760
Stoke of upper ejector (mm)	50
Stroke of lower ejector (mm)	60
Number of stations	3

3.1.2 Billet Heating Equipment

The characteristics of the billet during electroplating or induction heating are very complex in the preheating process. Therefore, an induction heating of billet has become increasingly important as a means of reducing the heating time and an effective control of heating temperature (B.H.Kim et all, 2005).

An induction heater, shown in Figure 3.2 and Figure 3.3, was used to heat the billet to the necessary forging temperature of 1200 ^{o}C. Compared to other heating methods, induction heater provides some advantages such as are quick heating, less scale loss, fast start-up, energy savings, and high production rates (Zinn and Smiatin, 1988).

The billets are feed manually into the induction heater. To prevent the adherence of the billets, one side of the billets are painted with a special paint. The maximum power capacity of this induction heater was 950 kWh. It has a Pillar Mark VII Power supply, which consists of a variable voltage, variable frequency AC source connected to an induction heating load by means of coupling capacitors. The coupling capacitors provide self-starting capability and act as a voltage multiplier to impedance match a wide range of induction heating loads. Other technical information of this induction heater is given in Table 3.2.

Figure 3.2 Billet feeding into the induction heater used in this study.

Table 3.2 Technical input and output values of the induction heater

Input Voltage (V)	480
Input current (A)	1900
Input frequency (Hz)	50
Coil Voltage (V)	1200
Output (inverter or closed circuit) Voltage (V)	800
Output Power (kW/h)	950
Output frequency (Hz)	50
Heating Capacity (kg/h)	2000

Figure 3.3 Billet Output from the induction heater used in this study.

Due to the high temperatures inside the coils, it is necessary to cool the coils. Otherwise, the coils could also reach the temperature of the forging billet, which is about 1200 ^{o}C. In this cooling cycle, softened water is used. The average values of pH, conductivity and hardness of the water used in the closed circuit and at the output of this induction heater are given in Table 3.3.

Table 3.3 The average values of pH, conductivity and Hardness of the deionized water used in the closed circuit and at the output of this induction heater

	Deionized water (closed circuit)	Output of induction heater
PH Value	6.2	8.8
Conductivity (µS)	20	1800
Hardness (Fr)	1	1

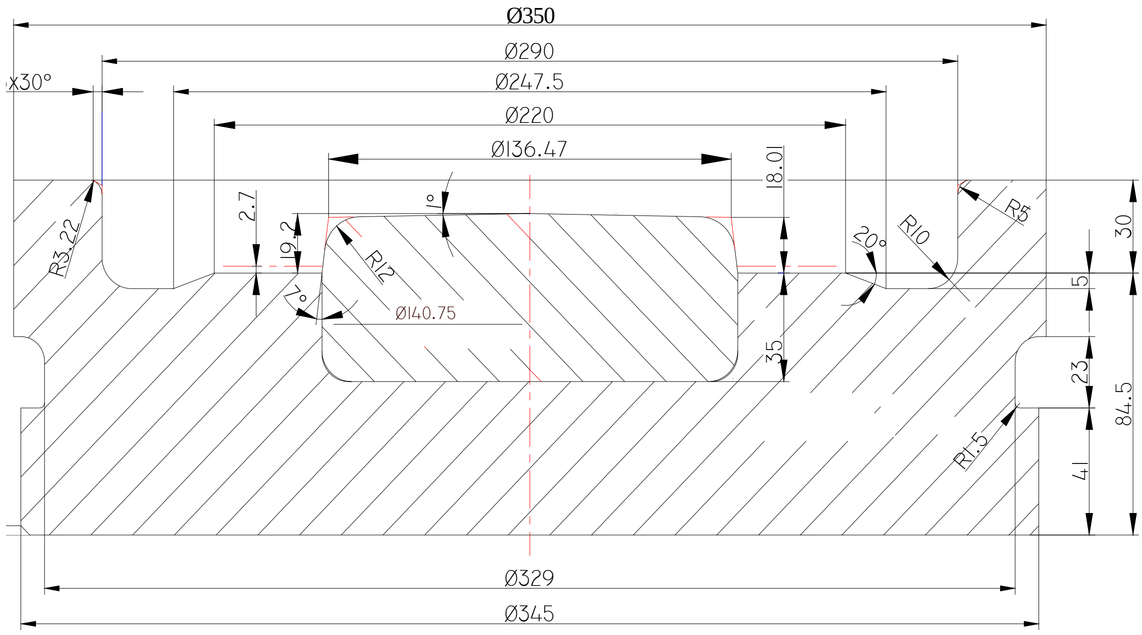
3.1.3 Forging Dies

DIN 1.2344 (AISI H13) hot work tool steel was used as the die material hot work tool steels are commonly used for hot – forging dies subjected to temperatures ranging from 315 to 650 ^{o}C. These materials contain chromium, tungsten, and in some cases, vanadium or molybdenum or both. These alloying elements induce deep hardening characteristics and resistance to abrasion and softening. These steels usually are hardened by quenching in air or molten salt bath. This type of steel has a high hot-wear resistance, high hot tensile strength and toughness. It has also a good thermal conductivity and insusceptibility to hot cracking. It is hardened to a hardness of 54 HRC and tempered at 630 ^{o}C to a hardness of 45 HRC. The chemical composition of this steel is given in Table 3.4.

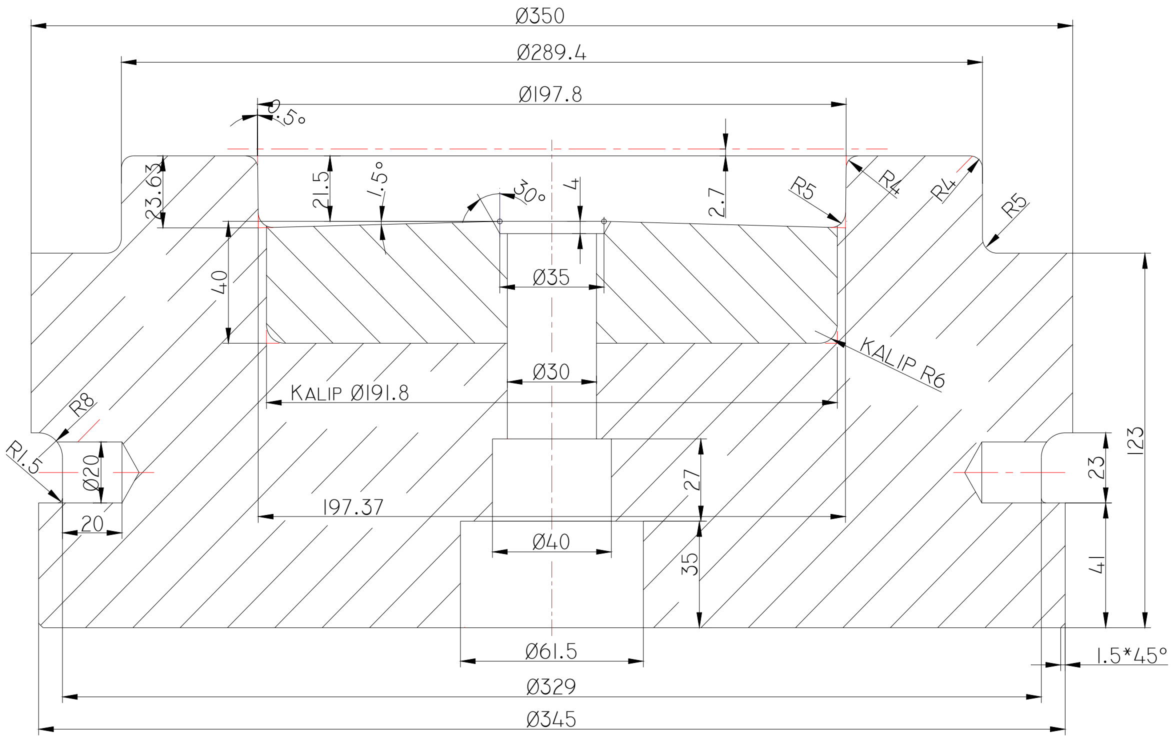
Table 3.4 Chemical Composition of DIN 1.2344 hot work tool steel

Element	C	Si	Cr	Mo	V
Combination (%)	0,4	1,0	5,3	1,4	1,0

The Forging process consisted of three stages : Blocker, preform and finishing stages. So there was a total of 6 dies : 2 dies for each stage; one upper and one lower. The technical drawings of the upper and lower preform and finishing dies are presented in Figure 3.4 and 3.5 respectively.

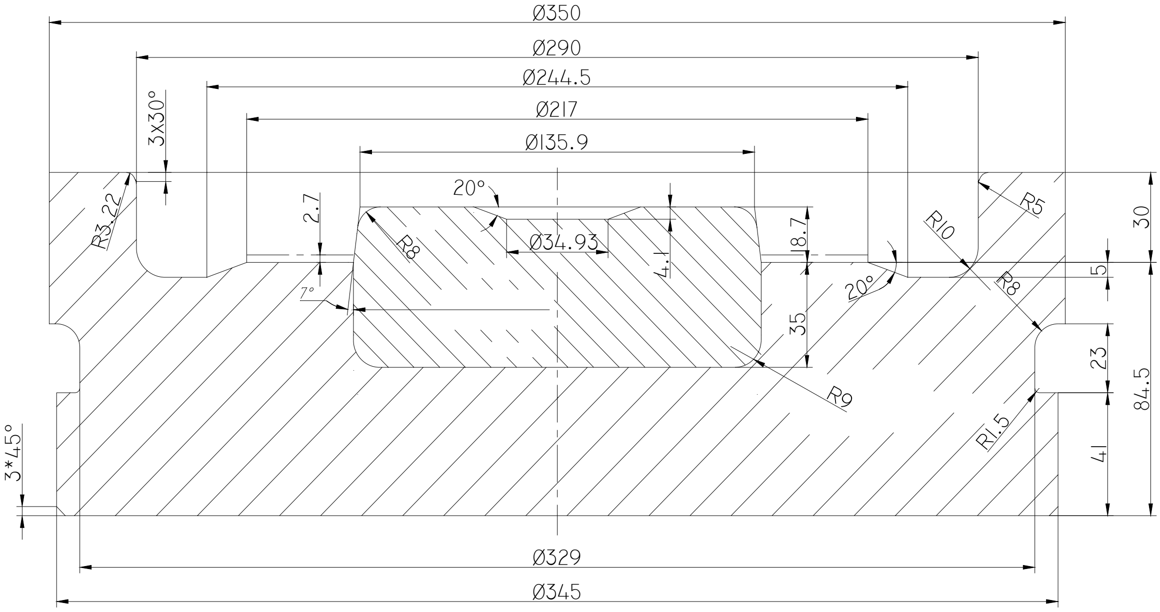


a)

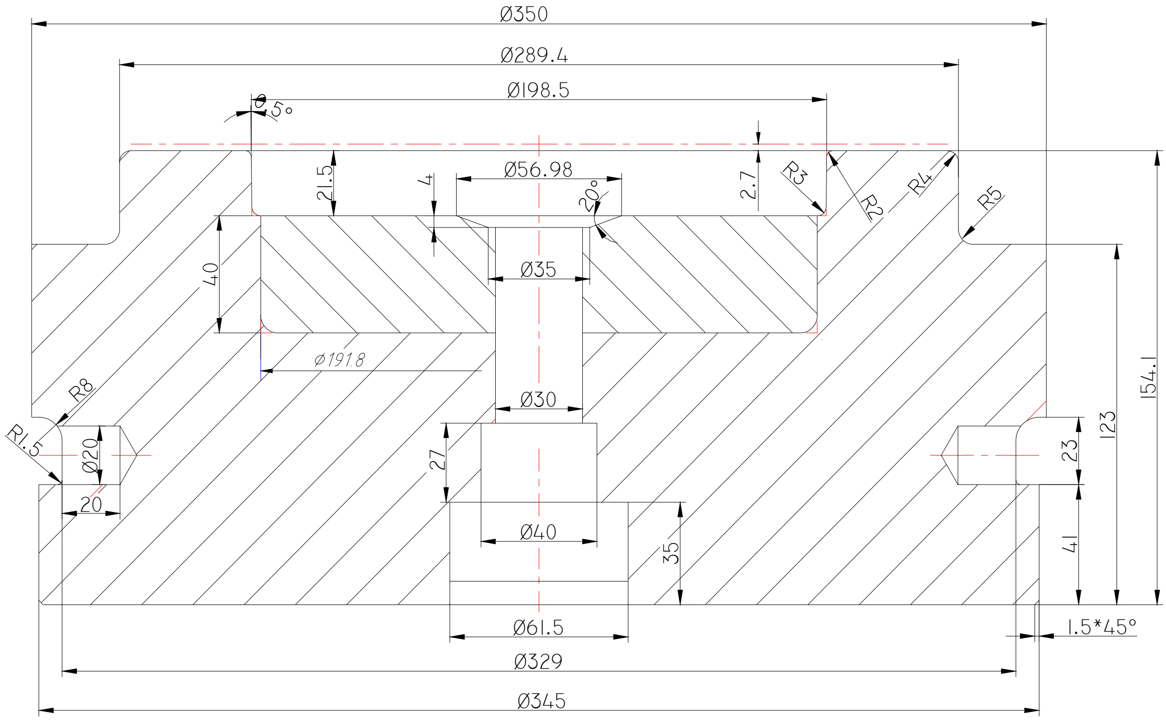


b)

Figure 3.4 The technical drawings of (a) upper and (b) lower preform dies



a)



b)

Figure 3.5 The technical drawings of (a) upper and (b) lower finisher dies

Each of the forging dies were cut using a sawing machine from a round of Ø350 mm diameter. The initial length of the upper and lower dies was 165 mm and 125 mm. After the cold sawing process the dies were machined in the turning machine TRAUB TNA 600. After this process, the surface coating techniques such as salt bath nitriding, plasma nitriding, single layer surface coating AlTiN, multi layer surface coating TOKTEK and weld overlay were applied to each set of dies in order to investigate their effects on the die life.

3.1.3.1 Nitrided Dies

Nitrided dies are commonly used in forging dies due to the physical properties they provide on the surface of the tool steel. They also increase the thermal fatigue resistance due to the residual state of compression in combination with improving tempering resistance of the diffusion layer. Nitrided tool steels also have a high microhardness, which reduces the wear at the die surface. Therefore, one set of the dies were nitrided in a salt bath to the thickness of 0,3 mm and surface hardness of 63 HRC.

3.1.3.2 AlTiN Coating

Optimisation of manufacturing processes in mechanical engineering which involve working temperatures higher than 600°C and high surface loads, like hot forging, is today under intensive investigation worldwide. Traditional production procedures and the enormous quantities of products in these industries are serious limitations to the introduction of any kind of improvement to moulds, tools and dies with PVD coatings. Some performance testing of new technologies must therefore be carried out in real industrial manufacturing. A very important improvement in tool or die life could be achieved as explained in the section 2.5.3.5. So, the monolayer surface coating AlTiN has also been applied to the dies in this study. The thickness of the coating was 3 μm ±0.3 μm.The dies were polished to a roughness (Ra) of 1 μm before the coating.

3.1.3.3 Multilayer Coating TOKTEK

The nitrided tool steel surface provides better mechanical support for the hard coating than the original hot working tool steel. The combination of plasma nitriding and PVD hard coating may also increase the thermal fatigue resistance due to high residual stresses. High microhardness of hard coatings is not sufficient for protection of hot forging tools. The coating must also have high fracture toughness, while crack initiation and growth cause degradation and failure of hard protective coatings. One of the possible ways to achieve high hardness in combination with high fracture toughness is to use multilayered coatings. Namely, multilayered coatings have higher cracking resistance than the corresponding single layer coatings, while cracks tend to branch and deflect at the interfaces. Therefore, the subject duplex treatment has also been studied in this work. The multilayer surface coating is called TOKTEK. The first layer of the multilayer coating was TOKTEK N-SAT/V and the second layer was TOKTEK N- KAT/V. The total thickness of the multilayer was 12 μm ±1.2 μm. The dies were polished to a roughness (Ra) of 1 μm before the coating.

3.1.3.4 Weld Overlay Coating with CASTOLIN N9080 Welding Electrode

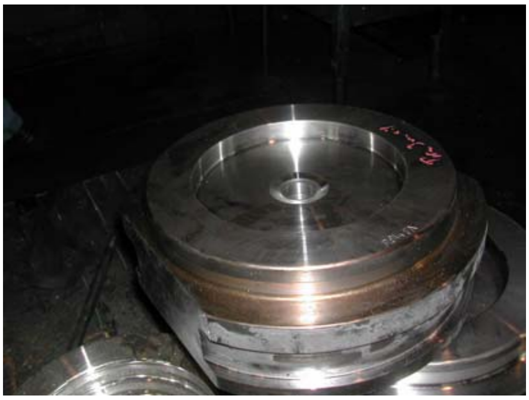
A weld overlay was applied to the forging dies. The selection of welding electrode has a great influence in weld overlay coating. After several trials in the forging shop and consultations with Oerlikon E717, GeKa ELHARD 25 Ni and other electrodes, it was decided to use a Stellite group cobalt base welding electrode as explained in the section 2.5.3.6. The welding electrode used for the weld overlay was CASTOLIN N9080 with a diameter of 5 mm. CASTOLIN N9080 is a Stellite group cobalt base welding electrode, which is especially used in hot forging tools. The photos taken from the weld overlay coated dies are shown in Figure 3.6

The weld path has a hardness of 28 – 34 HRC just after the welding process and is hardened uniformly to a hardness of 49 – 50 HRC during working (machining and forging). The welding has an elongation of 10% (for l=5d). The electrode used has distinct features such as an excellent resistance to heat (to 1000°C), and thermal shock, good creep resistance, low friction coefficient, crack resistance and good machinability. There are two welding procedures that can be applied with this electrode. These are the welding method A, which aims a fast welding rate, and the welding method B which aims the least material (die) heating and proper material flow. The current values for both of these methods for different electrode diameters are given in Table 3.5.

The chemical composition of the welding electrode is given in Table 3.6.

a) Lower preform die

b) Upper preform die



c) Lower finishing die

d) Upper finishing die

Figure 3.6 Photos taken from the weld overlay coated dies

Table 3.5 Current values used for different electrode diameters in welding method A and B.

	Current Values (A)	
Electrode Diameter (mm)	Welding Method A	Welding Method B
Ø3.2	100 – 120	70 – 90
Ø4.0	130 – 150	90 – 120
Ø5.0	160 – 180	120 – 150

In this study, the welding method B has been used. The electrode diameter was 5 mm. Before welding, similar to the study of Babu et all, 1999) the dies were preheated to a temperature of 300 ^oC for 3 hours. Then the dies have been welded in two layers, with a thickness of approximately 2,5 mm for each layer. During the welding process, the dies were continued to heating to prevent the fast cooling of the dies, which would cause thermal and residual stresses in the die. After the welding process, a stress relieving operation has been carried out for 5 hours at 400 ^oC. Then, the dies were cooled to the room temperature in still air. Afterwards, the dies have been machined in the CNC turning machine TRAUB, TNA600. At the end of the turning process, the thickness of the weld overlay was 3 mm.

Table 3.6 The chemical composition of the welding electrode CASTOLIN N9080

C	Cr	Mo	Ni	Fe	Co
0.15	28.5	6.50	3.00	1.50	remainder (60)

3.1.4 Billet Material

The billet material used in this study was a nitrocarburizing steel grade called 27 MC 5 according to the French standard AFNOR. This steel is a manganese – chrome steel. The chemical composition of this steel grade is given in Table 3.7.

The forging billet made from the steel grade 27 MC 5 had a cross section of 75 mm x 75 mm. The billet was cold sheared in a 630 ton cold shearing press according to the cold shearing work instructions to the length of 111 mm. The weight of the billet and forged part were 4,65 and 3,2 kg respectively. The billet has been heated to 1200 ^{o}C ± 25 ^{o}C in a 65-80 coil and the forging cycle was 10 seconds.

Table 3.7 Chemical composition of the billet material

C	Mn	Si_{max}	Cr	Al_{max}	Ni_{max}	Cu_{max}	P_{max}	S
0,23–0,3	1,1-1,4	0,4	1,0-1,4	0,05	0,3	0,3	0,025	0,2-0,4

3.1.5 Welding Equipment

An electric arc welding process was used to make the weld overlay coating. The welding equipment used in this process was an electric arc welding machine produced in 1982 in German Democratic Republic by MANSFELD Schweisstechnik. The type of the machine was KV 360 U1. The technical specification of the machine is given in Table 3.8.

Table 3.8 The technical specification of the electric arc welding machine

	%ED	A	V
Continuos work	100	280	30
Manual welding	55	380	35
Working Range		80 - 80	15 - 35
Idle motion voltage (max)		90	

3.1.6 Die Lubricant

In forging, friction greatly influences metal flow, pressure distribution, and load and energy requirements. In addition to lubrication effects, the effects of die chilling or heat transfer from the hot material to the colder dies must be considered. In forging, the ideal lubricant is expected to:

1) Reduce sliding friction between the dies and forging in order to reduce the pressure requirements, to fill the die cavity, and to control the metal flow.

2) Act as parting agent and prevent local welding and subsequent damage to the die and workpiece surfaces
3) Possess insulating properties so as to reduce heat losses from the workpiece and to minimize temperature fluctuations on the die surface.
4) Cover the die surface uniformly so that local lubricant breakdown and uneven metal flow are prevented.
5) Be nonabrasive and non corrosive so as to prevent erosion of the die surface
6) Be free of residues that would accumulate in deep impressions
7) Develop a balanced gas pressure to assist quick release of the forging from the die cavity; this is especially important where the use of ejectors may be not possible.

To fulfill the above mentioned expectations, the Deltaforge 144 lubricant from the worldwide lubricant manufacturing company Acheson was used. Then, the lubricant was mixed with water by the rate of 1/10. Deltaforge 144 is a high quality, widely used, die lubricant designed specifically for the forging industry. Composed of processed micro-graphite and proprietary substances in a dilutable base, Deltaforge 144 forms an adherent, oxidation resistant film that maintains high lubricity at forming temperatures. Deltaforge 144 is normally effective up to 816°C. The physical properties of Acheson Deltaforge 144 are represented in Table 3.9.

Table 3.9 Physical properties of Acheson Deltaforge 144 die lubricant (as supplied)

Lubricant	processed micro-graphite, proprietary substances
Fluid component	water
Diluent	water Consistency
fluid Density (kg/l)	1.242
Solids content (%)	40
Freezing point (°C)	0
Shelf life	one year under original seal

3.1.7 Measuring Equipment

As measuring equipment, a digital Mitutoyo caliper type 550 – 241-10 was used to measure the 26.5 mm width and the Ø185, Ø138, Ø136.5, Ø195.5 diameter measures of the forged part. The measuring range of this caliper was 300 mm, and the sensitivity was 0.01 mm . For measuring the draft angle of maximum 1 ^{o}, a protractor was used. Other measuring equipment were, a height gauge and a radius gauge.

3.2 Method

3.2.1 Forging Procedure

A forging billet made of 27 MC 5 according to French standart AFNOR produced in ASIL ÇELIK is cut to the length of 111 mm in a 630 tons cold shearing machine according to the shearing / cutting work instruction presented in Table 3.10.

Then the billet is heated to a temperature of 1200 ^{o}C in an induction heater. The induction heater consists of 2 coils, each with the length of 1,8 m. The cycle time of the forging process was 10 sec/part. So the total time spent inside the coils and induction heater for each separate billet, which affects greatly the formation of scale was 320 seconds, as calculated below:

Total length of 2 coils: 2 pcs * 1,8 m/pcs = 3.6 m
Length of each billet: 111 mm = 0.111 m /pcs
Total number of billets inside the coils: 3.6 m / 0.111 m/pcs = 32 pcs
Cycle time of the forging process: 10 sec / pcs
Total time spent inside the coil for each billet: 32 pcs * 10 sec/pcs = 320 sec

The billets are transferred to the forging press by means of conveyor. Then the billets are deformed in three stages to obtain the required shape on the part .

Table 3.10. Shearing / Cutting Work Instruction

SHEARING/CUTTING WORK INSTRUCTION

PART Nr	**8200261814**	**Part Name**	**Crown Gear**	**Company**	**OYAK RENAULT**
Material section	K75	**Machine**	**630 T.P.**	**Operatiýn**	**Cold shearing**
Paint code	**Blue - Yellow**	**Cutting Speed**	**-**	**Loading**	**Single**
Material	**27 MC 5**	**Feed**	**-**	**Cutting Rate**	**4500 pcs/shift**
Brut weight	**4,65 ± 50 gram**	**Compression**	**-**	**Prepared and Approved By**	
Net weight (For information)	**3,2**	**Shear**	? 75	**Date**	**22.03.2006**

INFORMATION : Each of 50 cut parts will be checked by weight and crack detection will be carried out with the rate of 10/500

FORM Nr : 20.02.002

In the first stage (blocker), the billets have been forged in open dies to the height of 22 mm. This stage has two purposes; first, to descale the billet, second, to preform the part to a shape, which can be put on the preform dies as fast and as right as possible. This helps reducing the forging cycle, and due to this, reducing the production cost.

In the second Stage (preforming), the part is deformed to a form like the finished part. Of course there are some differences, which aim to improve the material flow, and so, the filling of the finishing dies. One of the differences to improve material flow is to increase the radii. The flash thickness in this stage was 5.5 mm for each of the surface tretaed dies studied in this study.

In the third stage (finishing), the final shape of the part is obtained. But the punch (hole) in the centre of the part and the flash formed as a ring outside of the finish part must be reduced in the trimming press. The flash thickness in this stage was 5.5 mm for each of the surface tretaed dies studied in this study.

The lubricant used in the forging process was Deltaforge 144S from Acheson. The mixture rate of oil to water was 1/10 for each of the studied surface treatments.

The technical drawing of the forged part is illustrated in Figure 3.7. The raw billet and the forged parts after each forging step end after trimming of the inner and outer flash are shown in Figure 3.8.

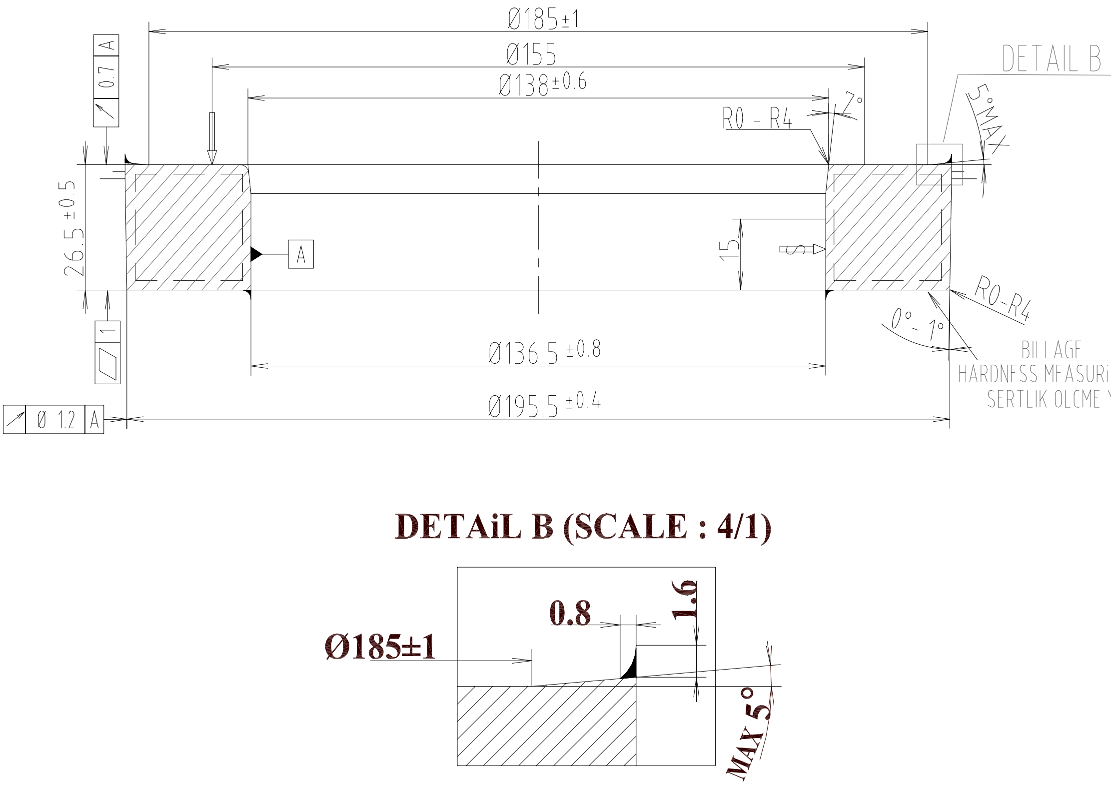


Figure 3.7 Technical Drawing of the forged Part

Figure 3.8. Views of the shape obtained at the end of each forging sequence. From left to right; raw billet, blocked part, preformed part, finish forged part, trimmed and punched part, flash and punched metal

3.2.2 Die Service Life

Before starting the serial run, a set – up was carried out to ensure that the produced part is OK. After the set – up, the serial run has started. Then the dimensions stated in the Part Inspection Instruction Sheet (Table 3.11) were measured after each production hour to ensure that the parts are produced within the given tolerances. The die service life was determined according to the amount of forged parts within the tolerances given in the Part Inspection Instruction Sheet. The service life of the preform dies were determined according to two criteria : 1) the deformation in the preform dies is at a value that the dimensions of the preform dies becomes greater than the dimensions of the finisher dies; 2) During the crack detection, the detected crack due to the wear track is as high as not to be corrected by polishing. The die service life of each surface treatment was compared to each other. This kind of method was also used by Çapa et all (2000).

In this study, scratches on the die surfaces were also observed visually by help of the adhesion and crack detection of the part. The amount of forged part until the polishing, called as “polishing life”, due to the scratches of the die surfaces, were also recorded and compared to each other for each of the surface coatings.

Table 3.11. "Part Inspection Instruction Sheet" for the part studied in this work

ÇUKUROVA İNŞ. MAK. SAN. ve TİC.	PARÇA KONTROL TALİMATI (PART INSPECTION INSTRUCTION SHEET)		Forge Quality Dept. Instruction No : 473	
Part No : 8200 261 814	Part Name : CROWN GEAR		Customer :	OYAK RENAULT
Item No	Characteristics	Measuring Equipment/Technics	Checking Frequency	Tolerance
1	Ø 185	Vernier caliper	5 Pc/hr	+ 1,0 - 1,0
2	Ø 138	Vernier caliper	5 Pc/hr	+ 0,60 - 0,60
3	Ø 136,5	Vernier caliper	5 Pc/hr	+ 0,80 - 0,80
4	Ø 195	Vernier caliper	5 Pc/hr	+ 0,40 - 0,40
5	26,50	Height Gage	5 Pc/hr	+ 0,50 - 0,50
6	max 0,8	Vernier caliper	5 Pc/hr	—
6	min15	Height Gage	5 Pc/hr	,
7	max1,6	Revel Protractor	5 Pc/hr	—
8	0,5 ° max	Vernier caliper	5 Pc/hr	—
9	***** FORGING DEFECTS : Over lapping, scale pits etc.	VISUAL	5 Pcs/hr	——
10	OOOOO- UNDERFILLING	VISUAL	5 Pcs/hr	——
				——
NOTES : 5 pieces at the start of the process and 15 parts an hour will be c The markings should be visible and readable				
CHANGES:		Prepared By	DATE	Approved By
				02.09.2003

Form No : 19.03.013
Change No : 01

3.2.3 Die Cost per Forged Part

One of the most important facts in a production process for a manufacturing company is the cost. The cost of the dies per forged part was calculated and compared to each other in order to compare the unit cost of the products produced by different die sets. In the calculation of the total cost of the die per forged part, following data has taken into account :

1) The cost of the raw die material (C_{die}).
2) The cost of sawing of the die materials (C_{saw}).
3) The cost of turning and milling of the dies (C_{mach}).
4) The cost of surface treatment ($C_{S.treat}$).
5) The cost of the break of the forging press due to die polishing (C_{press})
6) Resinking and reproduction with the same dies until the life of the surface treatment has been finished (C_{res}). This was only the case for the weld overlay, because the initial thickness of the weld overlay was 2,5 mm and after resinking of 1,5 mm, the same dies were used in the next production batch of the same part.
7) Total forged parts with the surface coated dies (PF_{tot}).
8) The profit, including the cost of pre - paid direct and indirect labor that can be made from the production, that could be made in the time of break due to die polishing and die exchange of the forging press ($C_{prof+lab}$).

The total initial cost (CD_{ini}) of the dies and the total cost were calculated by using Equations 3.1 and 3.2 respectively.

$$CD_{ini} = (C_{die}) + (C_{saw}) + (C_{mach}) + (C_{S.\ treat}) + (C_{res}) \qquad \text{(Eq. 3.1.)}$$

$$(CD_{parts\ forged}) = [(CD_{ini}) + (C_{press}) + (C_{prof+lab})] / (PF_{tot}) \qquad \text{(Eq. 3.2.)}$$

(C_{die}) and (C_{saw}) were the same for all of the studied parts and they were 3800 Euro for each set of dies. Taking into consideration that the die material is used three times with 2 resinkings, each with the cost of 350 €, total (C_{die}) and (C_{saw}) cost came to (3800 € + 2x350 € =4500 € for each set, and to 4500 €/3= 1500 € for each forging batch. In this study, one forging batch has been experimented. So, total (C_{die}) and (C_{saw}) hav been considered as 1500 €. The (C_{mach}) was about 1500 € for nitrided, single layer (AlTiN) coated and multilayer (TOKTEK) coated die sets and about

2500 € for weld overlay coated dies. ($C_{Surf\ treat}$) was 2.400 € for nitrided die set, 1700 € for single layer (AlTiN) coated die set, 3.300 € for multilayer (TOKTEK) coated die set and 2400 € for weld overlay coated die set. As resinking and reproduction was only possible with weld overlay coated dies C_{res} was 1000 € for weld overlay coated die set and "0" for all other die sets.

For C_{press}, the cost of press breaks was (C_{ph}) 135 € for each hour. Considering each polishing as one hour, the cost was 135 € for each polishing operation. The total cost of press breaks was calculated as follows :

$$(C_{press}) = k * C_{ph} \qquad \text{(Eq. 3.3)}$$

When the ($C_{prof+lab}$) is taken into account, it has been seen that each hour of reduction in the press brake time results the production of extra 700 kg products. This will give 580 € profit if it is sold with 10% profit.. In the production of this parts, it has been assumed that the direct labor and indirect labor have been pre – paid for the existing production conditions and don't need to be paid for the second time. Considering the rate of direct and indirect labor of 18% , the total profit of earned money for each reduced hour of press brake (C_{labh}) became 28%, that means 580 € x 28% =162 € / h.

The total cost of press breaks was calculated as follows :

$$(C_{prof+lab}) = k * C_{labh} \qquad \text{(Eq. 3.4)}$$

As an example, by using Eq. 3.1, the total die costs (CD_{ini}) for nitrided dies was calculated as :

$CD_{ini} = (C_{die}) + (C_{saw}) + (C_{mach}) + (C_{S.treat}) + (C_{res})$

$(C_{die}) + (C_{saw}) = 1.500$ €

$(C_{mach}) = 1.500$ €

$(C_{S.treat}) = 2.400$ €

$(C_{res}) = 0$ €

$CD_{ini} = 1.500$ € $+ 1.500$ € $+ 2.400$ € $= 5.400$ €

In the experiment carried out, the nitrided die sets were polished 3 times (total 3 hours) for the production batch of 9420 pcs. So; the press cost and the profit, including the cost of pre – paid labor were calculated respectively as follows :

(C_{press}) = 3 h * 135 € / h = 405 € and

$(C_{prof+lab})$ = 162 € / h* 3 h = 486 €

By using Eq. 3.2, the total cost of the die per forged part was calculated as

$(CD_{parts\ forged}) = [(CD_{ini}) + (C_{press}) + (C_{prof+lab})] / (PF_{tot})$

$(CD_{parts\ forged})$ = [5.400 € + 405 € + 486 €] / 9.420 pcs = 0,67 €/pcs

3.2.4 Break Even Point

Due to the additional cost of surface treatments, in the selection of the surface treatment technique, the break even point should be calculated in order to choose the most economical surface treatment according to number of forged parts.

The equation for the break even point is derived by means of previous equations as explained in the following paragraph :

The total die cost (CD_{ini}) of the dies for as received dies $(CD_{ini})_1$ and surface treated dies $(CD_{ini})_0$ was calculated by using Eq. 3.1 as follows :

$(CD_{ini})_1 = (C_{die})_1 + (C_{saw})_1 + (C_{mach})_1 + (C_{S.\ treat})_1 + (C_{res})_1$

$(CD_{ini})_0 = (C_{die})_0 + (C_{saw})_0 + (C_{mach})_0 + (C_{S.treat})_0 + (C_{res})_0$

considering that ;

$(C_{S.treat})_0=0$, $(C_{res})_0=0$,$(C_{die})_1=(C_{die})_0$, $(C_{saw1}=(C_{saw})_0$

The initial cost (CD_{ini}) of the dies for as received dies $(CD_{ini})_1$ and surface treated dies $(CD_{ini})_0$ becomes

$(CD_{ini})_0 = (C_{die})_0 + (C_{saw})_0 + (C_{mach})_0$

$(CD_{ini})_1 = (C_{die\ 0}) + (C_{saw})_0 + (C_{mach})_1 + (C_{S.treat})_1 + (C_{res})_1$

$(CD_{ini})_1 = (CD_{ini})_0 + (C_{mach})_1 + (C_{S.treat})_1 + (C_{res})_1 - (C_{mach})_0$

The die cost per Part was calculated by using Eq. 3.2 as :

$(CD_{parts\ forged})_1 = [(CD_{ini})_1 + (C_{press})_1 + (C_{prof+lab})_1] / (PF_{tot})_1$

$(CD_{parts\ forged})_0 = [(CD_{ini})_0 + (C_{press})_0 + (C_{prof+lab})_0] / (PF_{tot})_0$

By using Eq. 3.3 and 3.4, the the press cost and the profit, including the cost of pre – paid labor were calculated respectively as :

$(C_{press})_1 = k_1 * C_{ph}$

$(C_{press})_0 = k_0 * C_{ph}$

$(C_{prof+lab})_1 = k_1 * C_{labh}$

$(C_{prof+lab})_0 = k_0 * C_{labh}$

To find out the break even point, the total costs should be equalized:

$$(CD_{tot})_1 = (CD_{tot})_0 \quad \text{(Eq. 3.5)}$$

$(CD_{ini})_1 + (CD_{parts\ forged})_1 * (PF_{tot}) = (CD_{ini})_0 + (CD_{parts\ forged})_0 * (PF_{tot})$

$(CD_{ini})_1 - (CD_{ini})_0 = (PF_{tot}) * [(CD_{parts\ forged})_0 - (CD_{parts\ forged})_1]$

$[(CD_{ini})_1 - (CD_{ini})_0] / [(CD_{parts\ forged})_0 - (CD_{parts\ forged})_1] = (PF_{tot})$

$[(CD_{ini})_0 + (C_{mach})_1 + (C_{S.treat})_1 + (C_{res})_1 - (C_{mach})_0 - (CD_{ini})_0] / [(CD_{parts\ forged})_0 - (CD_{parts\ forged})_1] = (PF_{tot})$

$$[(C_{mach})_1 + (C_{S.treat})_1 + (C_{res})_1 - (C_{mach})_0] / [(CD_{parts\ forged})_0 - (CD_{parts\ forged})_1] = (PF_{tot}) \quad \text{(Eq 3.6)}$$

4. RESULT and DISCUSSION

In forging, hot working tool is subjected to repeated mechanical and thermal loading, which finally lead to heavy damage of the tool surface due to erosion, plastic deformation, thermal and mechanical fatigue. The critical areas of a hot forging tool are heavily loaded areas, internal corners with notch effect, areas with large sliding lengths and areas that reach very high temperatures during forming. Different types of wear are the cause for scrapping.

The maximum temperature as well as the temperature distribution in the hot forging tool has a significant influence on its wear. The maximum temperature determines the hardness of the tool surface, while the temperature gradient leads to dimensional variation, which generates stresses and deformations. During hot forging process, the die surface is heated partly by conduction of heat from the hot workpiece, partly by the friction between the tool and the workpiece. Maximum temperature of the tool surface layer is highly influenced by workpiece temperature, workpiece-tool contact time, contact pressure and sliding lengths, lubricant, tool base temperature.

The most important fact for a forging company is to reduce the cost and to increase its profit. There are only a few ways to reduce the manufacturing cost in forging. One of the most important ways is to reduce the tooling cost, i.e. die cost per part. The tooling cost per die can be calculated for each die set by using the following equation:

Die cost per part = Total die cost / total forged parts

So, the total forged parts with the same die, i.e. the die service life, have a great influence on the die cost per part. Die service life can be increased by improving the die surfaces with different surface treatments such as nitriding, single layer surface coating, multi layer surface coating, and weld overlay coating. The effect of each surface treatment on the die service life and cost of the part have been discussed in the following sections.

Due to the additional cost of the surface treatments, the best surface treatment technique, which will give minimum cost, can be selected according to the break even point. The break even point for each experimented surface treatment have been found and presented in the following sections.

4.1 Increase in Die Service Life

4.1.1 Nitrided Dies

One of the methods to improve die service life studied in this work was to apply nitriding to the surface of the dies. Polishing is applied to the dies when the scratches are visually observed on the die surface. For the nitrided dies, as seen from Table 4.1, after forging of 3920 pieces, the die surfaces became scratched and the dies need to be polished. Second and third polishing operations were applied after the production of 2140 and 2110 forgings respectively. After the third polishing another 1250 pieces have been produced within the service life of the dies. This means that total 9420 pieces could be produced with the same die. The decision about the end of useful die life is made by checking the deviation in the Ø185 dimension, as given in Table 4.3. If it is outside the limits, the required tolerances on the parts could not be obtained after polishing. Therefore it should be changed with the new one. As given in Table 4.2, as received dies (hardened and tempered to a hardness of 45 HRC) were first polished after 1440 pieces. The second and third polishing operations were applied after the production of 1260 and 1320 forgings respectively. After the third polishing further 270 pieces have been forged within the service life of the die. This means that total 4290 piecers could be produced with the same die. Compared to as received dies, an important increase (up to 175%) in the die polishing life, that is the amount of forged part until the polishing of the die sets, was obtained for the first polishing with nitrided dies. For the further polishing, the increase was approximately 60%. The reason for this is explained as the partial removal of the nitrided layer during each polishing operation.

Table 4.1 Polishing life of nitrided dies during the forging process

Operation	1st Polishing	2nd Polishing	3rd Polishing	Total prod.
Number of Forged Parts	3920	2140	2110	9420

Table 4.2 Polishing life of as received dies during the forging process

Operation	1st Polishing	2nd Polishing	3rd Polishing	Total prod.
Number of Forged Parts	1440	1260	1320	4290

As shown in Figure 4.3, the average die service life has changed from 4290 pieces to 9420 pieces, which is an increase of 119% compared to non surface treated dies. This is due to the loss in the hardness of non surface treated dies at high temperatures. This result was also found out by D.J.Jeong et all (2001). Çapa et all (2000) could achieve an increase of 700% in the die service life. The difference in the increase can be due to the nitriding parameter as explained in the studies of Çapa et all (2000) and M.A.Pessin et all (2000). M.Pant and W.Bleck (2005) could achieve an increase of 50%, which is less than obtained in this study. In the study of P.Panjan et all (2002), nearly the same values were obtained compared to this study.

The increase in the polishing life of nitrided dies can be explained by the increase of thermal fatigue resistance as stated by C.M.D. Starling and J.R.T Branco (1997).

The deviations measured on critical dimensions of the as received and nitrided dies are given in Table 4.3 and 4.4 respectively. Figure 4.1 and 4.2 represent the deviations measured on critical dimensions of the as received and nitrided dies. Deviation measurements were taken after the production of every 360 components. Measurements taken according to the “Part Inspection Sheet” showed that the deformation of the dies is rapid at the beginning of the forging process. Then, it slows down during the process and it increases again at the end of the die service life. The same behaviour has been observed in all of the studied coatings, with the exception of weld overlay coating.

Table 4.3 The deviations measured on critical dimensions of the as received dies (Die Material DIN 1.2344;hardened and tempered to a hardness of 45 HRC)

Forged Parts	Deviation from Dimension (mm)				
	Ø185	Ø138	Ø136,5	Ø195,5	26,5
0	0.00	0.00	-0.05	0.00	0.20
360	-0.20	-0.10	-0.05	0.10	0.20
720	-0.35	-0.10	-0.05	0.20	0.20
1080	-0.40	-0.10	-0.10	0.25	0.3
1440	-0.40	-0.10	-0.10	0.25	0.3
1800	-0.50	-0.20	-0.10	0.25	0.20
2160	-0.50	-0.20	-0.10	0.25	0.20
2520	-0.50	-0.20	-0.10	0.25	0.20
2880	-0.50	-0.20	-0.10	0.25	0.20
3240	-0.50	-0.20	-0.10	0.25	0.20
3600	-0.70	-0.20	-0.20	0.30	0.30
3960	-0.70	-0.20	-0.20	0.30	0.30
4290	-1.00	-0.20	-0.20	0.30	0.30

Table 4.4 The deviations measured on critical dimensions of the nitrided dies (nitrided layer thickness : 0.3 mm; hardness 63 HRC)

Forged Parts	Deviation from Dimension (mm)				
	Ø185	Ø138	Ø136,5	Ø195,5	26,5
0	-0.10	0.00	0.00	0.05	0.30
360	-0.20	-0.10	-0.10	-0.10	0.20
720	-0.25	-0.10	-0.15	0.15	0.20
1080	-0.25	-0.10	-0.15	0.15	0.20
1440	-0.30	-0.10	-0.15	0.15	0.20
1800	-0.30	-0.10	-0.15	0.15	0.20
2160	-0.35	-0.10	-0.15	0.15	0.20
2520	-0.35	-0.10	-0.15	0.15	0.20
2880	-0.40	-0.10	-0.15	0.15	0.20
3240	-0.40	-0.10	-0.15	0.15	0.20
3600	-0.45	-0.20	-0.20	0.25	0.30
3960	-0.45	-0.20	-0.20	0.25	0.20
4320	-0.45	-0.20	-0.20	0.25	0.30
4680	-0.45	-0.20	-0.20	0.25	0.30
5040	-0.50	-0.25	-0.20	0.25	0.25
5400	-0.60	-0.30	-0.25	0.25	0.25
5760	-0.60	-0.30	-0.25	0.25	0.20
6120	-0.60	-0.30	-0.25	0.25	0.20
6480	-0.65	-0.30	-0.25	0.25	0.30
6840	-0.65	-0.30	-0.25	0.25	0.30
7200	-0.70	-0.30	-0.30	0.30	0.30
7560	-0.70	-0.30	-0.30	0.30	0.25
7920	-0.70	-0.30	-0.30	0.30	0.25
8280	-0.70	-0.30	-0.30	0.30	0.30
8640	-0.80	-0.30	-0.30	0.30	0.30
9000	-0.90	-0.35	-0.30	0.30	0.25
9360	-0.90	-0.35	-0.30	0.30	0.20
9420	-1.00	-0.35	-0.30	0.30	0.30

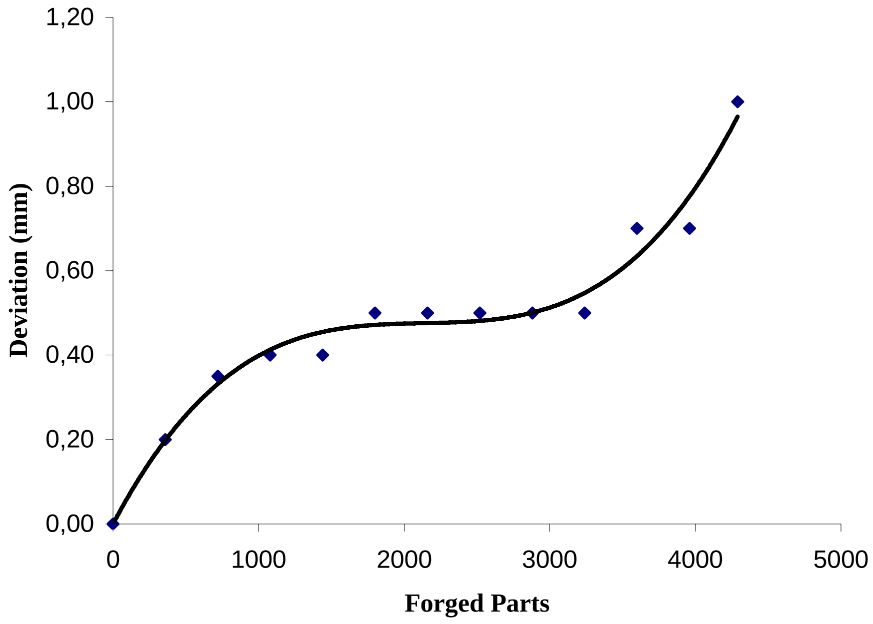


Figure 4.1 Deviation on Ø185 mm dimension of the as received dies

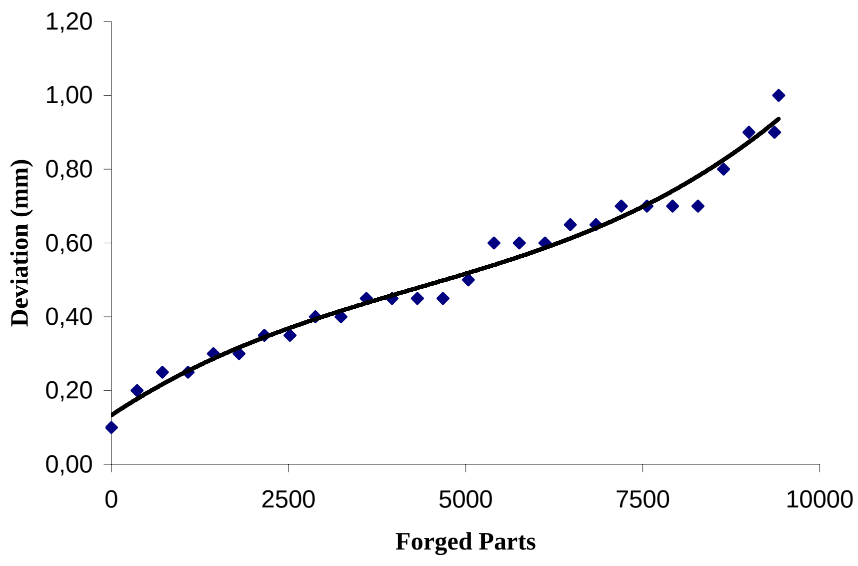


Figure 4.2 Deviation on Ø185 mm dimension of the nitrided dies

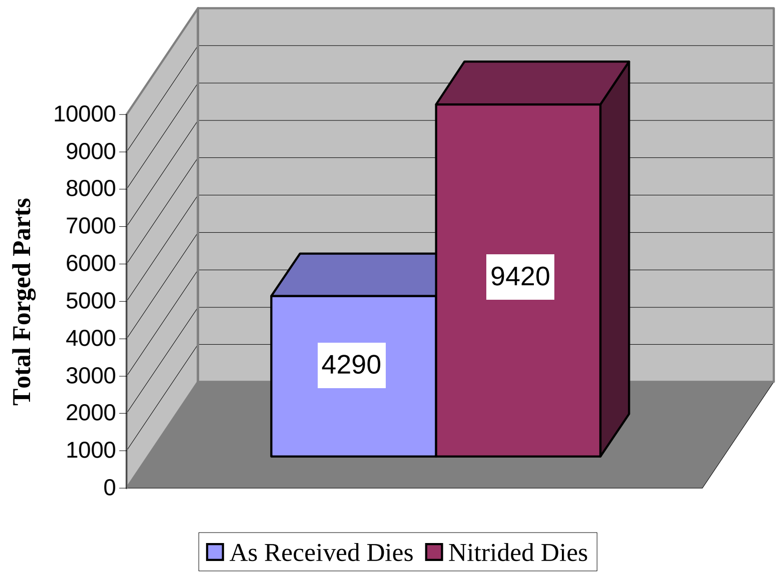


Figure 4.3 Comparison of total forged parts with as received and Nitrided Dies

4.1.2 AlTiN Coated Dies

As given in Table 4.5, with the single layer AlTiN coated dies, the dimension Ø185 came out of tolerance after forging of 12280 pieces. Compared to nitrided and as received dies (Figure 4.4), this refers to an increase in die service life of approximately 150 % with respect to as received dies and to an increase of 30% with respect to nitrided dies. Similar results were also obtained by Navinsek et all (2001). However, the increase in their study was 150% better than the results obtained in this study. The polishing life of single layer AlTiN coating is represented in Table 4.6. The results for the die polishing life show an important increase for the first polishing. There was a need for first polishing after 4810 pieces, after further 1980 forgings the dies needed to be polished the second time. After another 1860 forgings, the die surfaces became scratched and needed to be polished again. The forth and last polishing was carried out after another 1720 forgings, and after further 1,910 forgings, the dimension Ø185 came out of of tolerance. Compared to nitrided dies and as received dies, the polishing life for the first polishing was found 23% and

234% better respectivly. For the further polishing, the increase was approximately 57% with respect to as received dies, but 7% worse than the nitrided dies. The reason for this is that the thickness of nitrided dies was 0,3 mm and after the first polishing, there was a remainder partially nitrided layer with the thickness of approximately 0.15 mm. In the case of AlTiN coating, no remaining coating was there after the first polishing, because of the small thickness of 3 μm of the coating. This is explained as by polishing of the dies, the thin coating is partially removed from the die surface and then the dies became non coated and behave like non coated dies. The thermal fatigue resistance decreased due to this fact. The same statement is also concluded in the study of Jeong et all (2001).

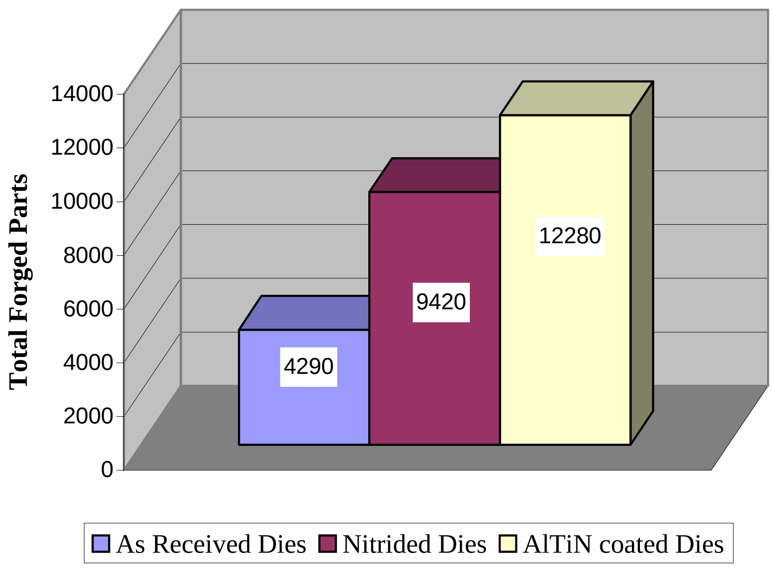


Figure 4.4 Comparison of total Forged Parts with As received, Nitrided and AlTiN coated Dies

Table 4.5 The deviations measured on critical dimensions of the single layer AlTiN coated dies (thickness of the coating : 3 μm ±0.3 μm)

Forged Parts	Deviation from Dimension (mm)				
	Ø185	Ø138	Ø136,5	Ø195,5	26,5
0	-0.00	0,05	0,05	0,00	0.10
360	-0.10	-0.10	-0.05	0,10	0.10
720	-0.15	-0.10	-0.10	0.20	0.20
1080	-0.15	-0.10	-0.10	0.20	0.10
1440	-0.15	-0.10	-0.10	0.20	0.20
1800	-0.15	-0.10	-0.10	0.20	0.10
2160	-0.20	-0.10	-0.10	0.20	0.10
2520	-0.20	-0.15	-0.10	0.20	0.10
2880	-0.25	-0.15	-0.15	0.20	0.20
3240	-0.25	-0.15	-0.15	0.20	0.10
3600	-0.30	-0.20	-0.20	0.25	0.10
3960	-0.30	-0.20	-0.20	0.25	0.20
4320	-0.30	-0.20	-0.20	0.25	0.10
4680	-0.35	-0.25	-0.20	0.25	0.10
5040	-0.35	-0.25	-0.20	0.25	0.20
5400	-0.40	-0.30	-0.25	0.25	0.10
5760	-0.40	-0.30	-0.25	0.25	0.20
6120	-0.45	-0.30	-0.25	0.25	0.20
6480	-0.50	-0.30	-0.25	0.25	0.10
6840	-0.50	-0.30	-0.25	0.25	0.20
7200	-0.55	-0.30	-0.30	0.30	0.20
7560	-0.55	-0.30	-0.30	0.30	0.20
7920	-0.60	-0.30	-0.30	0.30	0.20
8280	-0.60	-0.30	-0.30	0.30	0.30
8640	-0.65	-0.30	-0.30	0.30	0.20
9000	-0.70	-0.35	-0.30	0.30	0.20
9360	-0.70	-0.35	-0.30	0.30	0.30
9720	-0.75	-0.35	-0.30	0.30	0.20
10080	-0.75	-0.35	-0.30	0.30	0.20
10440	-0.75	-0.35	-0.30	0.30	0.20
10800	-0.80	-0.35	-0.30	0.30	0.20
11160	-0.80	-0.35	-0.30	0.30	0.20
11520	-0.80	-0.35	-0.30	0.30	0.10
11880	-0.90	-0.35	-0.30	0.30	0.20
12240	-0.95	-0.35	-0.30	0.30	0.20
12280	-1.00	-0.35	-0.30	0.30	0.20

Table 4.6 Polishing life for each polishing of single layer AlTiN coated dies during the forging process

Operation	1st polishing	2nd polishing	3rd polishing	4th polishing	Total prod.
Number of Forged Parts	4810	1980	1860	1720	12280

4.1.3 TOKTEK Coated Dies

The so called multi layer coating technique TOKTEK has also been studied in this work. Experimental results for the deviation of specified dimensions (in mm) according to total forged parts are given in Table 4.7. The results showed that TOKTEK coated dies also caused an increase in the polishing life and die service life. The increase in the die service life, shown in Figure 4.5, was about 168 % with respect to as received dies. This refers to an increase of 40% with respect to nitrided dies, and 8% increase with respect to the single layer AlTiN coated dies. 8% increase was not the expected value. The study of Navinsek et all (2001), showed that with a thicker coating, better results could be obtained. They could make 300% more forgings with the 150 μm plasma nitrided layer + 8 μm FUTURA coating than they forged with the 90 μm plasma nitrided layer + 4,2 μm FUTURA coating.

Another study carried out by Panjan et all (2002) showed that the damage starts after 300 and 1,100 forgings for heat treated dies and nitrided dies respectively. They stated that no damage was observed with duplex treated dies, except the roundings of the dies. The reason for the low increase in the service life of the die compared to AlTiN coated dies could be due to the structure of the coating, as stated by Smolik et all (2004).

For the multi layer TOKTEK coated dies, as seen from Table 4.8, after forging of 4660 pieces, the die surfaces became scratched and the dies need to be polished. Second and third polishing operations were applied after the production of 2030 and 1750 forgings respectively. After the production of another 1830 and 1780 forgings, the die surfaces were scratched again and the fourth and fifth polishing operations were applied to the dies. After the fifth polishing another 1160 pieces have been produced within the service life of the dies. This means that total 13210 pieces could be produced with the same die. The decision about the end of useful die life is made by checking the deviation in the Ø185 dimension, as given in Table 4.7. If it is outside the limits, the required tolerances on the parts could not be obtained after polishing. Therefore it should be changed with the new one. The results showed also an important increase for the first polishing, when multi layer coating TOKTEK was used. Compared to the single layer AlTiN coated dies, the results were 3% worse, but it was still 19% better than the nitrided dies and 223% better than the as received dies. The reduction of the polishing life compared to single layer AlTiN coated dies, is highly due to the fact that the observations for the polishing life are made visually. The results obtained for the second polishing were 3% better than the single layer AlTiN coated dies. This could be due to the visual observations for the polishing life. For the polishing life, it can be said that the polishing life of the multi layer TOKTEK coated dies is equal to the polishing life of the single layer AlTiN coated dies, which are 57% higher with respect to as received dies, and 7% lower with respect to nitrided dies. As explained before, the reason for this is that the thickness of nitrided dies was with 0.3 mm much more than the thickness of TOKTEK coating, which was only 12 μm and after the first polishing, there was a remainder partially nitrided layer with the thickness of 0.15 mm. Due to this remaining layer, the second polishing is made after more forgings.

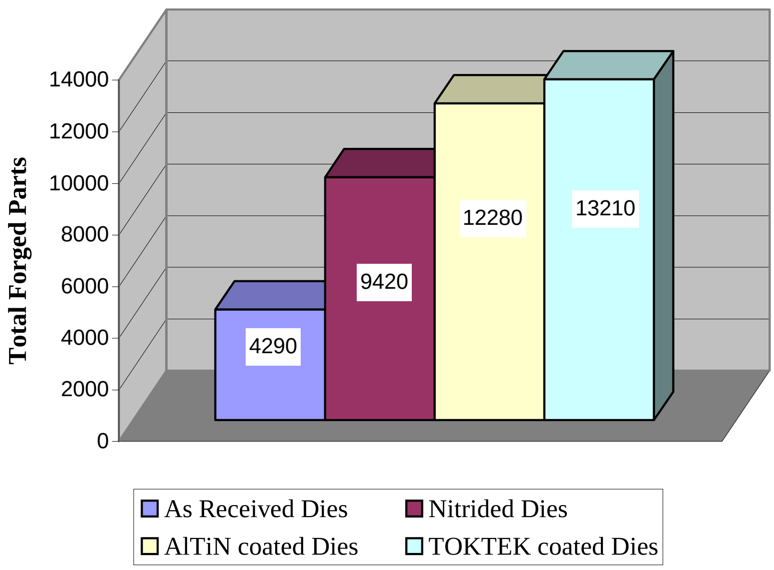


Figure 4.5 Comparison of total Forged Parts with as received, Nitrided, AlTiN coated and TOKTEK coated Dies

Table 4.7 The deviations measured on critical dimensions of the multi layer TOKTEK coated dies (thickness of the coating : 12 μm ±1.2 μm)

Forged Parts	Deviation from Dimension (mm)				
	Ø185	Ø138	Ø136,5	Ø195,5	26,5
0	0.00	0.10	0.05	0.00	0.20
360	0.00	-0.05	-0.05	0.10	0.20
720	-0.10	-0.10	-0.10	0.20	0.20
1080	-0.10	-0.10	-0.10	0.20	0.10
1440	-0.10	-0.10	-0.10	0.20	0.20
1800	-0.10	-0.10	-0.10	0.20	0.20
2160	-0.10	-0.10	-0.10	0.20	0.30
2520	-0.10	-0.15	-0.10	0.20	0.30
2880	-0.15	-0.15	-0.15	0.20	0.20
3240	-0.15	-0.15	-0.15	0.20	0.20
3600	-0.20	-0.20	-0.20	0.25	0.10
3960	-0.20	-0.20	-0.20	0.25	0.20
4320	-0.25	-0.20	-0.20	0.25	0.30
4680	-0.25	-0.20	-0.20	0.25	0.30
5040	-0.25	-0.20	-0.20	0.25	0.20
5400	-0.30	-0.25	-0.25	0.25	0.20
5760	-0.30	-0.25	-0.25	0.25	0.20
6120	-0.30	-0.25	-0.25	0.25	0.30
6480	-0.35	-0.25	-0.25	0.25	0.20
6840	-0.35	-0.25	-0.25	0.25	0.10
7200	-0.40	-0.30	-0.30	0.30	0.10
7560	-0.40	-0.30	-0.30	0.30	0.20
7920	-0.50	-0.30	-0.30	0.30	0.20
8280	-0.50	-0.30	-0.30	0.30	0.20
8640	-0.60	-0.30	-0.30	0.30	0.20
9000	-0.65	-0.30	-0.30	0.30	0.20
9360	-0.65	-0.30	-0.30	0.30	0.10
9720	-0.65	-0.30	-0.30	0.30	0.20
10080	-0.70	-0.30	-0.30	0.30	0.20
10440	-0.70	-0.30	-0.30	0.30	0.20
10800	-0.80	-0.35	-0.30	0.30	0.20
11160	-0.80	-0.35	-0.30	0.30	0.20
11520	-0.80	-0.35	-0.30	0.30	0.10
11880	-0.85	-0.35	-0.30	0.30	0.20
12240	-0.85	-0.35	-0.30	0.30	0.20
12600	-0.90	-0.35	-0.30	0.30	0.20
12960	-0.90	-0.35	-0.30	0.30	0.10
13210	-1.00	-0.40	-0.30	0.30	0.20

Table 4.8 Polishing life for each polishing of multi layer TOKTEK coated dies during the forging process

Operation	1st polish.	2nd polish.	3rd polish.	4th polish.	5th polish.	Total prod.
Number of Forged Parts	4660	2030	1750	1830	1780	13210

4.1.4 Weld Overlay Coated Dies

As given in Table 4.9 and 4.10, the deviation from the Ø185 dimension came out of tolerance after 27810 and 25930 forgings for the first and second serial forging productions respectively. As shown in Figure 4.6, the best results for the die service life were obtained with weld overlay coated dies. In this method a special Stellite 6 electrode CASTOLIN N9080 was deposited on the surface of the dies. Due to the thickness of the weld overlay, a resinking is applied to the die surface when the dies are worn out of tolerance. The change in the height of the forged part after die resinking is then compensated by a plate located under the dies. So the dies were put into production twice. The die service life for all types of studied coatings is given in Table 4.11. From this Table, it can be seen that in both of the forging productions with weld overlay coated dies, similar results were obtained. 27810 parts before resinking and 25930 parts after resinking were forged (total 53740 pcs) with the same die in two serial production runs. The average die service life was 206% better than multi layer TOKTEK coating, which held the second place in die service life and 892% better than as received dies.

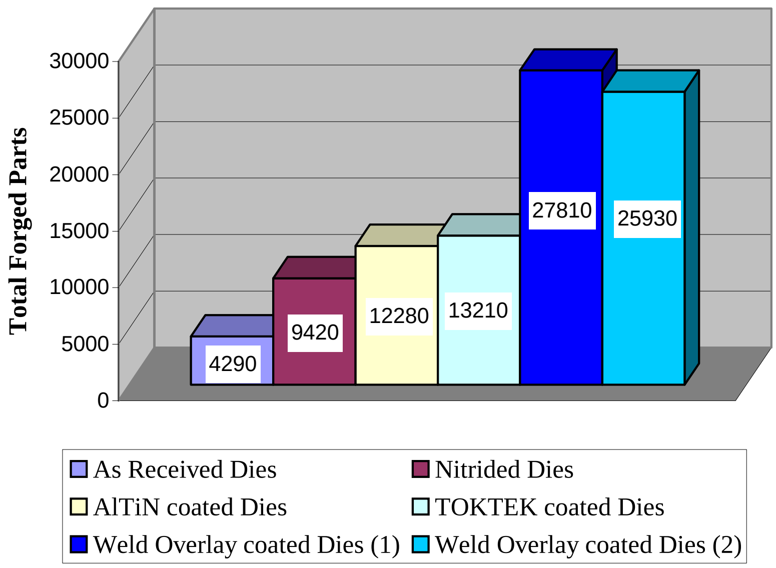


Figure 4.6 Comparison of total Forged Parts with As received, Nitrided, AlTiN coated dies, TOKTEK coated Dies and weld overlay coated dies.

The polishing life of weld overlay coated dies in this forgings is given in Table 4.12 and 4.13. Similar results were also observed for the polishing life. The average first polishing life was 8510 pcs , which shows a 77% increase compared to the second best results obtained with single layer AlTiN coating, and compared to as received dies, an increase of 491% was achieved.

Different from other surface coating techniques the polishing life characteristic of weld overlay coating remains nearly constant for further polishing. This has several reasons :

1 - The thickness of the coating is 3 mm and remains still on the die surface after each polishing.

2 – The electrode has a high cobalt concentration. This provides a good resistance to creep and a low friction coefficient. Thus the polishing life increases by delaying the formation of scratches due to friction between the die and forging billet under high loads.

3 –The weld overlay coating has superior properties such as excellent resistance to thermal softening, which reduces the wear on the die surfaces. The coating keeps its hardness up to 800 ^{o}C. As stated by D.J.Jeong, (2001) high hot hardness provides better results in die service life.

Table 4.9 The deviations measured on critical dimensions of the weld overlay coated dies (thickness of the coating: 3 mm)

Forged Parts	from Dimension (mm)				
	Ø185	Ø138	Ø136,5	Ø195,5	26,5
0	-0.10	0.10	0.05	0.10	0.30
360	-0.10	0.00	0.00	0.10	0.20
720	-0.10	0.00	0.00	0.10	0.20
1080	-0.10	0.00	0.00	0.10	0.30
1440	-0.10	0.00	0.00	0.10	0.30
1800	-0.10	-0.05	0.00	0.10	0.30
2160	-0.10	-0.05	0.00	0.10	0.30
2520	-0.10	-0.10	0.00	0.10	0.20
2880	-0.10	-0.10	0.00	0.10	0.20
3240	-0.10	-0.10	0.00	0.10	0.30
3600	-0.15	-0.10	-0.05	0.10	0.30
3960	-0.15	-0.10	-0.05	0.10	0.20
4320	-0.15	-0.10	-0.05	0.10	0.20
4680	-0.15	-0.10	-0.05	0.10	0.20
5040	-0.15	-0.10	-0.05	0.10	0.20
5400	-0.20	-0.10	-0.05	0.10	0.30
5760	-0.20	-0.10	-0.05	0.10	0.30
6120	-0.20	-0.10	-0.05	0.10	0.20
6480	-0.20	-0.10	-0.05	0.10	0.20
6840	-0.20	-0.10	-0.05	0.10	0.30
7200	-0.25	-0.10	-0.10	0.15	0.30
7920	-0.25	-0.10	-0.10	0.15	0.20
8640	-0.30	-0.10	-0.10	0.15	0.30
9360	-0.30	-0.10	-0.10	0.15	0.20
10080	-0.35	-0.10	-0.10	0.15	0.20
10800	-0.40	-0.10	-0.10	0.15	0.20
11520	-0.40	-0.10	-0.10	0.15	0.30
12240	-0.40	-0.10	-0.10	0.15	0.30
12960	-0.45	-0.10	-0.15	0.15	0.20
13680	-0.45	-0.10	-0.15	0.15	0.30
14400	-0.50	-0.15	-0.20	0.20	0.20
15120	-0.50	-0.15	-0.20	0.20	0.20
15840	-0.55	-0.15	-0.20	0.20	0.30
16560	-0.60	-0.15	-0.20	0.20	0.20
17280	-0.60	-0.15	-0.20	0.20	0.20
18000	-0.65	-0.20	-0.20	0.20	0.30
18720	-0.65	-0.20	-0.20	0.20	0.30
19440	-0.65	-0.20	-0.20	0.20	0.20
20160	-0.70	-0.20	-0.25	0.20	0.20
20880	-0.75	-0.20	-0.25	0.20	0.20
21600	-0.80	-0.20	-0.30	0.25	0.30
22320	-0.80	-0.20	-0.30	0.25	0.30
23040	-0.80	-0.20	-0.30	0.25	0.20
23760	-0.80	-0.25	-0.30	0.25	0.30
24480	-0.85	-0.25	-0.30	0.25	0.30
25200	-0.90	-0.30	-0.30	0.30	0.20
25920	-0.90	-0.30	-0.30	0.30	0.30
26640	-0.90	-0.30	-0.30	0.30	0.20
27360	-0.95	-0.30	-0.30	0.30	0.30
27810	-1.00	-0.30	-0.30	0.30	0.20

Table 4.10 The deviations measured on critical dimensions of the weld overlay coated dies after resinking (thickness of the coating of the dies: 2 mm)

Forged Parts	Deviation from Dimension (mm)				
	Ø185	Ø138	Ø136,5	Ø195,5	26,5
0	0.00	0.00	0.10	0.10	0.20
360	0.00	0.00	0.10	0.10	0.20
720	0.00	0.00	0.10	0.10	0.30
1080	0.00	-0.05	0.10	0.10	0.30
1440	0.00	-0.05	0.10	0.10	0.20
1800	0.00	-0.05	0.10	0.10	0.20
2160	0.00	-0.05	0.10	0.10	0.20
2520	0.00	-0.05	0.10	0.10	0.20
2880	0.00	-0.05	0.10	0.10	0.20
3240	0.00	-0.05	0.10	0.10	0.20
3600	-0.10	-0.10	0.05	0.10	0.20
3960	-0.10	-0.10	0.05	0.10	0.30
4320	-0.10	-0.10	0.05	0.10	0.30
4680	-0.10	-0.10	0.05	0.10	0.30
5040	-0.10	-0.10	0.05	0.10	0.30
5400	-0.10	-0.10	0.05	0.10	0.20
5760	-0.15	-0.10	0.05	0.10	0.20
6120	-0.15	-0.10	0.05	0.10	0.30
6480	-0.15	-0.10	0.05	0.10	0.20
6840	-0.15	-0.10	0.05	0.10	0.30
7200	-0.20	-0.10	0.10	0.15	0.30
7920	-0.20	-0.10	0.05	0.15	0.20
8640	-0.25	-0.10	0.05	0.15	0.30
9360	-0.30	-0.10	0.05	0.15	0.20
10080	-0.30	-0.10	0.05	0.15	0.30
10800	-0.35	-0.15	0.00	0.15	0.20
11520	-0.35	-0.15	0.00	0.15	0.30
12240	-0.35	-0.15	0.00	0.15	0.20
12960	-0.40	-0.15	-0.05	0.15	0.30
13680	-0.45	-0.15	-0.05	0.15	0.30
14400	-0.50	-0.20	-0.10	0.20	0.30
15120	-0.50	-0.20	-0.10	0.20	0.30
15840	-0.50	-0.20	-0.10	0.20	0.30
16560	-0.50	-0.20	-0.10	0.20	0.20
17280	-0.50	-0.20	-0.10	0.20	0.30
18000	-0.50	-0.20	-0.10	0.20	0.30
18720	-0.55	-0.20	-0.10	0.20	0.20
19440	-0.55	-0.20	-0.10	0.20	0.20
20160	-0.60	-0.20	-0.10	0.20	0.20
20880	-0.75	-0.20	-0.10	0.20	0.30
21600	-0.80	-0.25	-0.20	0.25	0.30
22320	-0.80	-0.25	-0.20	0.25	0.30
23040	-0.85	-0.25	-0.20	0.25	0.20
23760	-0.85	-0.25	-0.20	0.25	0.30
24480	-0.90	-0.25	-0.20	0.25	0.20
25200	-0.95	-0.30	-0.20	0.30	0.30
25930	-1.00	-0.30	-0.30	0.30	0.20

Table 4.11 Die life obtained for studied coatings

Type of coating	As received	Plasma nitrided	AlTiN coated	TOKTEK coated	Weld overlay coated
Total forging	4920	9420	12280	12310	27810 + 25930 (53740)

Table 4.12 Polishing life for each polishing of weld overlay coated dies during the first forging process

Operation	1st polishing	2nd polishing	3rd polishing	Total prod.
Number of Forged Parts	8690	8160	8240	27810

Table 4.13 Polishing life for each polishing of weld overlay coated dies during the second forging process

Operation	1st polishing	2nd polishing	3rd polishing	Total prod.
Number of Forged Parts	8330	8410	7830	25930

4.2 Die Cost per Part

The main reason for a company's existence is to get profit from its sales. In the past, the company added its profit to the cost of a product to determine the sales price. In other words, the main relation between the sales price and profit, is was Cost + Profit = Sales price. Nowadays, the market has determined its prices. So, the equation has now changed to Sales Price – Cost = Profit. That means, the profit is determined by the total production cost. If the total production cost is below the sales price, which is determined by the market itself, profit can be obtained. Otherwise, no profit can be obtained, and the existence of a company will not be possible. So, the total cost has to be reduced for each company.

In forging processes, the die cost per part is one of the partially costs, which affect the total cost of the part, and profit of a company. The aim of surface treatments applied to the dies is increasing the die service life, and thus, decreasing the die cost per part. Therefore, the die cost per part is used in this study in the comparison of surface treated dies.

4.2.1 As Received Dies

The total die cost (CD_{tot}) of the dies was calculated as follows :

$CD_{tot} = (C_{die\ mat}) + (C_{sawing}) + (C_{machining}) + (C_{Surf\ treat}) + (C_{res})$

$(C_{die\ mat}) + (C_{sawing}) = 1500$ €

$(C_{machining}) = 1500$ €

$(C_{Surf\ treat}) = 0$ €

$(C_{res}) = 0$ €

$CD_{tot} = 1500$ € + 1500 € = 3000 €

In the experiments carried out, the die sets were polished 3 times (total 3 hours) for the production batch of 4290 pcs. So;

$(C_{press}) = 3$ h * 135 € / h = 405 € and

$(C_{profit+labor}) = 162$ € / h* 3 h = 486 €

And the total cost of the die per forged part

$(CD_{parts\ forged}) = [(CD_{tot}) + (C_{press}) + (C_{profit+labor})] / (PF_{tot})$

$(CD_{parts\ forged}) = [3000$ € + 405 € + 486 €] / 4290 pcs = 0.91 €/pcs

4.2.2 Nitrided Dies

The total die costs (CD_{tot}) for nitrided dies was calculated as :

$CD_{tot} = (C_{die\ mat}) + (C_{sawing}) + (C_{machining}) + (C_{Surf\ treat}) + (C_{res})$

$(C_{die\ mat}) + (C_{sawing}) = 1500$ €

$(C_{machining}) = 1500$ €

$(C_{Surf\ treat}) = 2400$ €

$(C_{res}) = 0$ €

$CD_{tot} = 1500$ € + 1500 € + 2400 € = 5400 €

In the experiments carried out, the nitrided die sets were polished 3 times (total 3 hours) for the production batch of 9420 pcs. So;

(C_{press}) = 3 h * 135 € / h = 405 € and

$(C_{profit+labor})$ = 162 € / h* 3 h = 486 €

And the total cost of the die per forged part

$(CD_{parts\ forged})$ = [(CD_{tot}) + (C_{press}) + $(C_{profit+labor})$] / (PF_{tot})

$(CD_{parts\ forged})$ = [5400 € + 405 € + 486 €] / 9420 pcs = 0.67 €/pcs

Compared to as received dies, a reduction of 0.91 € / pcs – 0.67 € / pcs = 0.24 € / pcs is achieved for nitrided dies. The reduction in the die cost Per part was approximately 26%, which is an important value for companies.

4.2.3 AlTiN Coated Dies

The total die costs (CD_{tot}) for AlTiN coated dies was calculated as :

CD_{tot} = $(C_{die\ mat})$ + (C_{sawing}) + $(C_{machining})$ + $(C_{Surf\ treat})$ + (C_{res})

$(C_{die\ mat})$ + (C_{sawing}) = 1500 €

$(C_{machining})$ = 1500 €

$(C_{Surf\ treat})$ =1700 €

(C_{res}) = 0 €

CD_{tot} = 1500 € + 1500 € + 1700 € = 4700 €

In the experiments carried out, the AlTiN coated die sets were polished 4 times (total 4 hours) for the production batch of 12280 pcs. So;

(C_{press}) = 4 h * 135 € / h = 540 € and

$(C_{profit+labor})$ = 162 € / h* 4 h = 648 €

And the total cost of the die per forged part

$(CD_{parts\ forged})$ = [(CD_{tot}) + (C_{press}) + $(C_{profit+labor})$] / (PF_{tot})

$(CD_{parts\ forged})$ = [4700 € + 540 € + 648 €] / 12280 pcs = 0.48 €/pcs

Compared to as received dies, a reduction of 0.91 € / pcs – 0.48 € / pcs = 0.43 € / pcs is achieved for AlTiN coated dies. The reduction in the die cost Per part was approximately 47% , which is an important value for each company.

Compared to nitrided dies, a reduction of 0.67 € / pcs – 0.48 € / pcs = 0.19 €/pcs in die cost is achieved for AlTiN coated dies. The reduction in the die cost per part was approximately 28%, which is an important value for each company.

4.2.4 TOKTEK Coated Dies

The total die costs (CD_{tot}) for TOKTEK coated dies was calculated as :

$CD_{tot} = (C_{die\ mat}) + (C_{sawing}) + (C_{machining}) + (C_{Surf\ treat}) + (C_{res})$

$(C_{die\ mat}) + (C_{sawing}) = 1500$ €

$(C_{machining}) = 1500$ €

$(C_{Surf\ treat}) = 3300$ €

$(C_{res}) = 0$ €

$CD_{tot} = 1500$ € + 1500 € + 3300 € = 6300 €

In the experiments carried out, the TOKTEK coated die sets were polished 5 times (total 4 hours) for the production batch of 13210 pcs. So;

$(C_{press}) = 5$ h * 135 € / h = 675 € and

$(C_{profit+labor}) = 162$ € / h* 5 h = 810 €

And the total cost of the die per forged part

$(CD_{parts\ forged}) = [(CD_{tot}) + (C_{press}) + (C_{profit+labor})] / (PF_{tot})$

$(CD_{parts\ forged}) = [6300$ € + 675 € + 810 €] / 13210 pcs = 0.59 €/pcs

Compared to as received dies, a reduction of 0.91 € / pcs – 0.59 € / pcs = 0.32 €/pcs is achieved for TOKTEK coated dies. The reduction in the die cost Per part was approximately 35%, which is an important value for companies.

Compared to nitrided dies, the reduction in the cost 0.67 €/pcs–0.59 €/pcs = 0.08 € / pcs is achieved for TOKTEK coated dies. The reduction in the die cost per part was approximately 12%, which is an important value for each company.

Compared to AlTiN coated dies, an increase of 0.48 € / pcs–0.59 € / pcs = 0.11 € / pcs in the cost is calculated for TOKTEK coated dies. The increase in the die cost Per part was approximately 18%.

4.2.5 Weld Overlay Coated Dies

The total die costs (CD_{tot}) for weld overlay coated dies was calculated as :

$CD_{tot} = (C_{die\ mat}) + (C_{sawing}) + (C_{machining}) + (C_{Surf\ treat}) + (C_{res})$

$(C_{die\ mat}) + (C_{sawing}) = 1500$ €

$(C_{machining}) = 2500$ €

$(C_{Surf\ treat}) = 2400$ €

$(C_{res}) = 1000$ €

$CD_{tot} = 1500$ € + 2500 € + 2400 € +1000 € = 7400 €

In the experiments carried out, the weld overlay coated die sets were polished 6 times (total 6 hours) in two production runs and 2 hour additional time has spent after resinking for die exchange and set-up. The total production was 53.740 pcs. So;

$(C_{press}) = 8$ h * 135 € / h = 1080 € and

$(C_{profit+labor}) = 162$ € / h* 8 h = 1296 €

And the total cost of the die per forged part

$(CD_{parts\ forged}) = [(CD_{tot}) + (C_{press}) + (C_{profit+labor})] / (PF_{tot})$

$(CD_{parts\ forged}) = [7400$ € + 1080 € + 1296 €] / 53740 pcs = 0.18 €/pcs

Compared to as received dies, a reduction of 0.91 € / pcs – 0.18 € / pcs = 0.73 € / pcs is achieved for weld overlay coated dies. The reduction in the die cost Per part was approximately 80%, which is an important value for companies.

Compared to nitrided dies, the reduction in the cost 0.67 €/pcs–0.18 €/pcs = 0.49 € / pcs is achieved for weld overlay coated dies. The reduction in the die cost Per part was approximately 73%, which is an important value for each company.

Compared to AlTiN coated dies, the cost decreased 0.48 €/pcs – 0,18 €/pcs = 0,32 € / pcs for weld overlay coated dies. The decrease in the die cost per part was approximately 62%.

The cost details for each type surface coating are calculated according to the information given in section 3.2.2 and given in Table 4.14.

Table 4.14 Comparison of cost per part for each of the studied coatings

	As received Die	Nitrided Dies	AlTiN coated Dies	TOKTEK coated dies	Weld overlay coated dies
Die material + sawing (Euro)	1.500	1.500	1.500	1.500	1.500
Machining (Euro)	1.500	1.500	1.500	1.500	2.500
Surface treatment (Euro)	0	2.400	1.700	3.300	2.400
Nr.of Press breaks due to polishing	3	3	4	5	8
Cost of press breaks (Euro)	405	405	540	675	1080
Die resinking (Euro)	0	0	0	0	1000
Profit + labor (Euro)	486	486	648	810	1296
Total Cost (Euro)	3891	6291	5888	7785	9776
Forged Parts (pieces)	4290	9420	12280	13210	53740 *
Cost per Part (Euro/pieces)	0.91	0.67	0.48	0.59	0.18
Decrease in cost (%)	0	26.4	47.3	35.2	80.0

* Forged parts in the first and second forgings (after resinking the dies) with the same dies have to be taken into account

As it can be seen from Table 4.14, according to total die cost, the most cheapest is the as received dies, while the weld overlay coated dies are the most expensive. Considering the die cost per part, this situation changes widely. The most expensive weld overlay coating becomes the cheapest one with a cost of 0.15 Eu/pcs, and the cheapest one, the as received die, becomes the most expensive one with a cost of 0.91 Euro/pcs. Ranging the coatings studied in this work, from the cheapest to the most expensive, according to die cost per part results in a range of : 1 – weld overlay coated dies, 2 – single layer AlTiN coated dies 3 – multi layer TOKTEK coated dies; 4 – plasma nitrided dies, 5 – as received dies. Compared to the die service life, a similar range has been obtained, with the exception of that the TOKTEK coating has a higher die service life but is quite expensive than AlTiN coating.

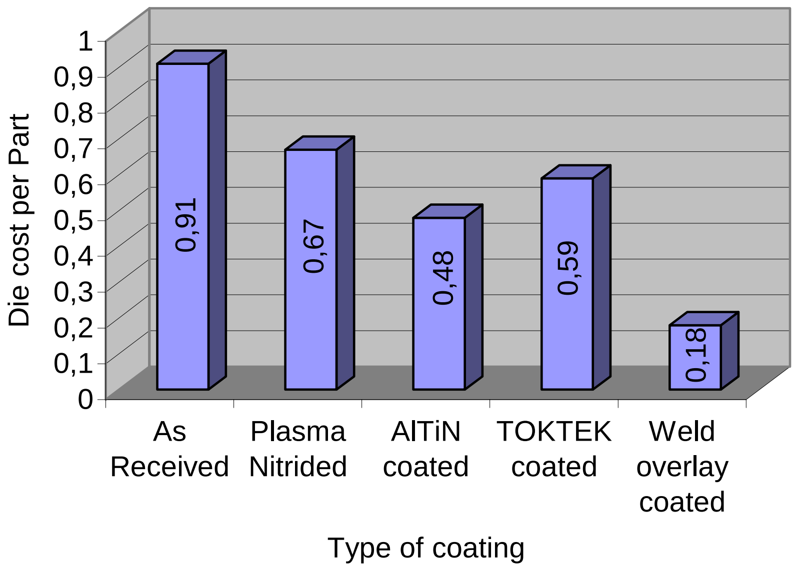


Figure 4.7 Comparison of die cost per part for each studied coating

The results obtained for different kind of coatings, showed that each kind of the studied coatings increases the die service life and decreases the die cost per part.

4.3 Break Even Point

The break even point is described as the point, where two different curves intersect. In this study, the intersecting curves are the curves of cost for different type of surface coatings. Due to the additional cost of the surface treatments, the selection of the best surface treatment technique, which will give minimum cost, can be done according to the break even point.

4.3.1 Nitrided Dies

The curve for the break even point is drawn according to the following Equations

$$(CD_{tot})_1 = (CD_{ini})_1 + (CD_{parts\ forged})_1 * (PF_{tot})$$

$$(CD_{tot})_0 = (CD_{ini})_0 + (CD_{parts\ forged})_0 * (PF_{tot})$$

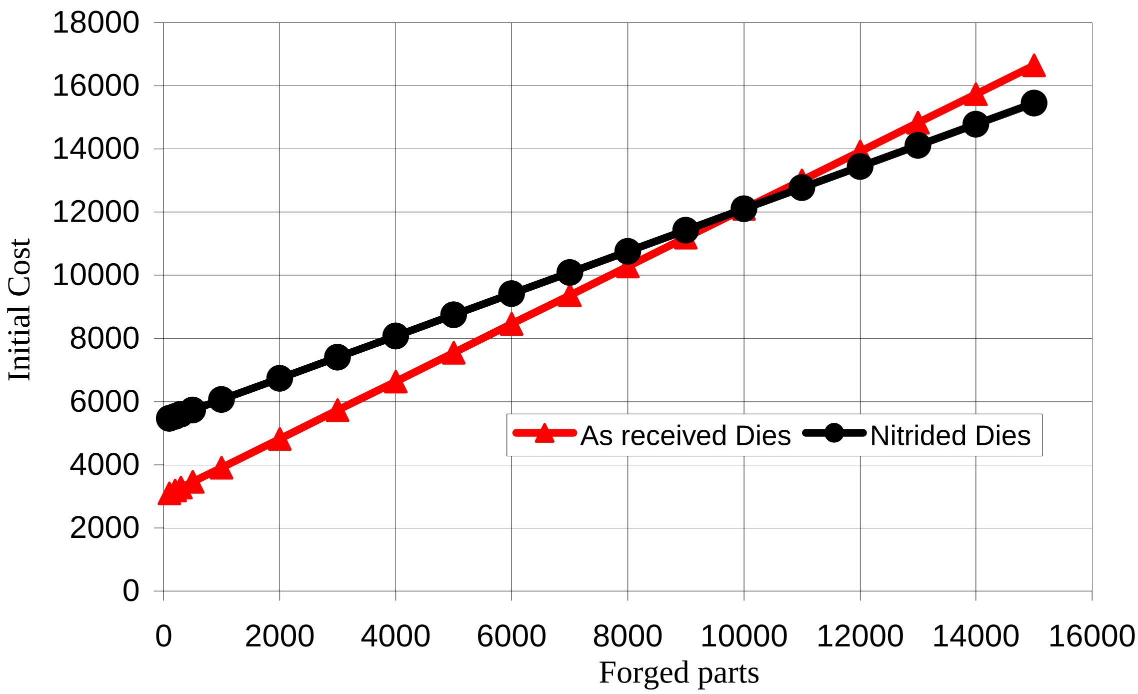


Figure 4.8 The total cost curve for as received dies and nitrided dies

As shown in Figure 4.8, the break even point for nitrided dies is 10000 pieces.

The break even point for for nitrided dies is calculated as follows :

$[(C_{mach})_1+(C_{S.treat})_1+(C_{res})_1-(C_{mach})_0] / [(CD_{parts\ forged})_0-(CD_{parts\ forged})_1]=(PF_{tot})$

$[1500 + 2400 + 0-1500] / [0.91-0.67] = (PF_{tot})$

$10000 \text{ pieces} = (PF_{tot})$

4.3.2 AlTiN Coated Dies

The break even point for for AlTiN coated dies is calculated as follows :

$[(C_{mach})_1+(C_{S.treat})_1+(C_{res})_1-(C_{mach})_0] / [(CD_{parts\ forged})_0-(CD_{parts\ forged})_1]=(PF_{tot})$

$[1500 + 1700 + 0-1500] / [0.91-0.48] = (PF_{tot})$

$3954 \text{ pieces} = (PF_{tot})$

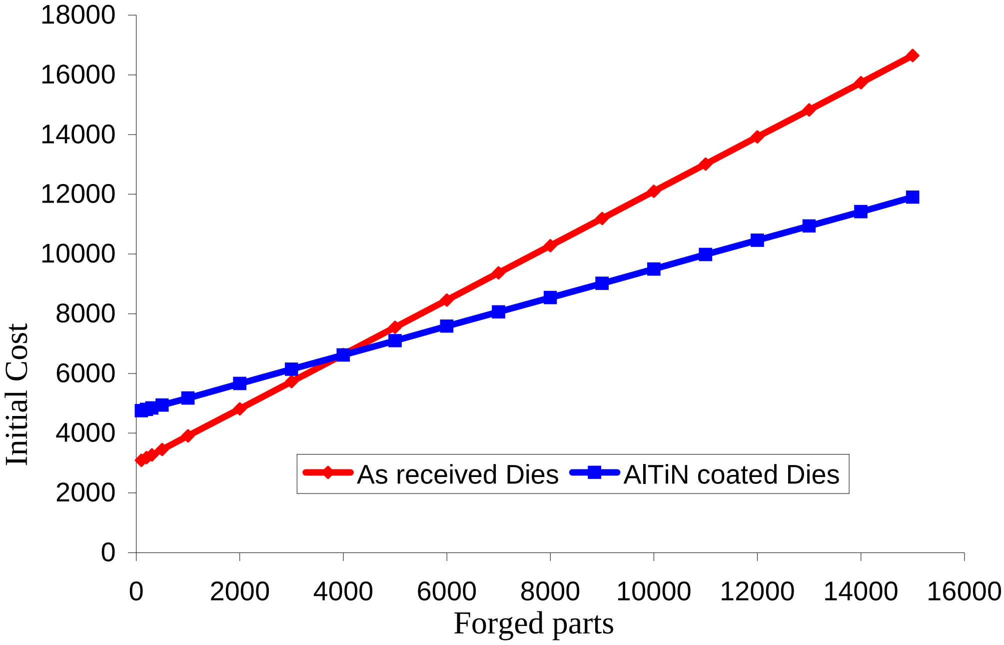


Figure 4.9 The total cost curve for as received dies and AlTiN coated dies

From Figure 4.9, it can be seen that the break even point is 3954 pieces as calculated.

4.3.3 TOKTEK Coated Dies

The break even point for for TOKTEK coated dies is calculated as follows :

$[(C_{mach})_1+(C_{S.treat})_1+(C_{res})_1-(C_{mach})_0] / [(CD_{parts\ forged})_0-(CD_{parts\ forged})_1]=(PF_{tot})$

$[1500 + 3300 + 0-1500] / [0.91-0.59] = (PF_{tot})$

10312 pieces = (PF_{tot})

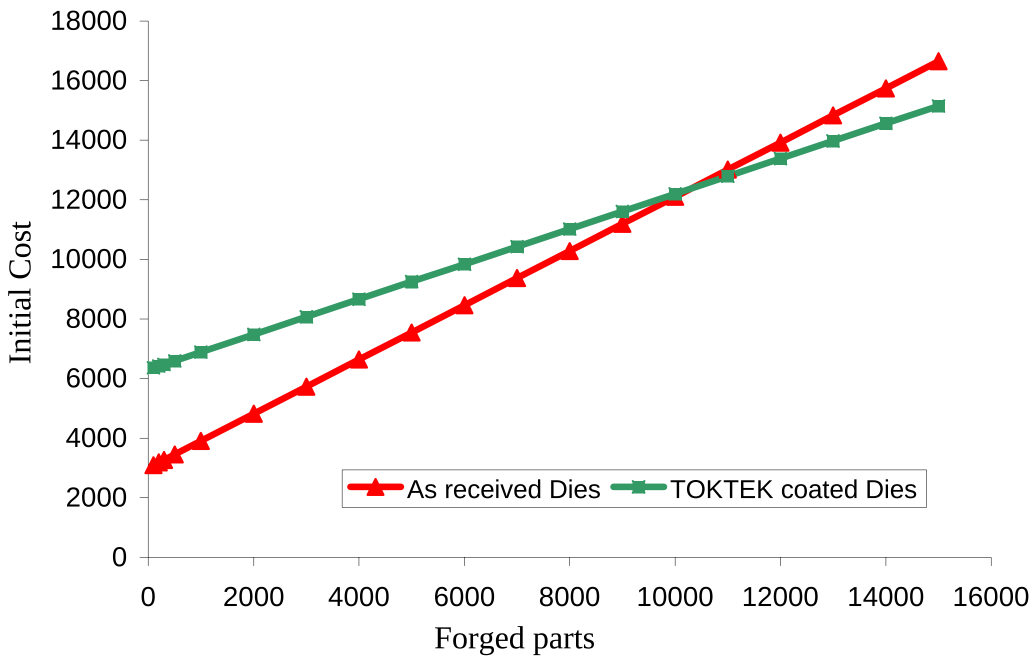


Figure 4.10 The total cost curve for as received dies and TOKTEK coated dies

As shown in Figure 4.10, the use of TOKTEK coating will only be economical if the total need of parts is more than 10312 pieces.

4.3.4 Weld Overlay Coated Dies

The break even point for for weld overlay coated dies is calculated as follows

$[(C_{mach})_1+(C_{S.treat})_1+(C_{res})_1-(C_{mach})_0] / [(CD_{parts\ forged})_0-(CD_{parts\ forged})_1]=(PF_{tot})$

$[2500 + 2400 + 1000-1500] / [0.91-0.18] = (PF_{tot})$

6027 pieces = (PF_{tot})

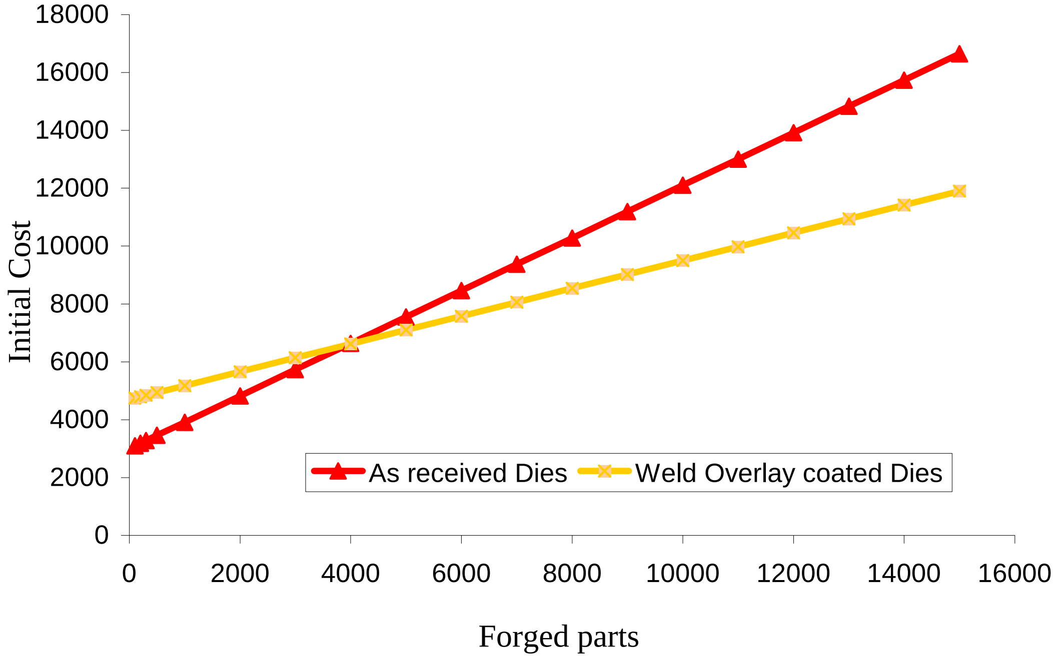


Figure 4.11 The total cost curve for as received and weld overlay coated dies

As shown in Figure 4.11, after forging of 6027 pieces, the weld overlay coating becomes more economical than as received dies.

.

5 - CONCLUSION AND FUTURE STUDİES

5.1 Conclusion

Due to new requirements on high productivity and improving cost in forging processes, forging industries have shown great interest in improving tooling used in hot forging processes. Due to the enormous quantities of products in these industries and the relatively short life of the dies necessary, even small improvements in this field bring a large economic effect.

The lifetimes of dies used in forging processes are very variable and are determined by the wear rate, plastic deformation, thermal fatigue and mechanical fatigue. To reduce the wear rate in materials, various surface engineering techniques are widely employed. These techniques are also being considered in the forging industry to improve the life of forging dies.

In this work, the polishing life, the die service life and die cost per part of 4 types of surface treated dies and an as received die were investigated. The following conclusions were derived after analysis of the real forging processes carried out in this work.

1. Each of the surface treatments studied in this work have an improving effect on the polishing life and the die service life of the forging dies.
2. The range from the best to the worst was the same for the polishing life and die service life.
3. Compared to as received dies, with the plasma nitrided dies, the polishing life increased up to 175% for the first polishing, and 60% for further polishings.
4. With single Layer AlTiN coated dies, the increase in polishing life compared to as received dies was 234%, which was 23% better than nitrided dies.
5. The polishing life obtaine for multi layer TOKTEK coating were similar to thosse obtained with single Layer AlTiN coated dies.

6. For the polishing life, the best results were obtained with weld overlay coated dies. Compared to as received dies, the results showed an increase of 491%. The results were 77% better than AlTiN and TOKTEK coatings, which held the second place.
7. The deformation (wear rate) for all types of coatings of the dies is rapid at the beginning of the forging process. Then, it slows down during the process and it increases again at the end of the die service life.
8. While the nitrided dies were used in the forging process, the die service life increased 119% with respect to as received dies.
9. A noticable increase has been obtained for the die service life for single layer AlTiN coated dies. The increase was 150% and 30% compared to as received dies and nitrided dies respectively.
10. Although the polishing life was similar for AlTiN coated and TOKTEK coated dies, the die service life for multi layer TOKTEK coated dies was 8% better than AlTiN coated dies. This was an increase of 40% and 168% in die service life compared to nitrided and as received dies respectively.
11. The best results for die service life were obtained for weld overlay coated dies. Compared to as received dies, the results showed an increase of 892%. The results were 206% better than TOKTEK coatings, which held the second place.
12. Although the initial cost was the minimum, the die cost per part was with 0.91 Eu/pcs the highest for as received dies.
13. Despite the highest initial cost for weld overlay coating, the lowest die cost per part was obtained for this type of coating with 0.18 Eu/pcs. This value was 80% lower than obtained for as received dies.
14. In die cost per part, AlTiN coated dies held with 0.48 Eu/pcs, 47% lower than as received dies, the second place.
15. Regarding the die cost per part, the multi layer TOKTEK coating drop to third place with the cost of 0.59 Eu/pcs, 35% better than for as received dies.

16. As their range in polishing life and die service life, the nitrided dies held for the die cost per part with 0.67 Eu/pcs, 26% less than as received dies,the forth place again.
17. The total forging amount has also to be taken into consideration by deciding for the type of coating used. The total forging amount should not be less than the amount calculated as the break even point. In this study, the break even points were : TOKTEK coating → 10312 pcs; nitriding → 10000 pcs; weld overlay coating → 6027 pcs; AlTiN coating → 3954 pcs

For the die service life of the coatings studied in this work, the dies can be ranged from the best to worst as 1 – weld overlay coated dies, 2 – multi layer TOKTEK coated dies 3 – single layer AlTiN coated dies; 4 – plasma nitrided dies, 5 – as received dies. This range is also valid for the die polishing life, with the exception of that it is equal for AlTiN and TOKTEK coatings.

5.2 Future Studies

This study has been concentrated on improving the die service life and reducing the die cost in hot forging by means of surface treatments. During this study, it was observed that the weld overlay coating has been investigated in very few studies, while other surface treatment techniques such as nitriding, single layer coating and duplex treatment have been investigated in many researches.

In Future, the investigations in weld overlay coating should be extended and alternative welding electrode to Castolin N9080, or in general Stellite 6 type electrodes should be studied.

A study to increase the initial thickness of the weld overlay coating, to make it possible to resinking the dies two times and to use the same coating in three serial production runs can also be realized.

REFERENCES

ALTAN, T., 1998a, Hammers and Presses for Forging, W.G. WOOD, ASM Handbook Volume 14 Forming and Forging; Library of Congress -in-Publication Data, ASM International, USA, 29-35

ALTAN, T., 1998b, Selection of forging equipment, W.G. WOOD, ASM Handbook Volume 14 Forming and Forging; Library of Congress -in-Publication Data, ASM International, Metals Park, Ohio, USA, 36 – 42

ALTAN, T., OH, S., GEGEL, H., 1995a. Impression and closed die forging. Metal Forming : Fundamentals and Applications. 143-170

ANDREIS, G., FUCHS, K.D., SCHRUFF, I., 1999. The wear behaviour of hot work tool steels used in forging processes. Proceedings of the fifth International Conference on Tooling, Leoben, 593 – 600

BABU, S., RIBEIRO, D., SHIVPURI, R., 1999. Material and Surface engineering for precision forging dies. Precision Forging Consortium - Ohio Aerospace Institute and National Center for Manufacturing. June 10, 1999

BAHRAMI, A., MOUSAVI ANIJDAN , S.H., GOLOZAR, M.A., SHAMANIAN, M., VARAHRAM, N., 2005. Effect of Conventional Heat Treatment on Wear Resistance of AISI H13 Tool Steel. Wear, 258: 846 – 851

BARRAU, O., BOHER, C., GRAS, R., REAZAI – ARIA, F., 2003. Analysis of Friction and Wear Behaviour of Hot Work Tool Steel for Forging. Wear, 255: 1444 - 1454

BIBA, N., STEBOUNOV, S., LISHING, A., 2001. Cost effective implementation of forging simulation. . Journal of Material Processing Technology, 113: 34 – 39

CERWİN, N., 1995, Die Life and the forging environment, N. CERWIN, M. PHILLIPS, Finkl and sons Co. Die Handbook Volume 1. Chicago, Illınois, USA, 36 – 38

CHIU, L.H., WU, C.H, CHANG, H., 2002. Wear behaviour of nitrocarburized JIS SKD61 tool steel. Wear, 253:778 – 786

ÇAPA, M., TAMER, M., GÜLMEZ, T., BODUR, C.T., 2000. Life enhancement of hot Forging Dies by Plasma Nitriding. Journal of Engineering Environment Science, 24: 111 – 117

DOBRZANSKI, L.A., MAZURKIEWİCZ, J., HAJDUCZEK, E., MADEJSKI, J., 2001. Comparison of the Thermal Fatigue Resistance and Structure of the 47CrMoWVTiCe-Zr-16-26-8 hot work tool steel with X40CrMoV5-1 type one. Journal of Material Processing Technology, 113: 527 – 538

DOBRZANSKI, L.A., MAZURKIEWİCZ, J., HAJDUCZEK, E., 2004. Effect of thermal treatment on structure of newly developed 47CrMoWVTiCe-Zr-16-26-8 hot work tool steel. Journal of Material Processing Technology, 157-158: 472 – 484

DOBRZANSKI, L.A., POLOK, M., PANJAN, P., BUGLIOSI, S., ADAMIAK, M., 2004. Improvement of wear resistance of hot work steels by PVD coatings deposition. Journal of Material Processing Technology, 155-156: 1995 – 2001

DOEGE, E., BOHNSACK, R., 2000. Closed Die Technologies for hot Forging. Journal of Material Processiing Technology, 98: 165 – 170

DOWEY, S.J., RAEHLE, B., 1998. Performance analysis of coated tools in real life industrial experiments using statistical technique. Surface and Coatings Technology, 99: 213 – 221

ERIE Steel Treating Inc., 2005. Technical Bulletin, http://www.erie.com /techbul.htm (27.02.2006)

FUNATANI, K., 2004. Low Temperature Salt Bath Nitriding of Steels. Metal Science and Heat Treatment, 46: 12 – 17

GOTO, H., AMAMOTO, Y., 2003. Effect of varying Load on Wear Resistance of Carbon Steel under unlubricated Conditions. Wear, 254:1256 – 1266

GRENESTEDT, J.L., 2003. Optimization of the weld path for overlay coatings. Structural and Multidisciplinary Optimization, 25: 215 - 224

HIROYUKI, S., MARUMO, Y., MINAMI, A., SONOI, T., 2001. Effect of the surface structure on the resistance to plastic deformation of a hot forging tool. Journal of Material Processing Technology, 113: 22 – 27

http://ses.confex.com/ses/2004tm/techprogram/P1173.HTM , URL 1, (23.03.2006)

http://www.ent.ohiou.edu/~raub/manufacturing/forging.htm#Forging;URL 2(27.02.2006)

http://www.forging.org/facts/faq9.htm#3 URL 3, (27.02.2006),

http://ses.confex.com/ses/2004tm/techprogram/P1173.HTM (23.03.2006)

JOENG, D.J., KIM, D.J., KIM, J.H., KIM, B.M., DEAN, T.A., 2001. Effects of Surface Treatments and Lubricants for Warm Forging Die Life. Journal of Material Processing Technology, 113: 544 – 550

KIM, D.H., KIM, B.M., KANG, C.G., 2005. Die life considering the deviation of the preheating billet temperature in hot forging process. Finite Elements in Analysis and Design, 41: 1255 – 1269

LAPOVOK, R., 1998. Improvement of die life by minimisation of damage accumulation and optimisation of preform designs. Journal of Material Processing Technology, 80-81: 608 – 612

LEE, H.C., KIM, B.M., KIM, K.H., 2003. Estimation of Die Service Life in hot Forging considering Lubricants and Surface Treatments. Journal of Engineering Manufacture, Institution of Mechanical Engineering Volume 217, Part B. EBSCO publishing.

LEE, J., SHAFRIK, R.E., 1999. Modern Manufacturing.F., KREITH, Mechanical Engineering Handbook. Boca Raton CRC Press LLC.

LIN, W.C., CHEN, C., Characteristics of thin surface layers of cobalt based alloy deposited by laser cladding. Surface and Coatings Technology, 200: 4557 – 4563

NAVINSEK, B., PANJAN, P., GORENJAK, F., 2001. Improvement of hot forging manufacturing with PVD and DUPLEX coatings. Surface and Coatings Technology, 137: 255 – 264

NAVINSEK, B., PANJAN, P., URANKAR, I., CVAHTE, P., GORENJAK, F., 2001. Improvement of hot forging processes with PVD coating and duplex treatment. Surface and Coatings Technology, 142-144: 1148 – 1154

PANJAN, P., URANKAR, I., NAVINSEK, B., TERCELJ, M., TURK, R., CEKADA, M., LESKOVSEK, V., 2002. Improvement of hot forging tools with DUPLEX treatment. Surface and Coatings Technology, 151-152: 505 – 509

PANT, M., BLECK, W., 2005. Continous impact wear resistance of duplex surface modified hot work tool steel H10. Wear, 259:377 – 382

PELLIZZARI, M., MOLINARI, A., STRAFFELINI, G., 2001. Thermal fatigue resistance of plasma duplex treated tool. Surface and Coatings Technology, 142-144: 1109 – 1115

SMOLIK, J., GULDE, M., WALKOWICZ, J., SUCHANEK, J., 2004. Influence of the structure of composite “nitrided layer / PVD coating” on the durability of forging dies madde of steel DIN 1.2367. Surface and Coatings Technology, 180-181: 506 – 511

SMOLIK, J., WALKOWICZ, J., TACIKOWSKI, J., 2000. Influence of the structure of composite “nitrided layer / PVD coating” on the durability of tools for hot working. Surface and Coatings Technology, 125: 135 – 140

SRIVASTAVA, A., JOSHI, V., SHIVPURI, R., 2004. Computer modelling and prediction of thermal fatigue cracking in die casting tooling. Wear, 256: 38 – 43

STARLING, C.M.D., BRANCO, J.R.T., 1997. Thermal fatigue of hot work tool steel with hard coatings. Thin Solid Films, 308-309: 436 – 442

VENKATESAN, K., SUBRAMANIAN, C., SUMMERVILLE, E., 1997. Three body abrasion of surface engineered die steel at elevated temperatures. Wear, 203-204: 129 – 138

VIEILLEDENT, D., FOURMENT, L., 2001. Shape optimization of axisymmetric preform tools in forging using a direct differentiation method. International Journal for Numerical Methods in Engineering, 52: 1301 – 1321

WERONSKI, W.S., GONTARZ, A., PATER, Z., 2005. Forming Process of screw spike in double configuration. E.ORIATE, D.R.J., OWEN, VIII. International Conference on Computational Plasticity, COMPLAS VIII, CIMNE, Barcelona

WOOD, W.G., 1998a, Dies and Die Materials for hot Forging, W.G. WOOD, ASM Handbook Volume 14 Forming and Forging; Library of Congress -in-Publication Data, ASM International, USA, 43 – 46

WOOD, W.G., 1998b, Closed Die Forging in Hammers and Presses, W.G. WOOD, ASM Handbook Volume 14 Forming and Forging; Library of Congress -in- Publication Data, ASM International, Metals Park, Ohio, USA, 75 – 83

ZINN, S., SEMIATIN, S.L., 1988. Elements of induction heating: Design Control and Applications. Carnes Publication Services, Inc., USA, 335 Pages

CURRICULUM VITAE

Haydar POLAT was born in 10.10 1972 in Malatya. He had been lived from 1976 to 1984 in Germany. He graduated from primary school Reichelsheimer Grundschule, Germany. In 1984, he came back to Turkey and visited Ankara Anadolu Lisesi. He graduated from this high school in 1990. In 1994, he graduated from Istanbul Technical University as mechanical engineer.

He started to work in 1995 in Sofregaz, a French company, dealing with natural gas pipelines in Istanbul, as sales engineer. In 1997, he started to work in Cukurova Sanayi İşletmeleri, a textile factory in Mersin. After he has finished his military service, he started to work in CİMSATAS. He is still working as Research and Development Engineer in CİMSATAS.

Haydar POLAT is married and has two daughters, Deniz and Derya. Deniz is 8 years old an visits the 2nd clas of a primary school. Derya was born in 22.04.2006. His wife Ayşegül Suzan is chemical engineer.