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Innovations in cold work tool steels - research and development

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Abstract

The tool and die steels are essential for nearly all industrial sectors; hence they are being used to shape all articles that e present around us. Tool steel refers to a spectrum of plain and medium or highly alloyed ones that are particularly tailor-made for specific purposes. Their performance comes from their special microstructures (martensite and carbides) which assure resistance to adhesive and abrasive wear as well as galling, and their ability to maintain a cutting edge at severe adhesive forces. As a result, die and tool steels are widely used in the forming and shaping of other metals and materials. Many types of tool steels are being applied in forging, rolling, cutting, pressing, and extruding metals and other materials. Their use to manufacture injection molds is outstanding due to their high resistance to the adhesive and abrasive wear, which is a vital and essential criterion for a mold that would be used to produce thousands of products or parts. The conventional production of tool steels is through the normal steelmaking route, ingot casting or continuous cast (CC), annealing, and final inspection. From these products tools and dies are manufactured through traditional machining operations using lathes, drillers, CNC machines, wire cut or EDM processes. During the past years, the so-called composite powder-metallurgy (PM) and powder spray forming (PSF) technologies have been developed to be implemented in industry and are suitable to produce high alloyed tool steels on an industrial scale. The metal spray-formed tool steel parts proved to have homogeneous, uniform, and fine microstructure if compared with PM or conventionally produced cold-work tool steel especially in texture and mechanical properties. Industrial applications advocate these tools made using spray-formed steel had higher performance and lifetime than those produced through the conventional route. High toughness is required in the case of steel grades used for pressing dies which depends on the contents of alloying elements (chromium, molybdenum, vanadium and tungsten). In the case of drop forging dies wide properties are required and the standard steel grades are different from each other according to their usage in specific type of die or tool parts. A balanced combination of strength, toughness, adhesion resistance and other properties are required. Dies produced using PM or metal spray forming are tested in forged conditions and it was found that the lifetime of the dies is increased on average by 50 % higher than that obtained from the conventional standard tool steel.

Keywords: Tool and die steels, cold working, Hot deformation, Electroslag refining, Powder spraying, Powder metallurgy, Nano-metallurgy, Heat treatment, Microstructures, Innovative tools.

1. Introduction

Tool and die steel family as in (AISI, ASTM and DIN) standards are designed to have hard, well distributed carbides in a matrix of tempered martensite with some retained austenite. Tool steels are superior quality steels produced with intended specific chemical composition to suit specific requirements and to develop mechanical properties suitable for cold forming and machining other metals or materials. The chemical composition of such steels has high carbon content (0.5 to 2.0%) to form ledeburitic carbides with other alloying elements such as chromium, molybdenum, tungsten, and vanadium.

Due to their superior adhesion and abrasion properties, die and tool steels are used in coining, machining, cutting, and pressing other metals and materials in cold basis. Meanwhile, special hot work die steels (0.3-0.5%C) are used in branches like injection molding and die casting. Such molds are subjected to severe abrasion during the production of thousands of shapes [1,2]. To ensure the success of a specific die

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usage, sophisticated die type selection, a well-chosen implementation route and suitable mechanical properties through selected cycles of heat treatment are keys to the success of dies or tools.

Cold work tool and die steels having carbon content between 0.5%, 2.0% and alloyed with other alloying elements (Cr, Mo, W, etc.) are produced using controlled steelmaking technologies to set the required quality. Following a suitable hardening process for every steel type ensures the precipitation of chromium carbides or carbonitrides in their matrix which plays an important role to define the qualities of die and tool steels. The alloying elements that contribute to super performance are Cr, W, V, Mo, and Nb, however, every element behaves separately in affecting type and amount of carbides that define the lifetime of the tool edge [3,4].

The presence of such high carbon and alloying elements refers to the obligatory implementation of a specific heat treatment cycle that produces at the end the required hardness and toughness. However, Mn and Si must be kept at the minimum level required to overcome their effect during treatment. Die and tool steels international standards are numerous and many types of cold-work, hot-work, high-speed and maraging tool steels are well defined as in DIN, AISI, AFNOR and JIS standards. The specific tool or die selection depends on cost, working temperature, required surface hardness, strength, shock resistance, and toughness requirements [5,6]. Undoubtedly, this group of steels can be classed among the biggest production tonnage used for tool manufacture because they do not contain expensive alloying elements and are reliable to be water quenched without any remarkable distortion after heat treatment. It is used for all types of blanking and forming dies, gauges, etc. [7-9]. Implementing new production technologies of tool steels resulted in advanced materials, easily lower maintenance costs, lighter weight, more precision, and increased lifetime like those produced using powder metallurgy (PM) and cast tooling processes [10,11].

Die and tool steels are being produced in tonnages using the traditional steelmaking processes and normally delivered in soft annealed condition to make them easy to handle (cutting, machining, shaping) before the final hardening process. The soft annealed microstructure consists of pearlite, retained austenite and some bainite matrix in which carbides are embedded [12, 13].

This review article emphasizes the importance of cold work tool and dies steels and projects the recent developments in their production processes. Comparison between the conventional and recent advanced production processes as well as evaluation of the microstructures of these steels is also emphasized with relation to heat treatment cycles applied.

2. Range of alloying elements

The mechanical properties of cold work tool and die steels depend not only on their chemical compositions but also on their microstructures created from hardening process applied. The way of quenching and tempering of tools defines the success of chosen heat treatment cycle. Differences between composition, properties and applications of cold work steels can be noticed as follow:

2.1 Cold-Work Die and Tool Steels

According to the International American Iron and steel institute standards (AISI) the cold-work die and tool steels are divided to the so-called water quenching types or W-series, oil quenching types or O-series, and the air or oil quenching types or A and D-series.[14]

2.1.1 W-Water Quenched Group

The die and tool steels that alloyed only with high carbon content without the addition of other alloying elements like Cr, Mo, W, and V are called W-group tool steel which acquires its mechanical properties after Water-Quenching from their austenitizing temperature; they are merely plain-carbon steels. This group of tool steels is produced in tonnages and is more widely used than the alloyed groups because of their low production cost [14,15].

2.1.2 O-Oil Quenched Group

The oil quenched series includes all the steels like O1, O2, till O7 steels. Table 1 projects the composition and usage of some of them. All steels in this group are typically hardened at 800°C, oil quenched, them like O1, O2 and O7. All the steels are quenched in heavy oil and then low-temperature tempered at 250°C [16,17].

2.1.3 Air-Quenched group

The first air-hardening-grade tool steel was Cr- steel, known as air-hardening steel at the time. Table 2 projects the composition and usage of Air-hardenable steels. The application of air quenching in D or A-tool steels assures good hardenability, negligible tool distortion, and minimal changes in dimensions because of high alloy content [18-20]. Table 2 illustrates some types and applications of Air-hardenable tool steel.

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Table 1. Composition and usage of some Oil-Quenched tool steels.

Grade	Composition	Notes
O1	0.80%C, 0.9–1.2%Mn, 0.80%Cr, 0.70%W, 0.30%Si, 0.20%V	Used for gauges, cutting tools, and knives. It can be hardened to 64 HRC.
O2	1.2%C, 1.0% Mn, 1.5% Cr, 0.30% Si, 0.20% V	Used in cutting tools, woodworking tools and knives.
O6	1.6% C, 2.0% Mn, 1.0% Si, 0.4% Mo	Resistant to adhesive wear and galling.

Table 2. Composition and usage of some A-series tool steels

Grade	Composition	Notes
A2	1.0%C, 1.0%Mn, 5.0%Cr- 1.0%Mo, 0.15–0.50%V	Used in fin blanking, punching, cutting, thread rolling and mold manufacturing.
A3	1.3% C, 0.5% Mn, 5.0% Cr, 1.4% Mo, 1.4% V	Nearly same usage with high effectiveness
A10	1.70% C, 1.8% Mn,1.0% Si, 2.0% Ni, 1.8% Mo	Used for gauge tools, razors, shearing tools, and punching dies.

2.2 D- Group (high carbon-chromium)

The D series of the cold-work class of tool steels, which originally included types D2, D3, D6, and D7, contains between 10% and 13% chromium. Table 3 shows features of D3-tool steel as an example from the oil or air quenched tool steel series. Due to their high alloy content these steels have massive carbide distribution within a hard martensitic matrix that ensures excellent hardness even at high temperature up to 400°C. Accordingly, these tools and die steels are extensively used in different applications like forming and cutting dies, extrusion, die blocks, and wearing cavities in brick manufacturing. The D-tool steel is also used in engineering industries that deal with the production of houseware products like stoves, fridges and many other appliances [21,22]. The unified standards UNS, American Iron and Steel Institute standards AISI and Standards of automotive engineers SAE classified the cold work tool steels as in Table (4).

Table 3. Features of widely used D3-D5 tool steel

Grade	Composition	Notes
D3	Carbon 2.0-2.3% , Chromium 10.0–13.0%, Molybdenum 1.0%, Tungsten 0.9%, Vanadium 1.0%	The cold-work D2 tool steel is widely used in the production of wearing plates used in cavity-forming bricks, press-forming heads, cutting tools, knife and razor blades.
D5	Carbon 14-1.6%, chromium 11-13%, Molybdenum 1.0%, Vanadium 1.o%, Cobalt 2-2.5%	The cold-work D5 tool steel is widely used in severe applications where long-life cutting edge is needed.

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Table 4. Cold work tool steel types, according to the US [UNS, AISI and SAE] classification. [22]

Tool steel type	Prefix	Specific types
Cold work	W= Water hardening O= Oil hardening A= Medium alloy air hardening D= High carbon, high chromium	W1, W2, W5 O1, O2, O6, O7 A2, A4, A6, A7, A8, A9, A10, A11. D2, D3, D4, D5, D7

3. Production of tool steels

Tool steels are being produced in many steel mills using the conventional well-established technologies, but there are some advances in their manufacturing processes. In the following paragraphs a comprehensive up to date survey is made to illustrate the differences and advantages of various steelmaking processes of die and tool steels.

3.1 Conventional production

Conventional steelmaking steps used to produce such steels are:

- Primary Melting
- Continuous Casting or Refining by Electroslag Melting (ESR).
- Rolling or Forging and Hot and Cold Drawing.
- Cast-Tooling

3.1.1 Primary melting

Melting of tool steels starts first from charge constituents which is composed mainly of shop scrap, purchased scrap or starting from the ABC-steelmaking using hot metal and ferroalloys (LD, BOF, EAF). The majority of tool steel production is done through Electric Arc Furnace (EAF) melting aided with oxygen jets to enhance melting and helping in oxidation of some unwanted impurities. The composition of the slag is very important to absorb any unwanted sulphides and oxides during the mutual reaction at the metal/slag interface. After complete melting and composition adjusted, the melt can be transferred to the outside-furnace refining units, like vacuum, stirring, heating and final composition correction. This process is known as secondary steelmaking or steel refining. The refined metal is then transferred into ingots or continuously cast into billets or slabs. The steel ingots or slabs are usually slowly annealed to prevent any unusual splitting or cracking. [23,24]

3.1.2 Electroslag and vacuum refining

One of the currently used processes to refine and homogenize the produced steel ingots is the so-called electroslag remelting (ESR) as shown in Fig. 1. In this process one or more ingots are to be melted and passed through liquid synthetic slag with a special composition depending on the chemical reactions to be applied. The ESR-produced refined ingots are characterized with smooth surfaces, homogenous texture, segregation-free, porosity free and smooth solidification contours along the length of the ingot. [25,26] Of course and from the economic point of view the application of electroslag remelting adds more expenses to the final steel price per ton, however for many reasons of tool steel quality and its specialized applications ESR is worth it. New advances are made to increase the productivity of that process by increasing the rate of melting using more efficient electricity supply and combined series of ESR units up to 5 stands, which is called electroslag rapid remelting (ESRR).[27] Application of vacuum arc remelting (VAR) beside the ESR is always possible and this is only the decision of the steel mill according to their economical point of view. The resulting steels are characterized with smooth surfaces, homogenous texture, segregation-free, porosity free and smooth solidification contours along the length of the ingot, has a refined microstructure together with excellent chemical uniformity. Fig. 2 illustrates the configuration of ESR equipment.[28]

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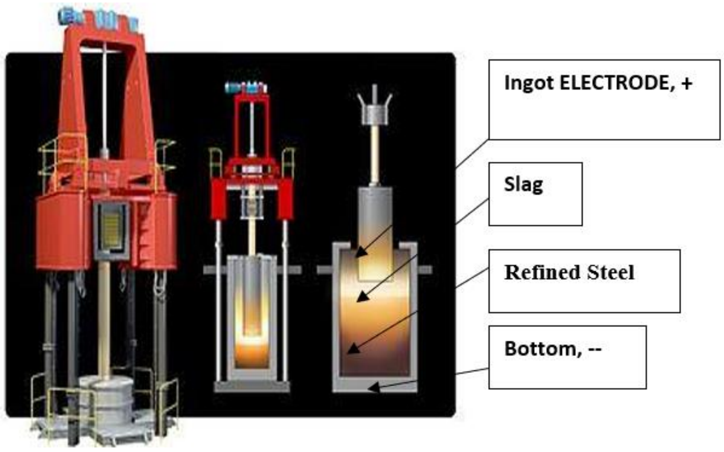

Fig. 1 Electroslag Refining system

3.1.3 Metal working

The produced die and tool steel ingots, billets or slabs are then subjected to forming process or metal working using rolling or forging mills. Before metal working the ingots are slowly heated in continuous pushing electric furnace to avoid any abrupt temperature change through ingot thickness or metal surface oxidation at the working temperature (1200-1250°C), then the steel ingots are now ready for rolling or forging. In modern steel manufacture, many rolling passes are used in a row. The metal working process is thoroughly controlled and automated by computer programming and measuring devices to control the size tolerance and surface quality of the produced tool steel bars or squares or even coils and plates.

Many clients prefer the usage of tool steel forged products specially used in heavy blanking or pressing dies for their excellent texture and homogeneous structure Fig. 2. [29-31]

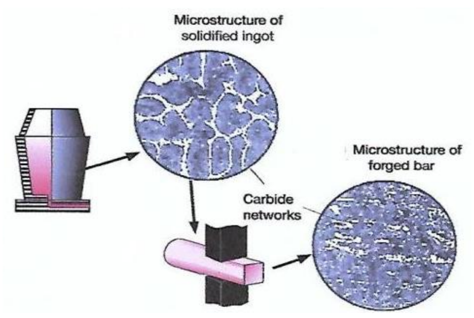

Fig. 2 Break down and distribution of carbides In conventionally produced tool steel.

3.1.4 Continuous Casting

Continuous casting of tool steel like all steels can be continuously cast to billets or slabs for economic reasons. The molten metal is poured into the casting ladle and then transferred to the continuous casting station where the metal is poured into the tundish and then flows through water-cooled molds to shape slabs or billets strands after cooling. Following casting, the billets are slowly soaked in pushing electrical furnace as mentioned before at1200°Cto be annealed then forged or rolled to the desired sizes. [32]

3.1.5 Cast Tooling

One of the recent techniques to produce near net shape tools is cast tooling, where tools are being produced using investment casting. Many researches and industrial production of tools and others were performed at the Labs of the Central Metallurgical R&D Institute. The recent research concerning cold work tool steel cast tooling is conducted by steel technology Laboratory, especially to refine the ledeburitic carbides of D2-tool steel from massive flakes and stringers to scattered globules of carbides. This was accomplished using treatment of the molten steel with FeSiMg, where the generated gas alters the morphology of carbides during solidification as shown in Figs. 3 and 4.[34]

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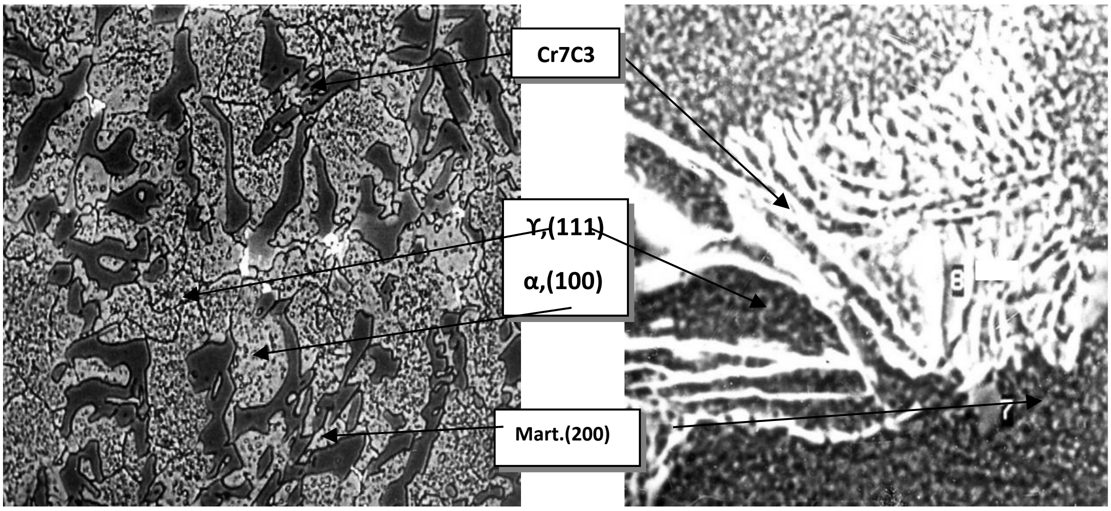

400x 2500x

Fig. 3 Microstructure of slowly sand-cooled cast D2 tool steel.

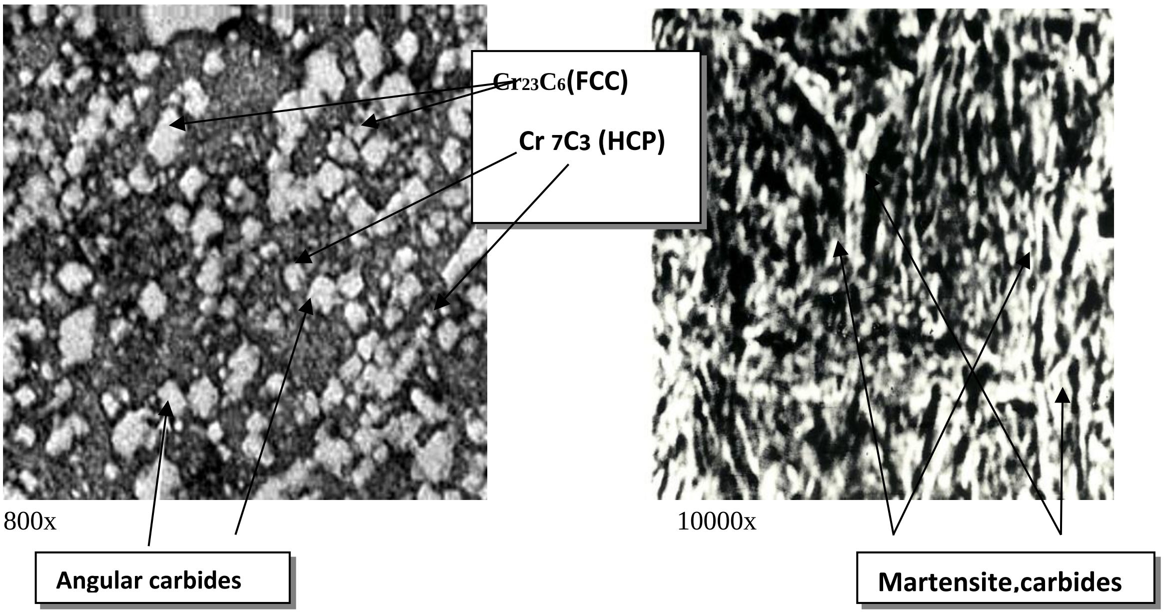

Fig. 4 Distribution and morphology of carbides after treatment with FeSiMg

3.2 Advanced PM Composite Tool Steel Production

Powder metallurgy (P/M) is one of the recent processes used to produce highly alloyed tool and die steels and high-speed steels. [34,35] In traditional steelmaking process, the production of high-carbon, high-alloy tool steels pass through relatively slow cooling rates which result in the formation of undesirable coarse carbides together with severe segregation of elements. However, tools and dies having fine, uniform microstructures with good distribution of carbides can be produced using P/M which results in improved mechanical properties and machinability in the annealed conditions. [36,37] Fig. 5 illustrates the flow of materials during implementing the powder metallurgy P/M process to produce tool steel ingots or final parts.[38]. In this process molten tool steel is sprayed using an atomizer at high pressure carrying inert gas or water jets, screened to size, milled to the required grain size, compacted using a hot isostatic process (HIV) and then sintered at elevated temperatures (1200-1300°C) under vacuum to the final shape of required tools, as shown in Fig. 6.

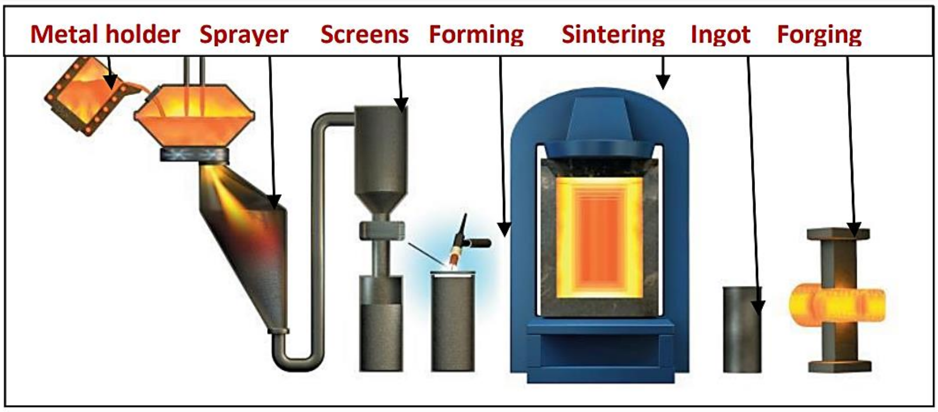

Fig. 5 Process diagram of powder metallurgy technique.

Fig. 6 Sintering of compacted tool steel parts.

4. Heat treatment & microstructures

The heat treatment of produced tools and dies is a final vital important operation because it defines their mechanical properties. Faulty heat treatment means a tremendous loss for the production line. Before subjecting the products to a heat treatment cycle always stress relief operation has to be followed, in which the machined or formed tools or dies have to be heated to about 550-600°C for 2 hours and then air cooled. The choice of austenitizing temperature (900-1100°C) is very important to avoid more grain gross at high temperatures or no complete transformation at low ones.

At austenitizing temperature all the carbides are re-dissolved again into the austenite phase to form carbon saturated austenite FCC phase, this requires certain time of soaking at that temperature. The steel matrix is transformed from soft structure (ferrite, pearlite and carbide) to FCC single phase austenite, this means that the Iron atoms change their position in the atomic lattice and generate a new lattice with a different crystalline structure. During rapid quenching of the tool it cools down until reaching a certain temperature, the martensite forming temperature where austenite begins to reject its carbon again forming a very hard phase called martensite through a severe shearing reorientation of carbides and other elements.

The final structure after quenching is composed of hard massive martensite, some retained austenite and different fine or coarse ledeburitic carbides. This structure is heterogeneous and full of stresses and is very brittle. Volume changes and internal stresses can happen for the tool due to the rejection of carbon from austenite and formation of other phases. In case of heavy dies or tools cascade quenching can be applied where the cooling is interrupted at about 80°C for a 30 minutes hold to avoid cracks and further stresses. However, risk of distortion and minute cracks can be reduced by the so-called martensite tempering or mar-tempering. In many cases all the tools and dies are heated in vacuum furnace or salt bath before quenching, in order to avoid any surface oxidation and loss of some carbon and alloying elements at that area.

Tempering operation is the last step in heat treatment, where the tool or die is just transferred after martensitic reaction to be tempered. The tool is reheated at moderate temperature (250-400°C) depending on its composition. Hardening of tool steel should always be followed by reheating for tempering process. Low-temperature tempering contributes to stress relief from martensite, meanwhile, high-temperature tempering enables the transformation of retained austenite to soft martensite contributing to more hardness, strength and light ductility. The overall tempered microstructure of the tool or die steel consists of tempered martensite, newly formed martensite, some retained austenite and different Me3C, Me7C3 ...etc. carbides. Precipitation of secondary carbides during tempering is always beneficial to increase strength, hardness and adhesion resistance, however and for a specific purpose, a certain hardness level is required for each individual application of the tool or die.

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Double and triple tempering cycle is used only in specific applications where toughness is not a matter, the tool or die is subjected to re-tempering to permit further reaction to convert retained austenite to martensite and precipitate secondary carbides, this would add an increment of hardness to the matrix. In some cases refrigerating tools at low temperatures (under zero tempering) helps in rapid and full transformation of retained austenite to martensite. [42,43] Fig. 8 projects the time-temperature-transformation (TTT) diagrams for highly alloyed tool D- tool steel [44,45].

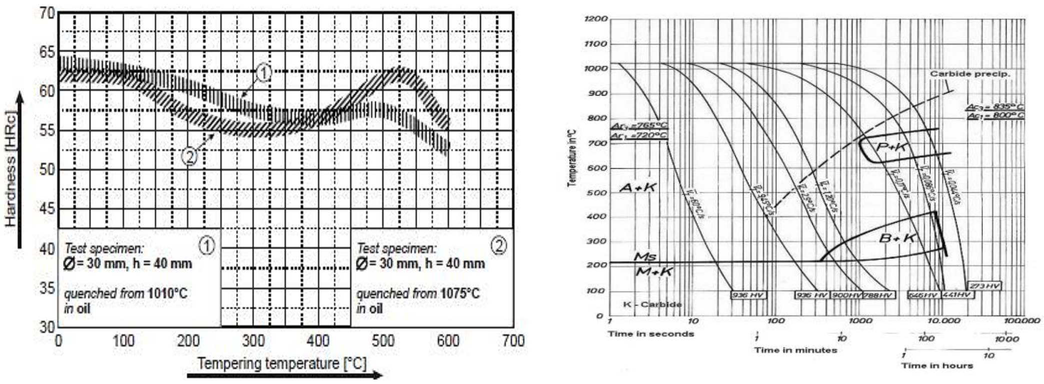

Fig. 8 TTT-diagram of D2-cold work tool steel (1.5%C,13%Cr,1.0%V, 1.0%M0)

5. Innovations in Microstructures

The main target of conventional, composites, Metal spray and any coming other new production technologies of tool and die steels is to obtain the maximum optimized distribution of carbides in a refined martensitic microstructure. Unfortunately, this is not the case in conventional production route; Fig. 9 projects the distribution of massive carbides in heat-treated tool steel after forging in flow and cross directions. However, Fig. 10 illustrates the microstructure of cold-work tool steel in the as sintered P/M and quenched condition. In Fig. 11 the homogeneous distribution of carbides is clear in as sprayed samples, however, the ledeburitic net of carbides can be more refined by slight forging of the tool steel. [46,47].

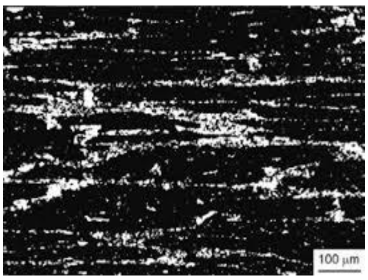

Fig. 9 Carbide print in conventional forged bars of D2-cold-work tool steel.

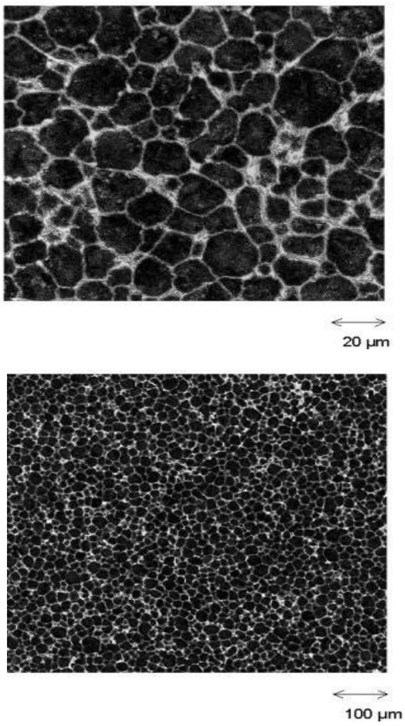

Fig. 10 Microstructure of D2-cold-work tool steel in the as sintered (up) and quenched condition (down).

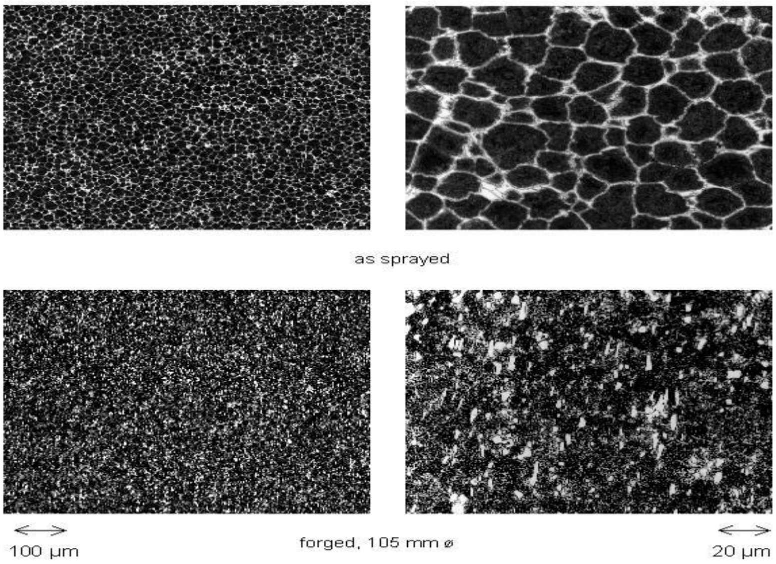

Fig. 11 Microstructure of spray formed billet of D2- tool steel.

6. Conclusions

1- A comprehensive up to date scientific survey in the field of cold work tool and die steel production innovations, heat treatment and application design has been reviewed.
2- The conventional production technology of such die and tool steels suffers the long –time process and the quality of product is more brittle before application, due to the presence of ledeburitic carbide net embedded inside the martensitic matrix.
3- The cold-work tool steels produced using advanced powder metallurgy by compacting and sintering proved to improve the toughness and hence performance of the tools.
4- Implementation of the recent metal-spray process to produce such tool and dies steels proved to add more flexibility, toughness and homogeneity to the products.

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