Tool steel quality and surface finishing of plastic molds

A qualidade do aço ferramenta e o acabamento superficial de moldes para plástico

Rafael Agnelli Mesquita
Industrial Engineering Post Graduation Program
Universidade Nove de Julho.
São Paulo – SP [Brazil]
rafael.mesquita@uninove.br

Reinhold Schneider
Professor for Metallurgy/Materials – Technology
Upper Austria University of Applied Sciences.
Wels – Upper Austria [Austria]
reinhold.schneider@fh-wels.at

Plastic industry is today in a constant growth, demanding several products from other segments, which includes the plastic molds, mainly used in the injection molding process. Considering all the requirements of plastic molds, the surface finishing is of special interest, as the injected plastic part is able to reproduce any details (and also defects) from the mold surface. Therefore, several aspects on mold finishing are important, mainly related to manufacturing conditions – machining, grinding, polishing and texturing, and also related to the tool steel quality, in relation to microstructure homogeneity and non-metallic inclusions (cleanliness). The present paper is then focused on this interrelationship between steel quality and manufacturing process, which are both related to the final quality of plastic mold surfaces. Examples are discussed in terms of surface finishing of plastic molds and the properties or the microstructure of mold steels.

Key words: Plastic mold. Cleanliness. Remelting technologies. Polishing. Photo-etching.

A indústria do plástico está atualmente em constante crescimento, demandando diversos produtos de outros segmentos e, entre eles, os moldes, principalmente os empregados em processos de injeção. Considerando todos os requisitos de moldes para plásticos, o acabamento superficial é de especial interesse, uma vez que o plástico reproduz todos os detalhes (e também defeitos) da superfície dos moldes. Portanto, vários aspectos de acabamento dos moldes são importantes, principalmente os relacionados às condições de manufatura – usinagem, retificação, polimento e texturização –, os quais também estão relacionados com a qualidade do aço ferramenta, em termos de homogeneidade da microestrutura e quantidade de inclusões não metálicas (limpeza microestrutural). Este trabalho, portanto, está focado na inter-relação da qualidade do aço e do processo de produção do molde, uma vez que ambos determinam a qualidade de acabamento final. Exemplos são discutidos, em termos de qualidade superficial dos moldes para plástico e das propriedades e microestrutura dos aços ferramenta empregados na produção dos moldes.

Palavras-chave: Moldes para plásticos. Limpeza microestrutural. Tecnologias de refusão. Polimento. Texturização.

1 Introduction

Molds are widely used in the manufacturing of plastic parts. In particular to injection molding process, molds play an essential role in the final quality of produced part, especially with regard to surface quality (HIPPENSTIEL, 2001). Due to their low viscosity and surface tension, molten plastics are able to reproduce practically all visible details on the mold surface. While this is beneficial to the production of different surface appearances on plastic parts, especially in fine polish or light-reflecting applications, such as headlight lens for automotive applications (HIPPENSTIEL, 2001).

Other details can be intentionally introduced on the steel surface for reproduction on the injected part, thereby producing matted surfaces or specially designed textures (BEAL, 2000). The purpose of such modifications is to give a normally smooth plastic part greater tactile and visual appeal. This is typically applied to industrial (automotive) or home-use plastic parts in order to change the visual appearance or improve friction. Figure 1 displays examples of polished and textured plastic surfaces.

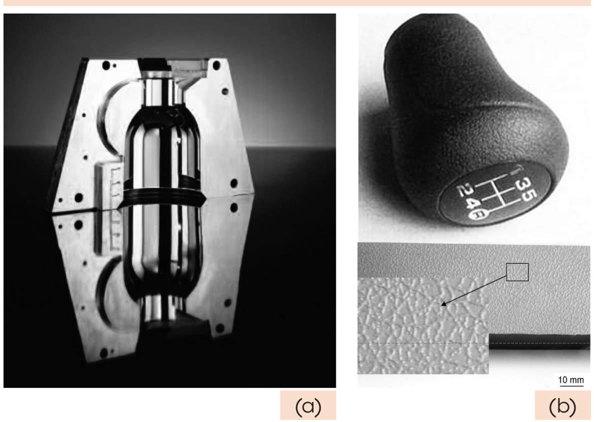


Figure 1: Examples of polished and textured surfaces of plastic molds
a) Polished injection mould for manufacturing a coffee pot with high polish; b) textured part from a laser grained mould (modified from the same reference)
Source: Hippenstiel, 2001.

Most final applications of plastic parts depend on the surface conditions, which are directly related to the mold surface. Injection molds are normally made with special steels due to a proper combination of properties such as strength (hardness), thermal conductivity and cost, but also because these materials are suitable for different manufacturing processes, such as machining, welding, polishing and texturing (MESQUITA; BARBOSA, 2007). Although all these topics have been discussed in the literature in recent years (BEISS et al., 2009; BERGSTRÖM et al., 2002; JEGLITSCH et al., 1999; ROSSO et al., 2006), no reports are found considering the totality of the interrelationship between steel quality and mold manufacturing aspects, especially with regard to the quality of the surface finishing. Thus, the present paper addresses this issue, discussing aspects of the steel manufacturing process for high quality mould production and mold manufacturing technologies, with an emphasis on polishing and texturing.

2 The plastic injection molding in Brazil

Injection molding is just one of the processes employed to produce plastic parts. Figure 2 presents the share of different manufacturing methods of plastic molds. Although all types of plastic polymer compositions can be molded through the injection process, most of this segment uses polypropylene (PP) or high-density polyethylene (HDPE), as shown in Figure 3. Other polymers are mainly dedicated to the production of films (low-density polyethylene) or extrusion processes.

Therefore, the analysis of the production, and especially the growth rate of plastic injection molds, which is based on the data for PP and HDPE. Considering the data for the Brazilian pro-

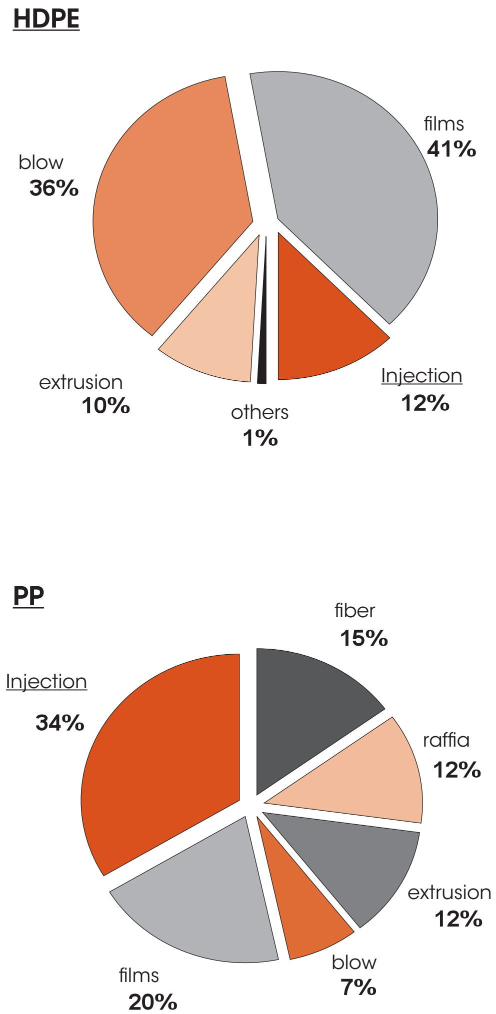
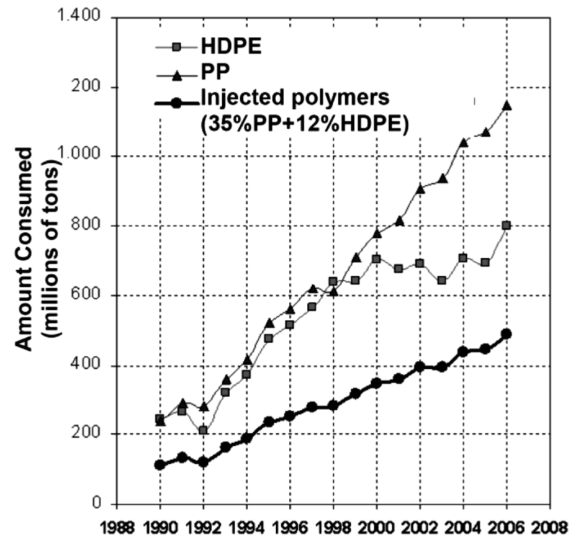


Figure 2: Processes of applications of the main polymers used in injection-molding HDPE = high density polyethylene and PP = polypropylene

Source: Brazilian Association for Chemical Industry Products (ABIQUIM, 2008).



Year	Annual Growth
1991	17.98%
1992	-7.48%
1993	32.15%
1994	15.94%
1995	26.15%
1996	7.23%
1997	10.63%
1998	2.12%
1999	11.76%
2000	9.53%
2001	3.07%
2002	9.18%
2003	0.75%
2004	10.85%
2005	2.00%
2006	8.92%
Average	**9.65%**

Figure 3: Annual evolution of main polymers used in injection-molding processes; HDPE = high density polyethylene; PP = polypropylene.

Source: Brazilian Association for Chemical Industry Products (ABIQUIM, 2008).

duction of PP and HDPE (Figure 3), linear growth of about 10% per year is observed. This figure indicates the strong progress in the production of molds, although the correlation is not direct.

On the one hand, the constant design of new plastic products contributes to a higher degree of mold replacement, thus increasing the growth rate of mold production beyond that of the plastics consumed. On the other hand, injection molding technologies are in a constant state of evolution, involving the rational use of molds by increasing the number of cavities, reducing the thickness of the mold walls or employing materials other than steels (e.g. Cu-Be or aluminum alloys).

However, regardless of the exact value, a high growth rate of injection molds in Brazil is clearly indicated by the polymer-consumption analysis. A more in-depth analysis regarding the resources for this industry is therefore important. Such an analysis includes injection molds and the interrelationship between the final quality of the injected part and the cost-related operations during the mold processing. This analysis is performed in the next items.

3 Polishing and machining of plastic mold steels

The complex shape of injected plastic parts is directly related to the mold geometry, but further aspects greatly increase the complexity of mold manufacturing. For instance, cooling channels, part extraction conditions, hot spots and a number of other items are required either for part quality or to improve productivity. Therefore, the machining process of plastic molds is normally a highly demanding step in mold production with regard to time, cost and technology. Several alternatives may be applied to improve the manufacturing conditions of molds, one of which is related to the machinability of plastic molds – the easier a mold steel is machined, the greater the cost reduction (BOUJELBENE et al., 2004). On the other hand, the design of high machinability steels usually leads to a trade-off in relation to polishability, with a decrease in the polishing quality of the steel (MESQUITA et al., 2003).

The inverse relationship between machinability and polishability is essentially by two features: soft non-metallic inclusions and material strength, normally quantified by the hardness (COOK, 1975). Steels with a high sulphur content, such as DIN 1.2312, have a large amount of non-metallic phases in the microstructure, denominated manganese sulfide inclusions (or MnS), which facilitate chip-breaking and lubrication in the shearing zone of the chip (KOVACH; MOSKOWITZM, 1969). However, large amounts of MnS inclusions in high-S steels also cause problems during the polishing process, as discussed below.

Non-metallic inclusions are phases found in the microstructure of all steels and metallic alloys. Oxides, sulfides and other complex ionic or covalent phases may be formed in the steel microstructure due to the reactivity of metallic atoms with oxygen or sulfur. Control in the formation of such phases is done by melting-shop techniques during steel manufacturing, as discussed in detail in Item 5 of the present paper. However, the effect of inclusions to the polishing process may be understood by analyzing Figure 4. During the polishing process, non-metallic inclusions may be extracted and small holes are formed. Before particle removal, larger areas may be affected, thus leading to polishing defects denominated "pin-hole" problems (SHIMIZU; FUJI, 2003). Therefore, a greater amount and size of inclusions leads to lower polishability, regardless of the inclusion type. While soft inclusions (like MnS) improve machinability, hard inclusions reduce machinability by creating hard obstacles for chip removal during machining, thus causing abrasive wear. Consequently, besides steel grade and hardness, the tool steel manufacturing process is of particular interest with regard to the final combination of machinability and polishability.

Another important aspect in the interrelationship between the machinability and polishability of mold steel is its strength or hardness. An increase in hardness leads to an increase in strength, which cause higher stresses in the machining shearing zone, thereby reducing the tool life, limiting the machining time and consequently decreasing machinability. On the other hand, the polishing process introduces small groves and strain on the steel surface, which are also influenced by hardness. An increase in steel hardness leads to shallower groves and lower strain induced on the surface by polishing, thus denoting a positive relationship between hardness and polishability.

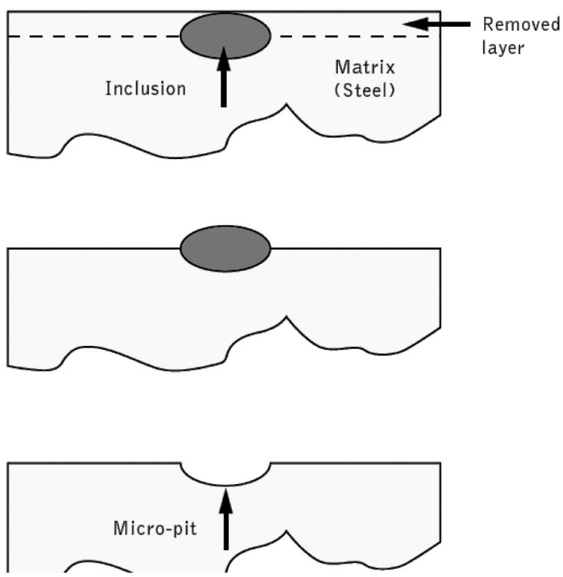


Figure 4: Pin-hole problems after mold steel polishing as a result of inclusion removal during polishing
Source: Adapted from reference Shimizu; Fuji, 2003.

Another important effect of the increase in hardness is the minimization of over-polishing problems, also known as the "orange-peel" phenomena. This is caused by localized strain-hardening on the mold surface, by the subsequent deformation induced on the surface. After the start of over-polishing effect, surface roughness does not decrease with polishing time, but rather increases with the continuation of the polishing process (Figure 5). The solution in such cases is regrinding and restarting the polishing. When this is not possible, the over-polishing effect cannot be removed and the quality of the injected plastic part is impaired. Other effects may accelerate over-polishing, such as microstructure inhomogeneity, leading to inconstant hardness or surface defects from previous regular machining or electro-discharge machining. The increase in the Rockwell C (HRC) hardness (compare the 32 HRC and the 60 HRC steels in Figure 5) and reduction in surface defects and heterogeneities are thus beneficial to avoiding over-polishing.

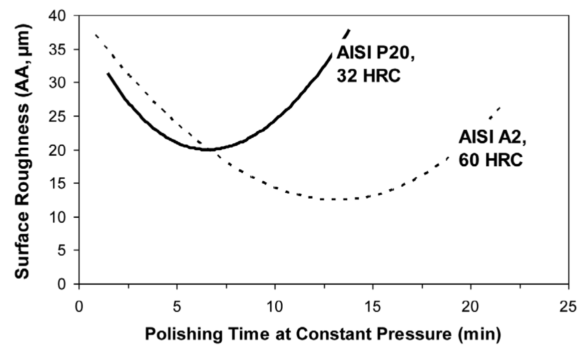


Figure 5: Effect of hardness in two different steels with different degrees of hardness
Source: Adapted from reference Uddeholm, 2010.

Therefore, two correlated features determine the polishability of plastic mold steels:

i) steel composition and cleanliness in relation to non-metallic inclusions;
ii) final hardness and principally microstructural homogeneity (microhardness homogeneity).

These two factors also affect steel machinability, which is important to consider due to the expressive cost of machining in the total cost of a plastic mold. The correlation of these four characteristics (cleanliness, hardness, polishability and machinability) is displayed in Figure 6, which clearly illustrates the compromise between machinability and polishability, while also considering hardness values. The effect of cleanliness is illustrated by the increase in polishability (increase in circle size in Figure 6a) for a fixed hardness. The beneficial effect of MnS inclusions is illustrated in Figure 6b, comparing the machinability index for a given hardness, which is increased when the S content increases. It is also interesting to compare the 40 HRC, precipitation hardening steels (MESQUITA et al., 2003), which are refined by vacuum-arc-remelting (VAR) and thus may combine high S with sufficient polishability. Details on electro-slag-remelting (ESR) or VAR refining processes are given in Item 5.

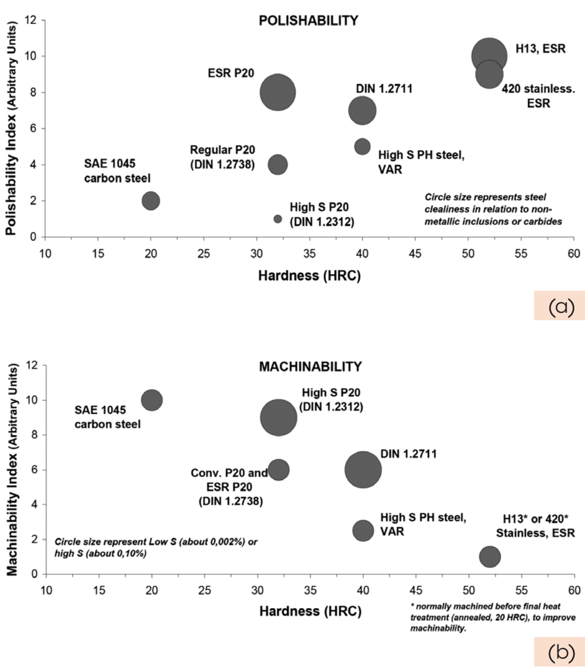


Figure 6: Effect of hardness on a) polishability and b) machinability. Note that steel cleanliness with respect to non-metallic inclusions or undissolved carbides (420 stainless steel) (a) and S content (b) are illustrated by circle size.
Source: The authors.

Before finishing this item, an important issue should be considered in relation to the determination of polishing quality. Most methods employ a visual evaluation of the mold surface for the approval of final quality. Surface roughness or other dimensional evaluations have proven insufficient for a number of conditions, such as the orange-peel phenomenon or other localized defects, which may represent proper roughness but not a proper optical appearance for the plastic part. Therefore, alternative optical methods are under research, leading to more coherent evaluation of polishing quality. One example is shown in Figure 7.

4 Texturing or photo-etching

Textured or grained surfaces are produced in parts through plastic injection molding when

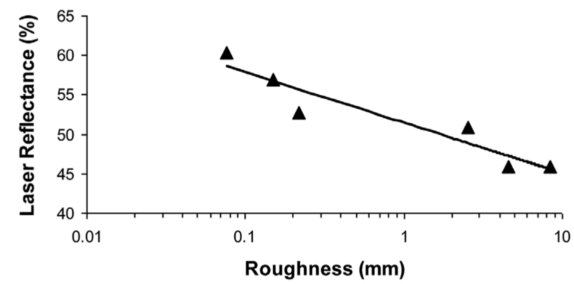


Figure 7: Roughness and laser-aided optical method applied to evaluate quality of surface finishing of mold steel. Note the good correlation between the two methods
Source: Zanatta et al., 2008.

the mold surface is designed to reproduce different patterns, such as leather-like matted surfaces or practically any kind of surface design. There are many reasons for texturing, but it is generally applied to improve the appearance of plastic part or change the surface-sliding coefficient, making it easier to hold onto a given part.

The process is schematically illustrated in Figure 8. First, a protection film is deposited on the mold surface containing the negative of the desired pattern (Figure 8a). After deposition on the entire mold surface that comes into contact with the injected part (cavity), the complexity of which sometimes requires considerable manual labor, the surface + film is placed into a acid tank for the etching process. Films are usually deposited under a photo-activated process. The combination of this method and acid corrosion gave rise to the term photo-etching, which is the main texturing process. During this acid etching, the unprotected parts of the cavity surface are corroded, with the removal of material and creation of deeper areas, while the areas under the film are protected from corrosion (Figure 8b). When the corrosion achieves the desired depth, which represents the peaks in the final texture, the corrosion process is stopped by removing the cavity from the tank and cleaning it. Finally, the film is mechanically or chemically removed and the cavity is ready for the injection process (Figure 8c).

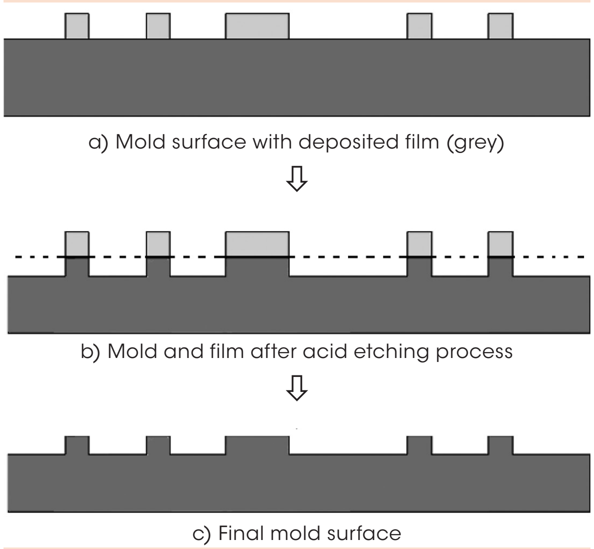


Figure 8: Schematic example of texturing process applied to plastic mold surface; note that the final mold surface is in negative relation to the deposited film
Source: The authors.

Although the process seems simple, a number of control aspects are important to the production of the actual texture. For example, the acid type and all other corrosion conditions (concentration, pH, Fe concentration in the tank, temperature, bath homogeneity, etc.) have a substantial effect on the etching process and, consequently, on the final quality of the mold surface and appearance of the injected part. Figure 9 shows three different patterns applied to the same mold steel under different acid conditions. The difference in appearance on the mold surface is easily seen.

Other variables are exemplified in Figure 10, such as the concentration of non-metallic inclusion in a high-S P20 steel (Figure 10a), the effect of welded areas (Figure 10b) and the modification of the tool steel (Figure 10c). Although all these aspects are different, the common point in terms of mechanism is related to changes in the microstructure, which affects corrosion resistance and thus modifies the photo-etching process. Firstly, inclusions may cause preferential points of corrosion, changing the final appearance after etching (Figure 10a). Secondly, welding may be considered as a local hardening treatment that introduces several alloy elements in solid solution martensite and thus increases corrosion resistance, thereby reducing the etching effect (note the lighter appearance of the welded area); of course, hardness heterogeneity from segregation or incorrect heat treatment would cause similar effects, as they are normally related to different phases with distinct corrosion resistance. Thirdly, the steel grade obviously affects the etching process, as the alloy content deeply modifies the corrosion resistance of all types of steel.

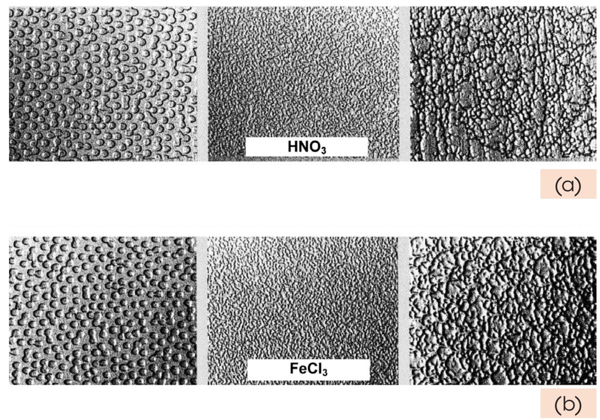


Figure 9: Changes in surface after texturing with photo-etching under different acid conditions: a) HNO3; b) FeCl3
Source: Haberling et al., 1990.

Therefore, all conditions in the photo-etching process must be controlled in such a way that the corrosive process is under control. High quality and reproducible results in texturing depend on this control. A further issue should be considered with regard to the quality control aspect in texturing. Although the texture depth is always measured and controlled, roughness in the texture “valleys” is only visually and qualitatively analyzed using a magnifying glass or stereoscope. The main problem is that these valleys on the steel

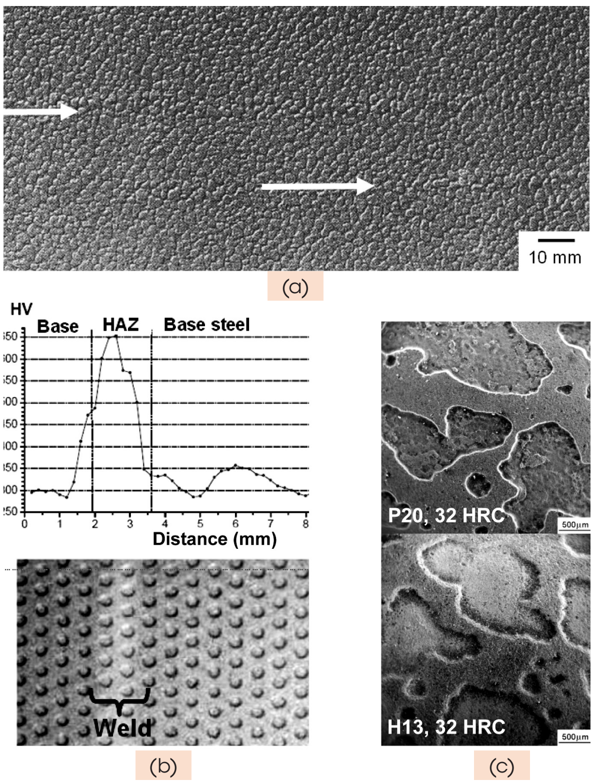


Figure 10: Defects observed after texturing process related to heterogeneous microstructure: a) excessive amount of inclusions (elongated in longitudinal direction) in high S P20 steel (DIN 1.2312 steel); b) hardness peak in welded area of P20 steel causing changes in microstructure and corrosion resistance during etching process; HAZ = heat affected zone; c) Roughness variation in deep areas of textured surface leading to changes on surface (peak positions) of injected plastic part using the same etching process.

Sources: Haberling et al., 1990 (a). Preciado and Bohorquez, 2005 (b), unpublished results from authors (c).

surface will be the peak areas of the injected plastic part, determining its tactile conditions and visual appearance. In summary, the photo-etching of plastic molds is a complex phenomenon, with several variables involved in an extensive corrosion process. However, it is not currently possible to properly control all aspects. The emergence of new measuring systems using laser or other refined techniques is important to quality control and the improvement of the photo-etching process in plastic mold indust

5 Remelting technologies and their impact on tool steel quality

From the previous items, the quality aspects in plastic mold steels are correlated to polishing, machining and photo-etching processes applied to the cavity surface. For more highly demanding applications, special melting shop processes may be applied in the production of mold steels. These processes are related to remelting technologies, in which an ingot (called an “electrode”) with the nearly final steel composition is remelted in an environment that enables the reduction of inclusions, followed by solidification with fast cooling rate, leading to refined microstructures. Details on the most important remelting technologies for tool steels are given in the present item with regard to the application in plastic mold steels as well as both cold-work and hot-work tools.

The use of remelting processes, especially electro-slag-remelting (ESR), in the production of high quality tool steels has found early applications (BECKER et al., 1989; KRAINER et al., 1971) and has been constantly improved since (HASENHÜNDL et al., 2009; HEISCHEID et al., 2006; KOCH et al., 1999; SCHNEIDER et al., 1999; SCHNEIDER et al., 2000; SCHNEIDER et al., 2001; SCHNEIDER et al., 2002). While the focus during the first decades was on low sulfur contents (and corresponding improvements in toughness properties) and covered high speed steels, cold- and hot-work tool steels alike (BECKER, 1989; KRAINER et al., 1971), the focus has recently turned to hot-work tool steels and plastic mold steel (LICHTENEGGER et al., 1999; SAMMT et al., 2002; SCHNEIDER et al., 2000; SCHNEIDER et al., 2003; SCHNEIDER et al., 2004; SCHWEIGER et al., 1999). A major reason for this shift was the successful introduction of powder metallurgy for steels with high carbide contents.

Besides standard (open) ESR-processes, pressure- and/or protective-gas-ESR (P-ESR) has found widespread application in the last decade as an improved process alternative (HASENHÜNDL et al., 2009; HEISCHEID et al., 2006; KOCH et al., 1999; SCHNEIDER et al., 1999; SCHNEIDER et al., 2000; SCHNEIDER et al., 2001; SCHNEIDER et al., 2002). Furthermore, vacuum-arc-remelting (VAR) – usually applied to steels and Ni-base superalloys in the aircraft industry – has also gained some share in the production of tool steels (SCHNEIDER et al., 2000; SCHWEIGER et al., 1999).

Table 1 gives an overview on the advantages of and the differences between the different remelting processes. Besides these material related effects, there are also some differences in the handling of the ingots. For instance, VAR-ingots require some surface conditioning and open ESR permits a more flexible ingot weight (KOCH et al., 1999).

Table 1: Advantages of and differences between the different remelting processes

	ESR	P-ESR	VAR
High ingot homogeneity	Yes	Yes	Yes
Micro segregations	Low	Lower	Lowest
White spots	No	No	Yes
Cleanliness (non-metallic inclusions)	Good	Better	Best
N-alloyment	No	Yes	No
N-content reduction	Limited	No	Yes
H-content	Increasing	Constant	Decreasing
Low Si & Al-content	No	Yes	Yes
Reduction of trace elements	No	No	Yes

Source: The authors.

The main advantages of P-ESR in comparison to standard ESR are the better material properties due to reduced segregations, non-metallic inclusions and the possibility of producing high nitrogen alloyed steels. VAR-materials have the highest homogeneity regarding segregations and cleanliness, but has the risk of white spots. Furthermore, lowest contents in volatile trace elements such as antimony, arsenic or tin, as well as H- and N-contents can only be achieved by this vacuum process. The typical appearance and configuration of a modern P-ESR-plant according to Koch et al., 1999 and other authors (SCHNEIDER et al., 1999; SCHNEIDER et al., 2001; SCHNEIDER et al., 2004; KORP et al., 2007) can be taken from Figure 11.

The main advantages of remelted materials for application in the tooling industry, mainly for dies and molds, are their superior homogeneity and isotropy of mechanical properties, especially regarding toughness, and the outstanding polishability for the most demanding surface requirements (BECKER et al., 1989; KRAINER et al., 1971). Toughness properties are dominantly affected by segregations, which range from trace elements to carbide stringers at grain boundaries. Besides the improvement of the solidification conditions regarding direction and local solidification time, which are dominant in hot-work tool steels, the alloyment of nitrogen has proven very beneficial to improving the microstructure of corrosion-resistant plastic mold steels (BECKER et al., 1989; KOCH et al., 1999; KRAINER et al., 1971; SCHNEIDER et al., 1999).

Non-metallic inclusions, such as oxides and sulfides, mainly affect the surface quality after polishing, especially for mirror finish surfaces, but can have a significant impact on (thermal) fatigue properties and corrosion resistance as well (SAMMT et al., 2002). While the sulfur content can be reduced to very small levels by modern

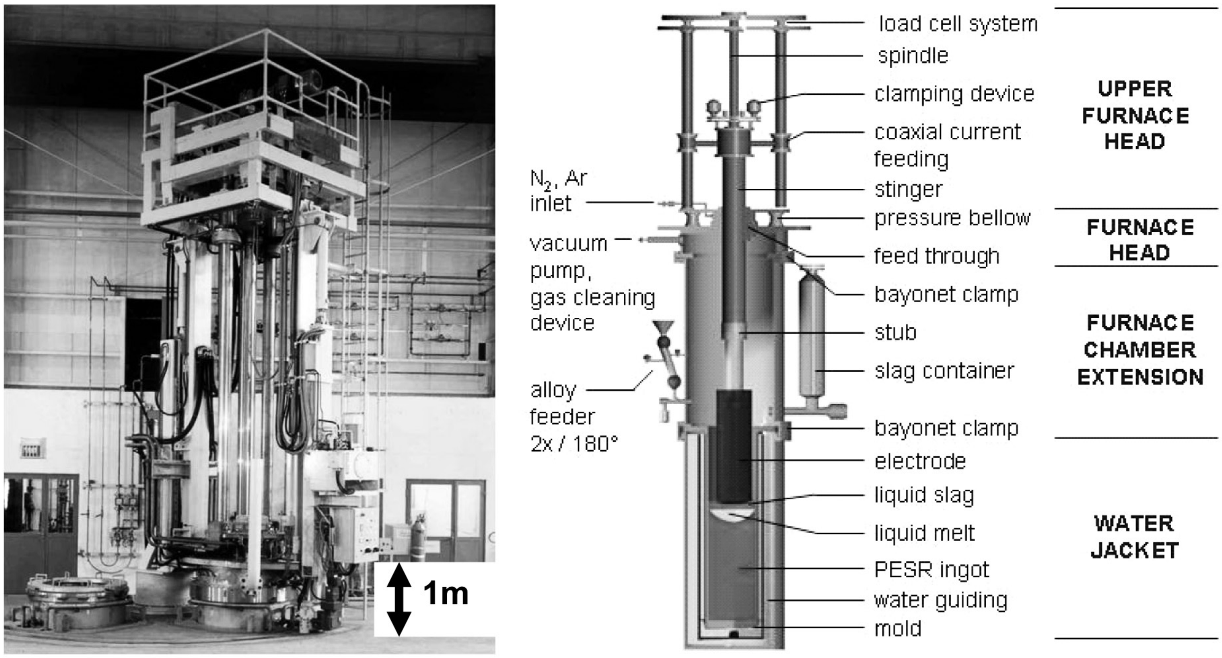


Figure 11: Appearance and configuration of modern P-ESR-plant
Source: Koch et al., 1999.

ladle metallurgy, lowest contents in oxides can only be achieved through remelting. Thus, good ladle metallurgy is again an important precondition for satisfactory results after remelting. Higher levels of cleanliness can be achieved through by electro-slag remelting under a protective atmosphere in combination with adapted slag compositions and through by vacuum-arc-remelting (HASENHÜNDL et al., 2009; KOCH et al., 1999; SCHNEIDER et al., 2002; SCHWEIGER et al., 1999). The typical limits to for high quality tool steels regarding non-metallic inclusions, according to ASTM E45 - Method A, can be taken from Figure 12. Thereby, areas indicated by “a)” and “b)” can be avoided by good ladle metallurgy.

6 Conclusions

The results discussed in the present paper are summarized by the following points:

Severity level number	Inclusion Type							
	A		B		C		D	
	Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick
0.5	a)	a)	b)					
1.0	a)		b)					
1.5							b)	
2.0								

Figure 12: Limits regarding non-metallic inclusions for high quality tool steels; green = possible occurrence; dark grey = not observed with proper remelting process
a) depending on prior steel desulfurization; b) depending on ladle metallurgy
Source: Adapted from Schneider et al., 2000.

- The surface aspects of plastic molds are the most important points in relation to the quality and cost of injected parts. Both the manufacturing process and tool steel quality affect the surface conditions.
- Hardness affects the machining and polishing processes, but in different ways. An increase in hardness facilitates polishing and reduces the possibility of common prob-

lems, such as the orange-peel phenomenon; but it also accelerates the time wear of machining tools, thus raising manufacturing costs.

- Non-metallic inclusions are deleterious to the final polish quality and are avoided in a number of applications. In relation to machining, soft inclusions, such as MnS, can be beneficial and high S grades are known for their good machinability and low polishability. On the other hand, hard (oxide) inclusions are harmful to both polishing and machining and are therefore always avoided.
- Photo-etching or texturing processes are currently increasing their application to plastic molds and are related to different metallurgical concepts. A high degree of microstructural homogeneity in terms of segregation, hardness and the absence of non-metallic inclusions is the main characteristic for proper texturing quality.
- The understanding and control of corrosion during the etching process for textured molds is also essential to the final quality of the mold surface and, consequently, the injected part. Although simple in nature, this process is based on non-trivial corrosion aspects, which should be evaluated in terms of reproducible results.
- To improve polishability, a number of refining processes (remelting technologies) related to the control of inclusions may be applied, such as ESR, P-ESR and VAR, with the final cleanliness increased in this respective order.

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