40 HRC PLASTIC MOULD STEELS: MANUFACTURING PROPERTIES CONSIDERATIONS

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Abstract. *Mould material accounts for only a small part of the total cost of the plastic injection moulds as its leaves the mould maker's facility. Therefore when the mould maker adopt a specific steel grade, the manufacturing properties are crucial, especially the machinability, the polishability and the heat treatment response. The present work compares such properties in two plastic mould steel grades, heat treated at 40 HRC. This hardness is higher than that usually applied in most mould cases, in which steels similar to P20 are utilized, may lead to processing difficulties. The first analyzed steel, DIN 1.2711, is a medium carbon steel, using quenching and tempering as heat treatment process. The second one, designated as VP50IM, refers to a new steel grade, using the precipitation hardening mechanism with improved machinability by the presence of a fine sulphide distribution. This material can be machined at low hardness levels, allowing to be easily drilled, to be further final heat treated without any cracking or distortion risk, because the quenching is not necessary. For the steel DIN 1.2711, to avoid distortion and cracks problems, the material is supplied to the mold maker in the hardened condition at 40 HRC. However, such condition impairs the machinability, especially the drilling operation. The obtained results in the present study, however, aim to help the mould maker to do the best steel choice, considering the all the mould manufacturing process.*

Keywords: *plastic mould steel, machinability, heat treatment, drilling.*

1. Introduction

In the plastic industry the injection moulds takes a very big role, being considered very complex production issue influencing besides the production capacity also the product quality. The current plastic mould steels applied in the industry, many times low alloyed steels, require microstructural cleanness and processing characteristics that turn this class of steels very differentiated from conventional and carbon steels (Roberts, Krauss and Kennedy, 1998).

The machining and the superficial finishing are critical steps in the mould production and usually correspond to the main total cost fraction. As the mould life expectative is high (in same cases ultrapassing 10 years), the most important properties of such materials relates to the processing characteristics, as polishability, machinability and heat treatment response.

The present paper discusses, therefore, the mould steels properties related to manufacturing. The discussion focus on moulds using high hardness levels of 40 HRC. Although most moulds are produced in the 32 HRC hardness level, in the steel series P20, there is a growth tendency to utilize 40 HRC moulds. In this condition we can take the higher mechanical strength, wear resistance and better polishability as advantages. And, due to the machining technology process advances, turns out possible, with very few problems, the machining in such hardness.

Therefore, the present study is applied to two typical steels usually applied in moulds in the 40 HRC level - the steels VP50 IM and the DIN 1.2711. The DIN 1.2711 steel is a medium carbon steel and low alloyed usually supplied in the heat treated condition, with 40HRC. Conversely, the VP50 IM is supplied with low hardness, for subsequent hardening via a simplified heat treatment – called aging (Pinedo and Barbosa, 1995). This leads to many advantages during the mould production, especially machinability and polishability.

Such properties comparison is important to the decision maker during the mould steel selection. Of course the total mould manufacturing cost depends on the type of chosen steel, but it is heavily influenced by the mould manufacturing conditions. In general, around 5% of the mould total cost refers to the steel itself (Frederick and Gerson, 1996), the remainder being related to the manufacturing process and heat treatment. Consequently, the steel selection should consider not only the steel price but also its impact on the manufacturing operations downstream.

2. Plastic mould steels main properties

Considering that the present paper compares two mould steels, a short properties description is made here.

2.1. Machinability

For plastic moulds due to the high volume of material to be removed out to form the cavities, the machinability is one of the processing properties most relevant. The high volume of material to be removed in the manufacturing of a mould turns the steel machinability very important. The concept of machinability is wide and depends on metallurgical factors as well as of the machining conditions like kind of tool and cutting speed, and is a result of the interaction between the metal with the cutting conditions. The term is broadly applied to express the state of the machined surface, the material removal rate, easy chip removal or the tool life (Cook, 1975). From the steel basic characteristics point of view, the machinability must be improved not only to reduce the tools consumption but mainly the machining time.

The mould steel machinability is influenced not only by the mechanical and physical steel properties, related to its chemical composition, but also from the production processes utilized in its production. For example, large dimensions moulds requires blocks produced from large ingots in the melting shop, where it is necessary to utilize advanced secondary steel refining in order to eliminate large non-metallic inclusions. Further hot deformation in high power hydraulic press is necessary in order to refine the microstructure and to eliminate the defects coming from the cast state.

The machinability can be improved in many ways (Mesquita, Sokolowski and Barbosa, 2003), being one of most common the utilization of slightly high sulphur residual content (Kovach and Moskowitzm, 1969). This element forms inclusions combining with manganese (MnS), which has low melting point and high deformability, improving the machinability. Such inclusions have a lubricant effect in the cutting edges and easing the chipping in the shear zone. In steels produced by conventional process, the MnS inclusions are elongated after the plastic deformation in the forging process, increasing their size with the block size. Larger inclusions size can impair the polishability and, consequently, steels produced by conventional process are normally produced with reduced sulphur levels.

However the machinability deteriorates with the increasing amount of hard inclusions, like Al2O3 inclusions. Therefore in the VP50IM steel, the production throughout the utilization of VAR (vacuum arc reemitting – ISOMAX® process) improves the machinability reducing such inclusions, also harmful to the polishability. Moreover, this process increases the solidification speed, opening the possibility to produce steels with slightly high sulphur contents. The MnS inclusions produced, beneficial to the machinability, are small and do not jeopardize, in such case, the polishability. In the VP20 ISO steel, as we will see later, the Al2O3 inclusions are modified by a calcium treatment, promoting in this way a machinability improvement.

2.2 Polishability and Texturizing Response

The mould surface is fundamental to the finishing of the plastic part being produced, requiring different polish levels for different applications. Pretty well polished moulds are necessary in many applications, as in glasses or even CDs production. In the production of texturized plastics, the mould surface needs evenly an adequate polish. The polishability measures how easy is the polishing operation in one specific mould steel, being affected by many metallurgical factors. Non-metallic inclusions like oxides e sulphides, can reduce the polishability, as a function of the size and how are distributed. Moreover, the hardness must be uniform and decarburization is not allowed.

The texturizing response measures how easy the texture application in one mould steel is. The texturizing treatment is usually applied by chemical photo-etching.

2.3. Heat Treatment Response

Usually heat treatment is a necessary production step to reach the appropriated final mould properties. The most common heat treatment are quenching and tempering, that leads the correct hardness for most applications.

Dimensional and shape variations are a crucial issue when mould heat treatment is concerned. In order to avoid then, high dimensional stability steels are preferred. They provide a reliable heat treatment and also the possibility to reduce the metal stock, reducing the high hardness material volume to be machined. Precipitation hardening steels, as in the case of VP50IM steel, are very adequate for such purpose, because they show a very high dimensional stability. Such kind of steels present only small contraction, evenly distributed and fully foreseeable, contributing to the heat treatment reliability and the amount of final finishing machining (or even its elimination).

2.4. Mechanical and Wear Resistance

The steel has to afford the mechanical stress involved during application, avoiding the occurrence of plastic deformation under load pressure. The plastic mould steel mechanical resistance is directly related to the hardness obtained by the heat treatment. It is also very important the relationship between hardness and how easy is to polish the mould. The harder the steel the easier is to polish the mould. Many moulds have deep cavities and, in such cases, the adequate hardness has to be reached even in the central regions of the bar.

High pressure liquid plastic, especially when charge additions are made, can cause wear debris in the mould surface. The charge particles or even fibbers normally have hardness much higher then the utilized steel that, associated to the high sliding velocity and to the contact pressure, can cause abrasive wear. In this situation, the tool steel wear resistance has a role to be placed in such applications, including moulds for engineering plastics.

Besides the chosen steel, the wear resistance can also be further improved applying a superficial treatment, like nitriding as an example. Such treatments, besides increase the wear resistance, improve a lot the polishing conditions, caused by the higher superficial hardness obtained, and the demolding conditions of the part, due to its influence in the friction coefficient.

2.5. Weldability and Electro-erosion Response

Due to the medium to high carbon content normally present in tools steels, most of the processes where high temperatures are generated we can find certain difficulties when utilizing such steels. Two examples are welding and electro-erosion. The superficial layer after a welding turns out quenched with high hardness and brittle. Therefore, cracks and surface defects can arise, damaging, in the case of plastic moulds, the polishing as well as the superficial aspect of the injected part.

2.6. Corrosion Resistance

The corrosion resistance plays a role in cases when the moulds are applied in corrosive environments. As a typical examples of such situation, are chloride polymer injection or mould stored in places where the humidity is high or even corrosive. In this paper, this property will be not focused, because the discussed steels are not designed for such applications.

3. Experimental procedure

The typical chemical compositions of the analyzed steels in this work, DIN 1.2711 and the VP50 IM are shown in the Tab. 1. The first one is a typical medium carbon steel low alloyed, while the second one is a steel with a low carbon content. The elements Al e Cu in the VP50 IM are responsible, together with Ni, by the precipitation hardening of the material.

Table 1. Typical chemical compositions of the steels VP50IM e DIN 1.2711. Mass percentage, Fe-balance. Others elements not shown are usual residuals one.

Steel	C	Si	Mn	Cr	Mo	Ni	S	Al	Cu	Normal Hardness as supplied (HRC)	Utilization Hardness (HRC)
VP50 IM	0.15	0.3	1.6	0.3	0.3	3.0	0.10	1.0	1.0	32	40
DIN 1.2711	0.56	0.3	0.7	0.7	0.3	1.7	residual	-	-	40	40

In the comparison of the two steels, the properties were determined from laboratory samples analysis. The machinability was evaluated from the tool flank wear during the turning test. Hardness profiles measurements were done to evaluate the hardness stability in the steel VP50IM. The nitriding response is compared using the hardness curves, for nitride samples by the Nitreg® process [1]. The process is a nitriding in a gas controlled atmosphere, involving heating temperature of 510 ºC during approximately 6h. The wear resistance was established using the pin test against sandpaper, 15 N force, velocity of 1.72 m/s, #120 mesh sandpaper (Al2O3 abrasive). The polishability was not studied in this work. However, information obtained from specialized companies regarding this operation has considered the steels DIN 1.2711 e VP50IM equivalents regarding polishability.

4. Results and discussion

4.1. Machinability

As described before, machinability is a wide technical concept. Thus, the following results are focused in the concept points important for mould making industry. Firstly, tool wear versus machined length is considered, on the approach of tool consumption. Secondly, in terms of chip formation. Mould making industry normally involve milling operations in manufacturing properties; in spite of that, the present work used turning machining tests, as this test is easier to perform than milling. This approach was taken because this paper does not aim to quantify processing, but only lead to material comparison in a uniform basis.

In this context, the tool life (Fig. 1) and chip formation (Fig. 2) can now be analyzed. In Figure 1 one can note substantial reduction in tools wear from DIN 1.2711 to VP50IM grade. The comparison was based with VP50IM and DIN 1.2711 in their delivered condition: solution treated condition, with 32 HRC, and hardened to 40 HRC

[1] Nitreg is a Nitrex trade mark. Representative in Brazil: Combustol.

respectively; this approach follows the use in mould manufacturing, which applies the rough machining in the delivered condition materials. Based on Fig. 1 results, for a VB tool wear equal to 0.20 mm, the machined length is eight times higher for VP50IM. In the same figure, one can see that VP50IM machinability is even higher (around 50% more) than that of VP20ISO (modified P20), which is the main grade employed in plastic moulds.

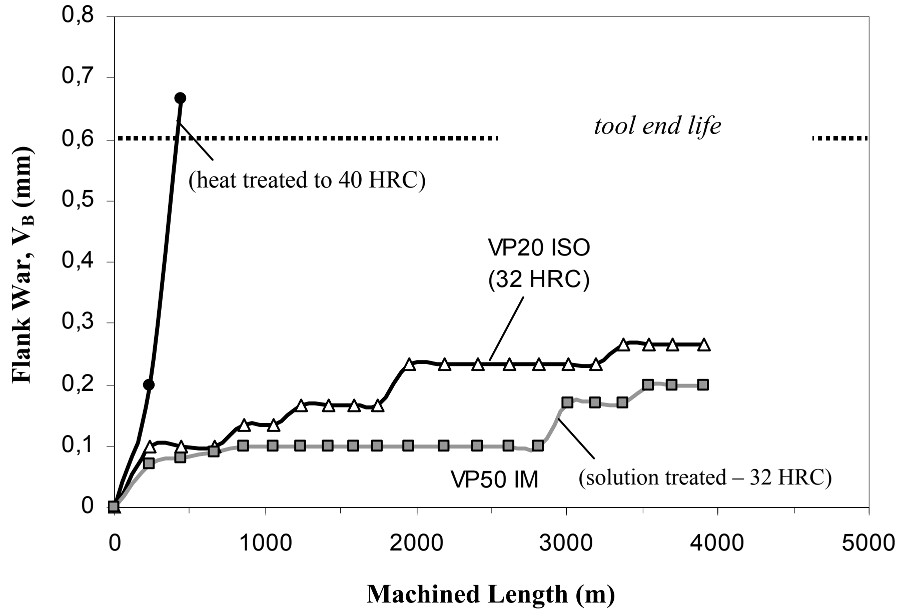
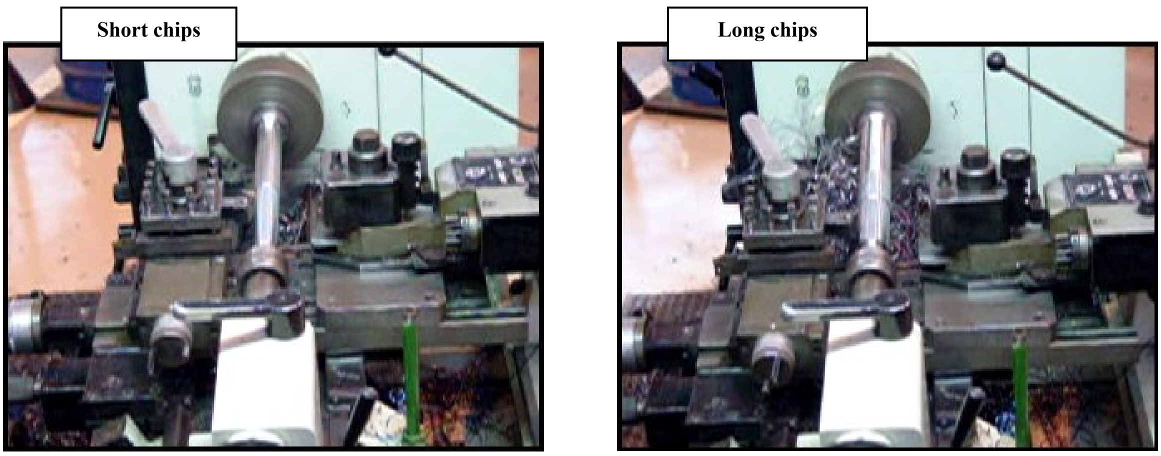


Figure 1. Flank wear of cutting to versus machined length, for grades VP50IM, DIN 1.2711 and VP20 ISO. Parameters: turning test, cutting speed 130 m/min, cutting depth 1 mm, feed 0.25 mm/r

The machinability aspects, observed in Fig. 1, can be correlated to material microstructure, shown in Fig. 3. VP50IM presents fine dispersion of Mn sulphides (Fig. 3a), which are present in the 2711 material in much lower quantity (Fig. 3b). Such inclusions have low hardness and melting point. They thus lubricate the cutting tool, during the material removal, and help chip breaking. This also explains the higher machinability of VP50IM compared to VP20 ISO, which has the same hardness. However, if compared to 2711 grade, VP50IM also offers an advantage regarding hardness level. And, in addition, the refining promoted by VAR process strongly reduce hard and large inclusions, like alumina, which wear cutting tools and are deleterious to machining. This process also refines the Mn sulphides, in other not to impair mould polishability. Therefore, the VP50IM improve in machinability of can be summarized in three points: 1- fine dispersed Mn sulphides; 2- low hardness and 3- low concentration of hard inclusions.



a) **b)**

Figure 2. Test formed chips, from turning machining, of grades a) VP50IM e b) DIN 1.2711. Both for conditions with V_B= 0.20 mm.

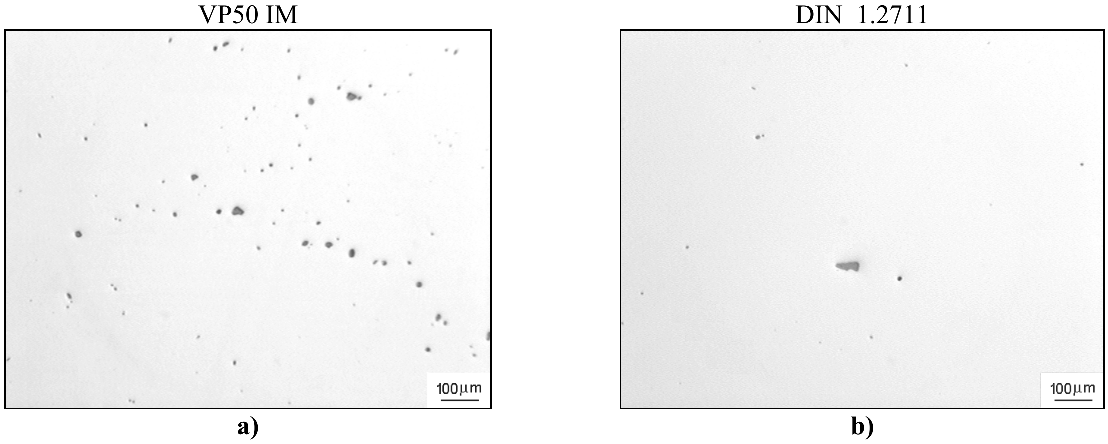


Figure 3. Mn sulphide inclusions in: a) VP50IM e b) DIN 1.2711.

Chips resulting from the test also show an interesting result, being substantially smaller in the VP50IM (see Fig. 2). This effect is, again, caused by Mn sulphides, as they facilitate breaking of formed chip. This result is of special importance for drilling operation, extremely important in moulds manufacturing. Moulds normally present very long holes, for refrigeration and extraction pines, which are normally produced after end heat treating (when mould steel requires quenching and tempering). Such conditions lead to several difficulties and an improved machinability in drilling is thus also desired in plastic moulds. Therefore, VP50IM and DIN 1.2711 steels were compared in drilling operation, being the main result shown in Fig. 4. VP50IM shows again enhanced machinability and longer tool life in drilling conditions.

Drilling machinability difference is significant comparing VP50IM and 2711 steels with 40 HRC, but is more intense if VP50IM in the solution treated condition is considered. As will be shown in item 3, the hardening treating in this material does is given by precipitation mechanism and thus final heat treating can be performed after drilling. The same strategy is less easily applied in quenched and tempered steels, like 2711, due to the risk of distortion or cracking. Therefore, the peculiar condition of heat treating and machinability of VP50IM can lead to important advantages for mould manufacturing industry, as it is a critical operation.

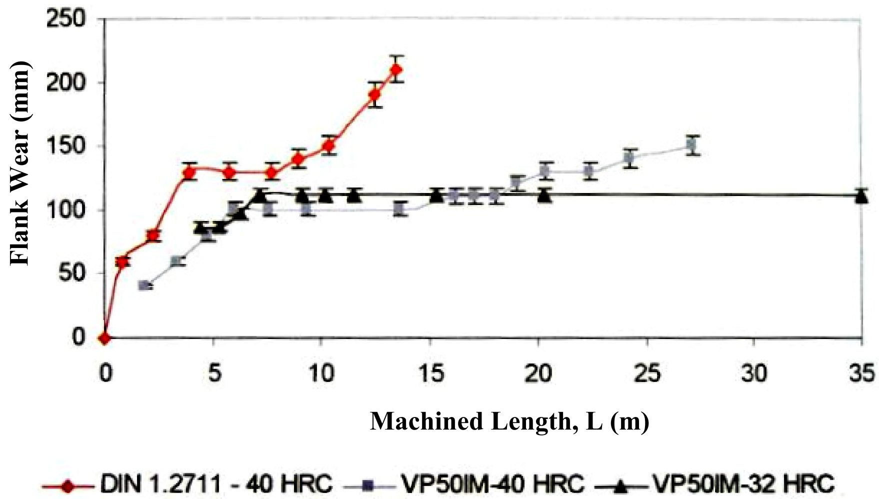


Figure 4. Results from drilling test, relating flank wear and machined length, for VP50IM and DIN 1.2711 steels. VP50IM was evaluated in two conditions: solution treated (delivered condition) and after hardening to 40 HRC. 2711 steel was only analysed in 40 HRC, the normal delivered hardness. Cutting speed 50 m/min, 0.25 mm/r, hole depth 25mm, extreme cooling (Vasco 1000 emulsion, 9%), ∅ 8 mm tool, solid carbide micrograin K03.

4.2. Heat Treating Response

There is a fundamental difference in DIN 1.2711 and VP50IM heat treating. The former makes use of a traditional hardening mechanism, produced by quenching and tempering. Although it can offer high hardness, some problems may arise, such as distortion or cracks, important especially when rough machining is performed before. As already mentioned, DIN 1.2711 steel is normally delivered in the pre-hardened condition with 40 HRC. Thus, this could avoid heat treating cost and the mentioned problems, but prevent that machining could be done in the low hardness condition.

On the other hand, VP50IM steel is normally delivered in low hardness (solution treated) condition, allowing mould machining to be totally done before final heat treating. This treating, on the contrary of quenching and tempering, does not involve rapid cooling and phase transformation. It thus leads to no distortion and lower risk for cracks. In addition, the dimensional variation is rather low (not considering machining stress relief) – a shrinkage around 0.0006 mm/cm. For usual moulds, this shrinkage can even be neglected and the previous machining is performed to the final dimensions. This strategy leads to high material removal in rough machining of steel with low hardness and, as shown before, with high machinability due to its alloy design. Accordingly, low tool consumption and high productivity can be attained, which is of major interest in manufacturing industry.

VP50IM heat treating involves a simple procedure, with heating to 510 ºC for a minimum time of around 6 hours, after temperature homogenization. After this treatment, 40 HRC is attained homogeneously throughout the cross section, as shown in Fig. 5. The same result is hardly attained in large section martensitic grades, as quench cooling is limited in bar core positions and this region normally reaches lower hardness.

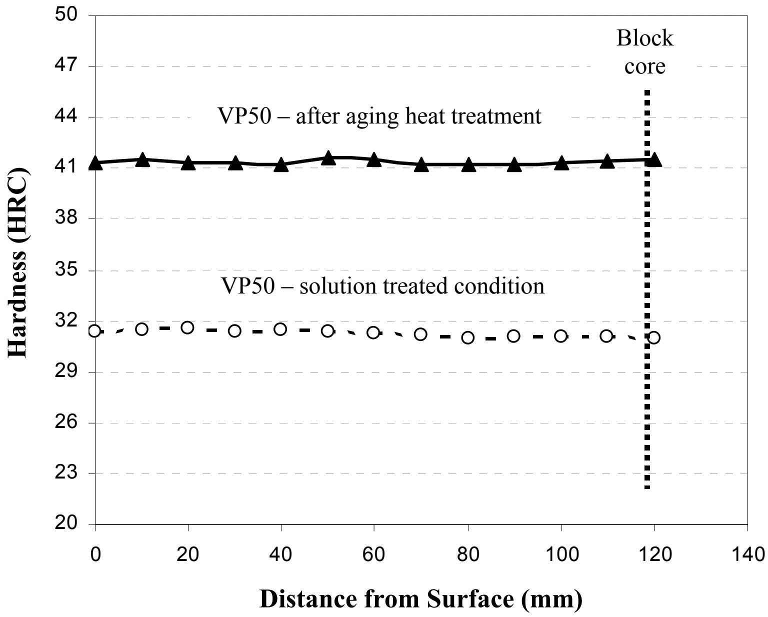


Figure 5. Hardness profile through cross section for VP50IM block before and after heat treatment (aging).

4.3. Welding and EDM issues

One secondary result of non-quench hardening treatment in VP50IM is the possibility of carbon content reduction. Quenched and tempered grades normally need enough some carbon for martensite hardening, as as-quench hardness is directly related to carbon in solid solution.

Accordingly, high carbon content also leads to disadvantages regarding welding and electro-discharge machining. Both of these manufacturing processes are usual in mould production, and involve cooling from high temperature austenite phase. As the steel carbon content increase, the as-quench martensite hardness also increase, leading to possibility of cracking or polishing problems, due to the heterogeneous hardness near welding regions. These problems may commonly occur in medium carbon steels, like DIN 1.2711, but are unlike in low carbon grades as VP50IM. For this steel, recent results have shown its improved weldability (Preciado and Bohorquez, 2005).

4.4. Nitriding Response

Nitriding may be useful in plastic moulds, enhancing wear resistance and productivity, as described in item 2.4. This treatment was evaluated in both VP50IM and 2711 steels, as shown in Fig. 6. One can see in this figure the higher hardness obtained in VP50IM steel. For the nitriding after hardening condition, grey curve, surface hardness around 900 HV is attained (approx. 67 HRC). This is caused by Al-rich nitrides, formed in this steel due to the its 1% Al content (see Tab. 1). In low alloyed grades, like DIN 1.2711, Fe nitrides are normally formed, with much lower hardness than alloy elements nitrides, such as Al, Cr or V nitrides. Therefore, the chemical chemistry of the different grades is the main responsible for the strong hardness difference observed in Fig. 6.

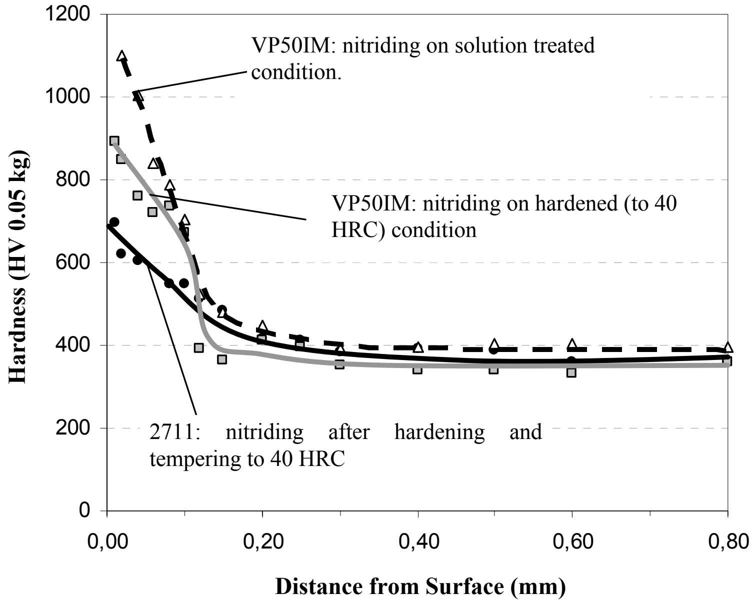


Figure 6. Surface hardness in nitride specimens for the studied grades. DIN 1.2711 was hardened and tempered to 40 HRC before nitriding. VP50IM was nitrides in two different conditions: from sulution treated condition and after hardening (aged) condition.

One second nitriding condition is especially important in VP50IM steel. If the treatment is performed on the solution treated condition, dashed black curve in Fig. 6, higher surface hardening occurs and core hardness also reaches 40 HRC. The higher surface hardness is promoted by the distinct Al condition. If nitriding is performed in aged material, most Al is forming precipitation hardening compounds, bounded with Cu or Ni. However, if solution treated steel is nitrided, most Al is in solid solution and more prone to nitride formation. This enhances the nitriding response, leading to higher hardness.

Simultaneously to the surface hardness increase, core regions also reach the aged condition, with 40 HRC (see Fig.6). This effect is caused by the coincidence of nitriding and aging temperatures for VP50IM, around 510 ºC. And this late aspect is useful for mould making, for decreasing manufacturing lead time. In summary, two treatments (hardening plus nitriding) are not necessary, as they occur in a single treatment. Joining this reasoning with machinability discussion of item 3.1, several advantages arise, in the case of nitrided moulds. Machining can be performed in low hardness and high machinability condition and, during the nitriding treatment, a higher hardness and wear resistance (discussed in item 3.4) is produced, with simultaneous hardening in the whole mould.

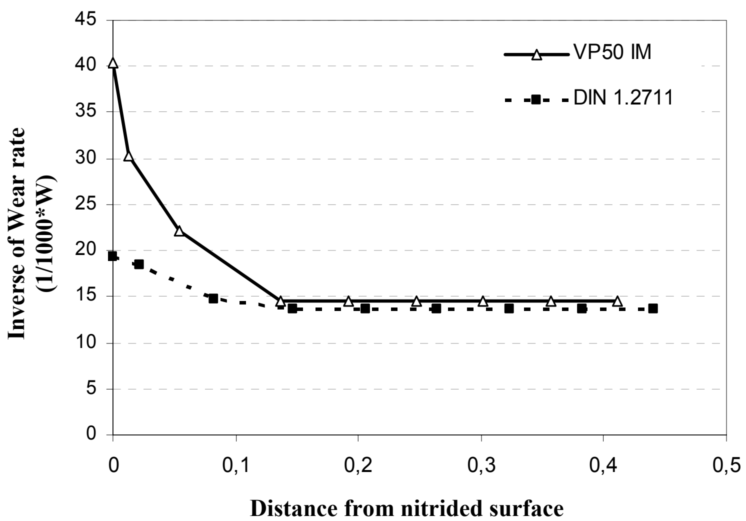


Figure 7: Inverse of wear rate, which evaluate material wear resistance by mass loss. W =$\Delta m/(\rho.A.L)$, being Δm the mass loss, ρ the density, A the test worn and L the sliding distance (pin on sand paper # 120). VP50 IM nitriding was performed on solution treated condition (see Fig. 6 and discussion item 4.3); 2711steel was nitrided after hardening and tempering to 40 HRC.

4.5. Wear Resistance

Abrasive wear resistance is mainly important in injection of reinforce polymers, with abrasive particles such as glass fibber and ceramic particles. If the materials are used only in hardened condition, wear resistance is equivalent for VP50IM and 2711 materials (Mesquita and Barbosa, 2004). This effect occurs because this class of materials, with no carbides in the microstructure, has abrasive wear resistance only dependent on hardness. However, if final application regards to nitrided condition, the higher surface hardness of VP50IM can enhance wear resistance. The comparison of both materials in this condition is shown in Fig. 7, where it is evident the improved wear resistance of nitrided VP50IM in relation to nitrided 2711.

5. Final remarks

As discussed in the previous items, steel specification is a careful choice in mould manufacturing, considering several factors. This is of special interest because the steel is only the start condition of the whole manufacturing process and involve the lowest part of total mould cost. Nevertheless, the steel strongly interact to all subsequent manufacturing processes as well.

In this approach the data presented hear may be useful as well as the discussed issues. Properties differences, such as machinability and heat treating and nitriding response have significant variation between steel grades, as shown in DIN 1.2711 and VP50IM comparison.

6. Conclusions

Manufacturing properties are primordial in steel selection for plastic moulds, as the steel strongly interacts with manufacturing processes, which are the major part of total mould cost.

In terms of machinability, VP50IM steel is substantially superior to DIN 1.2711. VP50IM presents lower delivered hardness and simple final heat treating, with no distortion and very low dimensional changes. These characteristics strongly contribute to increase productivity in rough machining.

In drilling tests, the improved VP50IM machinability was remarkable, either in solution treated or after hardening conditions. This fact is essential for moulds, especially if the long cooling holes are considered.

After nitriding, VP50IM reaches superior surface hardness, leading to strong improve in abrasive wear resistance. If applied in the solution treated condition, VP50IM hardening (by precipitation) occurs simultaneously to nitriding treatment.

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8. Responsibility notice