Vanadium Microalloyed Non-Quenched Steel Family for Plastic Mould

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Abstract  The vanadium microalloyed non-quenched steel family for plastic mould, namely B20, B20H, B30 and B30H, was developed. Those steels are all alloyed with microalloying elements of titanium and vanadium and are produced without any quenching process after hot working. Of them, B20 and B20H can be applied for plastic mouldbase while both B30 and B30H for moulds. The hardness is 20~23 HRC for B20, 24~27HRC for B20H, 28~32HRC for B30 and 33~37HRC for B30H. Those vanadium microalloyed non-quenched steels have more uniform distribution of hardness, better machinability and repairing weldability, similar polishability as compared with their normalised counterpart for mouldbase and quenched and tempered ones for moulds.

Keywords: microalloying, steel for plastic mould, hardness, machinability, weldability

Introduction  For current plastic mould steel family, the medium carbon steel S45C-S55C and the medium carbon low alloyed steel family P20 have long been extensively applied as the typical material for manufacturing mouldbase and moulds, respectively. While S45C-S55C is applied in the normalized condition with a hardness of less than 200 HV, P20 is applied in the quenched and tempered condition with a hardness of 28~32HRC. Within P20 family, both DIN2311 and DIN2738 were developed and applied in the mould industry. The difference between them is the nickel content. Around 1wt% nickel is added into DIN2738 in order to increase the hardenability of the steel plate. Therefore, DIN2738 is mainly applied for manufacturing the heavier plate with a thickness larger than 150 mm. To meet the high requirement of the
plastic mould industry, the quenched and tempered steel S45C-S55C is applied for manufacturing mouldbase with a hardness of over 24 HRC, while the quenched and tempered DIN2711 and NAK80 (Japan’s Daido) steels with a hardness of 33~42HRC are applied for manufacturing moulds with mirror surface finish.

The thickness of steel plate for plastic mouldbase or mould is often in a big range of 30-500 mm. The quenching and tempering process is economically uncompetitive, since it adds to the cost of the whole product, especially for the heavier plate. More importantly, there are some drawbacks technically. First, there exists high risk for stress and therefore, for cracking during quenching process due to the large section. The higher carbon equivalent leads to the higher risk. In such case, DIN2738 and DIN2711 have a higher risk to crack. Secondly, the hardness distribution of large section moulds for the quenched and tempered steels, such as DIN2738, is not so uniform due to the alloying element segregation during solidification, the non-uniform distribution of hot deformation during hot working and the large difference of cooling rate through the whole section of plate during quenching process. At least 3 HRC difference exists in the whole section of the steel plate with a thickness of 400 mm [1]. Finally, the repairing weldability for the quenched and tempered steels is not satisfactory due to their high carbon equivalent. The thick modified layer after welding process needs extra time and cost to remove.

There exists, therefore, the need to develop new steel grades to avoid the above-mentioned technical and economical drawbacks in both the steel and the plastic mould industry. The non-quenched steel is worth notice. In fact, such type of steel has already been developed and applied in the auto industry to make the crank and shaft [2]. All of them are alloyed with microalloying elements of vanadium and produced without quenching process after hot working. They can gain the strength of 800-1200MPa with the comparable toughness by means of the vanadium precipitation hardening during air cooling, in addition to the solution hardening of alloying elements manganese, chromium, etc. The hardness distribution of the non-quenched steel is more uniform than the corresponding quenched and tempered steel with the similar strength level, since the former is not so sensitive to the cooling rate [3].

Based on the current technical status of the quenched and tempered steel for plastic mould and the technical development of the non-quenched steel,
the vanadium microalloyed steel family for plastic mould was developed in Baoshan Iron and Steel Cor. Lit.

**ALLOY DESIGN**

**TARGET OF THE DEVELOPED NON-QUENCHED STEEL GRADE**

The target for the development of non-quenched steel for plastic mould-base is to replace the current grade S45C-S55C at both the normalized and the quenched and tempered conditions. The hardness of the developed steel grade for plastic mouldbase should be 220-260 HV and 24-27 HRC, being comparable to S45C-S55C at normalized and quenched and tempered conditions, respectively. For the application of plastic moulds, the developed non-quenched steel should have the hardness of 28-32HRC, 33-37 HRC and 38-42 HRC, being comparable to DIN2311(2738), DIN2711 and NAK80, respectively, as shown in Table 1.

**ALLOY DESIGN FOR NON-QUENCHED STEEL FOR PLASTIC MOULDBASE**

B20 and B20H are alloyed by the addition of nitrogen and vanadium, together with manganese and chromium. Both have the ferritic-pearlitic microstructure. It has been reported that the strength is raised as the index of \( 'N+5V(\text{wt\%})' \) in steel is increased [4]. This should be attributed to the precipitation hardening of carbonitride particles during air cooling directly after hot working. Manganese is often co-added with vanadium in the non-quenched steel, since it is an effective solution hardening element. The upper limit for the application of manganese is its segregation during solidification. Chromium is added to increase the weathering resistance on one hand and to increase the hardness further on the other hand. Carbon content in both B20 and B20H steel grades is reduced as compared with S45C-S55C to improve the repairing weld ability and reduce the segregation extent. The above-mentioned alloying elements are adjusted and optimized to gain the right hardness and the low segregation extent.
ALLOY DESIGN FOR NON-QUENCHED STEEL FOR PLASTIC MOULD

B30, B30H and B40 are alloyed by the addition of vanadium, together with manganese, chromium, molybdenum, copper and nickel. All of them have the bainitic microstructure. The role of vanadium in these steels is to gain the flat bainitic transformation curve so that the cooling rate has little influence on both the initial and the finishing transformation temperature. The importance of vanadium is, therefore, to gain the uniform distribution of microstructure and hardness. Manganese and molybdenum are two important elements to promote bainite phase transformation, while chromium, copper and nickel are added for improving the corrosion resistance. In addition, copper can improve the machinability of steel, while nickel could balance the negative effect of copper on hot work embrittlement. Carbon content is reduced to lower than 0.20% in order to improve the repairing weld ability. The above-mentioned alloying elements are adjusted and optimized to gain the right hardness, the low segregation extent and the good technical properties.

CONTINUOUS COOLING TRANSFORMATION BEHAVIOUR

STEEL FOR PLASTIC MOULDBASE

As an example, the continuous cooling transformation behaviour of B20 after hot working was simulated, as shown in Fig. 1. It can be seen that B20 would have the ferritic-pearlitic microstructure with a hardness of 250 HV under the cooling rate range, 0.05-0.5°C/s. The hardness changes little within this cooling rate range. It should be mentioned that the cooling rate for the mould steel plate is often in this range during air cooling. This indicates that B20 would have the ferrite plus pearlite microstructure, hardness of 250 HV and more importantly the uniform distribution of hardness.

STEEL FOR PLASTIC MOULD

Both B30 and B30H steels were simulated. Figures 2 and 3 show their continuous cooling transformation curve after hot working [5]. It can be seen that both steels would have the bainitic microstructure and the designed hardness of 28-32HRC and 33-37HRC, respectively within the cooling rate range, 0.05-0.5°C/s. The transformation is flat indicating little effect of cooling rate.
on both the initial and the finishing bainitic transformation temperature. The cooling rate has little effect on hardness of both steels. This indicates that B30 and B30H would have the bainitic microstructure with the hardness of 28-32HRC and 33-37HRC and, more importantly, a uniform distribution of hardness.

TECHNICAL PROPERTIES AND MICROSTRUCTURE OF PRODUCED NON-QUENCHED STEEL GRADES

HARDNESS DISTRIBUTION

For mouldbase steels, the hardness distribution of the steel plate with a thickness of 230 mm made of B20, B20H and S50C steels was shown in Fig. 4 [6]. It can be seen that B20 and B20H have a hardness of 240-260HV (20-23HRC) and 25-27HRC through the whole section, respectively, while S50C steel has a hardness of 160-200HV. The former two have not only the higher hardness, but also the more uniform distribution of hardness.

For mould steels, the hardness distribution of the steel plate with a thickness of 400 mm made of B30, B30H and DIN2738 was shown in Fig. 5. It can be seen that B30 [1] and B30H have a hardness of HRC30-32 and HRC34-36 through the whole section, respectively, while DIN2738 has a hardness of HRC28-31. The former two have not only a higher hardness, but also a more uniform distribution of hardness.

MICROSTRUCTURE

For mouldbase steels, B20, B20H and S50C all have the microstructure of ferrite plus pearlite. As an example, the microstructure of B20 and S50C is shown in Fig. 6. Much finer microstructure can be observed in B20 steel as compared with that in S50C steel.

For mould steels, B30 and B30H have a microstructure of bainite. As an example, the microstructure of B30, granular bainite, is shown in Fig. 7.

MACHINABILITY

The flank wear when milling mouldbase steels, B20 with a hardness of 250HV and S50C steel with a hardness of 180HV using a high speed steel tool M2 at a cutting speed of 37.5 m/min, is shown in Fig. 8 [6]. Even though B20 has a higher hardness, the flank wear when milling it is slightly
lower than milling S50C steel. This indicates that B20 has slightly better machinability.

The flank wear when milling mould steels, B30 and DIN2738, with a hardness of 30HRC using a cemented carbide tool at a cutting speed of 24 m/min is shown in Fig. 9 [7]. Much lower flank wear can be observed when milling B30 steel as compared with milling DIN2738 steel.

**POLISHABILITY**

Since polishability only refers to mould steel, the comparison test was made on only B30 and DIN2738 steels, as shown in Fig. 10 [7]. It can be seen that both steels have a similar polishability.

**REPAIRING WELDABILITY**

Repairing weld is often necessary when some damage or breakage or cracking occur during application or manufacturing processes. The important feature of the repairing weld ability is the hardness change of the modified layer after welding. Less hardened layer is beneficial for the subsequent manufacturing process, such as removal grinding and polishing, etc. The repairing weld test was made for B20 and S50C steels using the welding wire rod of J707Ni, while for B30 and DIN2738 steels using the welding wire rod of J107Cr. The hardness changes for the four steels are shown in Fig. 11 and 12 [6, 8].

Obviously, less modified layer can be observed when welding B20 as compared with welding S50C steel. The similar conclusion can be drawn when welding B30 steel is compared with welding DIN2738 steel. In such sense, B20 has a better repairing weld ability than S50C steel, while B30 is better than DIN2738 steel.

**SURFACE NITRIDING**

The surface nitriding for both B30 and DIN2738 steels were performed at 525°C for certain time. The surface nitriding layer for 5hr is 0.015 mm for both, while the hardness within the nitriding layer is 750HV and 800HV for B30 and DIN2738, respectively. Higher hardness for DIN2738 is due to its higher chromium content, which forms chromium nitride within the layer.
CONCLUDING REMARKS AND THE FUTURE TREND

Through the continuous effort, some non-quenched steels, namely B20, B20H for mouldbase and B30, B30H for plastic moulds were developed in Baoshan Iron and Steel Cor. Lit. Such type of steels are produced through controlled air cooling directly after the hot working process. Within such processes, the required phase transformation is ensured while the stress during phase transformation and cooling is released properly. These non-quenched steels have the comparable technical properties in terms of machinability, polishability, repairing weldability and surface nitriding property, etc. Of vital importance is their more uniform distribution of hardness than the traditional steels in the plastic mould industry. Due to such feature, the non-quenched steel family is now gaining more applications in the mould industry.

S50C and DIN2738 are two most common traditional steels in the plastic mould industry. Just after the successful development of the non-quenched higher hardness steel grade, B20 and B30 are now applied to replace at least partly S50C and DIN2738, respectively. As the plastic mould industry is developing towards mirror surface polishing for mould and the prehardened condition for mouldbase, higher steel grade, such as B30H is applied to replace DIN2711 while B20H is applied to replace the quenched and tempered steel S50C or AISI1040. The most attractive properties is their uniform distribution of hardness on one hand. On the other hand, such type of non-quenched steels can be easily reproduced by the hot forging process in some industry area in China. No quenching process is needed after the hot forging process while the same microstructure and hardness can be maintained.

Based on the successful development mentioned above, the even higher steel grade B40 is now on the way to develop. The comparable technical properties to that of NAK80 is expected for B40. The co-addition of microalloying elements, such as vanadium and titanium, together with certain alloying elements, would act to refine the grain size and improve the toughness, corrosion resistance and raise the hardness level. The nonmetallic inclusion metallurgy will also be engaged to improve the polishability and the chemical etching pattern.
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REFERENCES

### Table 1. Target of developed non-quenched steel for plastic mouldbase and mould

<table>
<thead>
<tr>
<th>Non-quenched steel grade</th>
<th>Hardness HRC</th>
<th>Current steel grade</th>
<th>Heat treatment condition and hardness</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>B20</td>
<td>$\geq 220$HV</td>
<td>S45C-S55</td>
<td>Normalized, $\leq 200$HV</td>
<td>Mould base</td>
</tr>
<tr>
<td>B20H</td>
<td>24-27</td>
<td>S45C-S55</td>
<td>Quenched and tempered, 24-27HRC</td>
<td>Prehardened Mould base</td>
</tr>
<tr>
<td>B30</td>
<td>28-32</td>
<td>DIN2311-DIN2738</td>
<td>Quenched and tempered, 28-32HRC</td>
<td>Mould with normal finish</td>
</tr>
<tr>
<td>B30H</td>
<td>33-37</td>
<td>DIN2711</td>
<td>Quenched and tempered, 33-37HRC</td>
<td>Mould with good finish</td>
</tr>
<tr>
<td>B40</td>
<td>38-42</td>
<td>NAK80</td>
<td>Quenched and tempered, 38-42HRC</td>
<td>Mould with mirror finish</td>
</tr>
</tbody>
</table>

**Figure 1.** Continuous cooling transformation curve of B20.
**Figure 2.** Continuous cooling transformation curve of B30 [5].

**Figure 3.** Continuous cooling transformation curve of B30H.
Figure 4. Hardness distribution for a plate with a thickness of 230mm made of both B20 and S50C steels [6].

Figure 5. Hardness distribution for a plate with a thickness of 400mm made of both B30 and DIN2738 steels [1].
Figure 6. Microstructure of both (a) B20 and (b) S50C steels under hot-rolled condition.

Figure 7. Microstructure of B30 steel under hot-rolled condition.
Figure 8. Flank wear when milling both B20 and S50C steels using a HSS tool [6].

Figure 9. Flank wear when milling both B30 and DIN2738 steels using a HSS tool at a cutting speed of 24 m/min [7].
Figure 10. Polishability comparison in terms of surface roughness [7].

Figure 11. Hardness change through the welding joint when welding both B20 and S50C steels using a J707Ni welding wire rod at room room temperature [6].
Figure 12. Hardness change through the welding joint when welding both B30 and DIN2738 steels using a J107Cr welding wire rod at room temperature [8].