Die material properties needed for Hot Stamping of High Strength Sheet Materials

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Abstract. Industries performing hot forming of high strength sheets are constantly requesting improvements in aspects of die material to achieve a suitable die life and production efficiency. The die material performance to resist the upcoming failure mechanisms based on thermal or mechanical loading is crucial for production efficiency and competitiveness. Therefore, die material for hot stamping needs to have the correct combination of properties to resist upcoming failure mechanism such as cracking, premature wear and plastic deformation. Surface softening during heat exposure contributes to plastic deformation due to hardness loss and has shown to have a direct impact in the potential of wear resistance. The purpose of this paper is to present tool steel solutions from Uddeholms AB, which contains key properties within several fields of hot forming to increase production efficiency.

1. Introduction

In automotive segments, demands for lightweight components have increased in order to obtain low fuel consumption. To fulfill these demands, an interest in high strength parts manufactured through hot stamping has increased. These parts are normally used in the car body where high yield strength and suitable elongation, in order to resist high mechanical load in a crash situation, is desired. These parts are manufactured in large series and therefore high demands are placed on die material requirements and their properties in order to achieve cost effective production. The determining requirement hence, in order to achieve large series production without interruptions, is the die materials performance. This is dictated by its ability to withstand applied load and resulting wear while exposed to heat under long time. The die material selection phase is therefore of highest importance to address the desired properties for the achievement of long series and sustainable production.

2. The process of Hot Stamping

There are two main process types within hot stamping, direct and indirect. Both process are conducted through forming high strength steels such as 22MnB5 into complex shapes. In the indirect process, the sheets are formed in soft condition due to the lower required forces and reduced risk of spring-back. Indirect process consists of forming sheets in cold condition. The formed, trimmed and pierced components are then heated up to austenitization temperature and quenched in the die to obtain strength. Direct hot stamping is the most common process where the sheets are formed in hot condition and
subsequently quenched in the die. The process also has the biggest challenge to address in terms of tool failure due to the longer heat contact resulting in high die wear [1].

There are several steel grades used as sheets for hot stamping, all of which receive their strengths after quenching, but the most commonly used one is 22MnB5. The sheet materials can either be coated or un-coated; coated sheets with aluminum silicon- or zinc based coatings are used to reduce oxide scale formation and decarburization during forming and for protection against corrosion. The usage of coated materials is not possible in the indirect process. The material in soft condition consists of a ferritic-pearlitic microstructure in which, during the heating process, carbon is dissolved into the matrix and transformation to the new phase austenite occurs. Austenite is normally not stable at lower temperature and therefore transformed to other phases depending on the cooling rate applied and the alloy composition. For high strength steel, a fast cooling rate is desired in order to receive the hardest microstructural formation, which also results in high yield and ultimate tensile strength. However, some sections require higher elongation in order to absorb energy. This is achieved by tailored cooling locally, and the cooling rate is lowered to reduce the amount of hard martensite and therefore some amount of the phase bainite is instead formed resulting in a soft zone. A tooling setup with both cooled zone dies in order to achieve hard and high strength areas, and hot zone dies to receive soft and ductile areas result in a combined forming process resulting in tailored properties in the formed material [2].

![Figure 1. The process of hot stamping](image)

3. Failure mechanism
In order to have a cost effective hot stamping production, the number of formed sheets needs to be manufactured with minimum amounts of die sets. This means that the die material needs to have properties to withstand the potential failure mechanism and thereby receive a suitable die life. Some of the properties needed to meet the requirements are a) wear resistance, b) toughness to prevent cracking, c) temper back resistance to avoid softening due to high heat and thereby minimizing risk for plastic deformation while preserving wear resistance. The die material also needs to be weldable for repair in case of unplanned maintenance [3].

![Figure 2. Illustration of failure mechanism from left abrasive wear, cracking and plastic deformation.](image)
The hot forming method and the selection of sheet materials affects the die life in different ways and therefore it is of highest interest to address the selection and performance of tool steel. The use of uncoated sheets results in an oxide scale at elevated temperature on the sheets. This hard oxidized surface layer causes higher abrasion on the tool surface compared to AlSi-coated sheets which don’t receive the same abrasive scale. However, in terms of adhesive wear or galling the risk is higher for the usage of coated sheets since the AlSi coating interacts and sticks on the die [4].

Material properties often rely on the tool steel hardness. However, when the die is in contact with high heat, it can temper back and softens. What happens during the softening, because of the drop in hardness the material loses its strength and therefore it’s potential to withstand plastic deformation during mechanical loading. Another negative effect of softening is the reduction in wear resistance. A material’s ability to keep its hardness is dependent on the time and temperature the heat contact is between the die and sheet. Since soft zone dies are used in sections, which are heated to elevated temperatures, these sections will be exposed to heat for extended periods of time and therefore be more prone to temper back effect. To extract heat quicker and improve production rate, a high thermal conductivity is desirable, this is normally received as a material property.

However, over the last years trends have suggested higher need for thermal conductivity, which has been achieved by adjusting the placements of cooling channels closer to the surface, see Figure 5. This results in a better heat transfer but also increases demands on die material due to the increased risk for cracking in the cooling channels. The source for crack initiation could vary from high stress level, thermal or mechanical but also due to corrosion. The most significant requirement in terms of cracking resistance is high toughness, which is the ability to resist the crack to propagate. Low toughness can lead to crack propagation towards the surface causing water leakage and total interruption in production.
Figure 5. Illustration of cooling channel design and placement in Hot Stamping die.

4. Experiments

Based on discussion in the previous section, it can be understood that wear resistance and temper back resistance are crucial to achieve suitable die life. However, in terms of heat contact, how the abrasive wear resistance behaves in combination with temper back resistance needs to be understood. To investigate this, evaluation between high abrasive wear resistance grades such as Uddeholm Caldie and Unimax compared to Uddeholm QRO 90 Supreme which is a high temper back resistance grade, are conducted.

4.1. Method

The experiments are conducted to obtain abrasive wear resistance according to pin on disc wear test in combination with temper back resistance. In Table 1, the chemical composition of the chosen grades is provided which also indicates the capability of obtaining a high wear resistance which again depends on achievable hardness that varies between the grades through the heat treatment shown in Table 2.

| Table 1. Chemical composition of the selection steel grades. |
|-------------|--|--|--|--|--|--|
| Uddeholm Steel grades | C | Mn | Si | Cr | Mo | V |
| Unimax       | 0.50 | 0.50 | 0.20 | 5.00 | 2.30 | 0.50 |
| QRO 90 Supreme | 0.38 | 0.75 | 0.3 | 2.60 | 2.25 | 0.90 |
| Caldie       | 0.70 | 0.50 | 0.20 | 5.00 | 2.30 | 0.50 |

| Table 2. Heat treatment parameters and hardness for the selected steel grades. |
|-------------|----------------|----------------|----------------|----------------|----------------|
| Uddeholm Steel grades | Austenitizing temperature (°C) | Holding time (minutes) | Tempering temperature (°C) | Time (hours) | Hardness (HRC) |
| Unimax       | 1025           | 30             | 540             | 2x2           | 57             |
| Unimax       | 1025           | 30             | 580             | 2x2           | 52             |
| QRO 90 Supreme | 1050           | 30             | 590             | 2x2           | 52             |
| Caldie       | 1050           | 30             | 560             | 2x2           | 60             |
| Caldie       | 1050           | 30             | 610             | 2x2           | 52             |
The first step in the experiments is to investigate the temper back resistance of the chosen grades. This will be conducted with starting hardness values for Uddeholm Unimax at 57 HRC and Uddeholm Caldie at 60 HRC. Since they both can reach the performance hardness of 52 HRC for Uddeholm QRO 90 Supreme, all three grades will be tested with a starting hardness of 52 HRC. Samples will be heat treated to reach the set hardness values. One sample each from the five different groups are then placed in a furnace set to 600 °C. After 10 hours, the samples are removed from the furnace in order to measure hardness drop in comparison with start hardness. The second step in the experiments is to conduct the wear test. Wear testing was performed using a pin on abrasive paper tester, where the pin materials were Uddeholm Unimax, Uddeholm QRO 90 Supreme and Uddeholm Caldie, and the abrasive papers contained Al₂O₃ (800 Mesh). Samples were held against the abrasive papers using dead weights for a prescribed amount of time and the relative wear resistance was calculated from the mass loss, with lower mass loss indicating higher resistance to wear. Tests were conducted in 57 HRC for Uddeholm Unimax, 60 HRC for Uddeholm Caldie, 52 HRC for Uddeholm QRO 90 Supreme and at the received hardness after 10 hours in 600 °C. Tests were conducted in each hardness condition two times on the same sample and on a parallel sample to ensure repeatability.

4.2. Results

The results of the temper back resistance shown in Figure 7 suggests that after 10 hours at 600 °C Uddeholm QRO 90 Supreme had minimum loss in hardness, i.e., only 3 HRC. In comparison with the other grades, Uddeholm QRO 90 Supreme had, together with Uddeholm Caldie with start hardness of 60 HRC, the highest hardness values of 49 HRC after 10 hours.
Wear test results, see Figure 8, showed that Uddeholm Caldie had the best abrasive wear resistance when the tests performed with starting hardness were compared. However, after 10 hours in 600 °C the results looks different where Uddeholm QRO 90 Supreme had the best abrasive wear resistance followed by Uddeholm Caldie. This result shows clearly that a good temper back resistance delays the loss of abrasive wear resistance. The pin on disc method provides a qualitative comparison between the steel grades which can advise for tool steel selection. The limitation is that it does not simulate wear conditions which are prevalent in the real application but in comparison testing it provide information of the grade with highest wear resistance. However, the wear mechanisms can be more complex in reality than described in the experimental set up.

![Figure 8. Results of abrasive wear resistance in combination with temper back dark blue, compared with original hardness in light blue, longer staple stands for higher wear rate and lower wear resistance.](image)

5. Tool steel selection

As mentioned earlier, there are several potential failure mechanisms that can reduce the potential die life of hot stamping dies that needs to be in mind during selection of right die material. The use of coated or un-coated sheets also effects the failure mechanism differently. The Uddeholm die materials for hot stamping, shows several grades for selection to meet the requirements based on abrasive wear resistance and toughness, see Figure 9. The figure illustrates relative ranking of the materials based on the average product properties. The scale chosen in the Y-axis is normalized with regard to wear rate mg/min. The X-axis is based on Charpy V impact toughness values in Joules normalized to the range obtained in these materials the details of which can be found in the respective technical brochures for these products available online.

If cracking is the main problem, Uddeholm Dievar has the highest toughness to resist crack propagation. However, if the crack initiated in the cooling channels due to corrosion is instead the issue, Uddeholm Tyrax ESR should be selected since it is a corrosion resistant material with also high abrasive wear resistance. In terms of abrasive wear resistance, Uddeholm Caldie has the highest level and is the steel grade that can receive the highest hardness. In many cases of hot stamping, a combination of toughness and abrasive wear resistance are needed where Uddeholm Unimax has universal properties. Uddeholm QRO 90 Supreme has the highest temper back resistance and highest heat conductivity of all grades. This makes the steel extremely suitable for hot stamping dies in general but hot zone dies in particular since they are exposed to high heat constantly.
Figure 9. Product chart for Hot Stamping die, ranked after abrasive wear resistance and toughness.

6. Summary
Die material requirements for hot stamping of high strength sheet materials stands out in order for the material to keep its mechanical properties in a consequence of high heat contact. Several failure mechanisms are delayed based on the ability of the die material to withstand against softening, such as loss in strength and wear resistance. Traditional selection of die material for hot stamping has been based on mechanical properties before the die material has been in contact with the heated sheets. Experiments in the current study have shown the importance of temper back resistance in order to avoid loss of mechanical properties such as abrasive wear resistance over time. These results indicate what can be expected in hot stamping production since failure should not occur at an early stage of the production series.

References

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