NON-PEER-REVIEWED PAPER

Research on the optimization of heat processing parameters in die-casting mould manufacturing with high-speed steel W18Cr4V

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Keywords

high-speed steel, die-casting mold, retained austenite, martensite, hardness, roughness, parameter optimization

Abstract

The study in this paper aims at improving heat processing parameters in die-casting mold manufacturing with high-speed steel W18Cr4V, the optimization of quenching temperature, and tempering temperatures and times, and the influence of the volume of retained austenite on surface hardness and roughness of the material. The results indicate that high-speed steel W18Cr4V at different quenching and tempering temperatures can create different volumes of retained austenite and that the relation between surface hardness and the volume of retained austenite can be illustrated with an open downward quadratic curve. When the volume of retained austenite amounts to 30 %–55 % (vol %), surface hardness of high-speed steel W18Cr4V quenched is high whereas the grindability is good and the surface roughness is low. If a new heat processing program of quenching at 1,150 °C and double tempering at 300 °C–400 °C and 570 °C respectively is adopted, a stable Martensite structure, the maximum of surface hardness and the minimum of surface roughness will be achieved. The adoption of new process parameters in manufacturing die-casting molds can reduce the time spent on the traditional theoretical process by 40 % and save energy consumption. Also, it can reduce electric power consumption by nearly 40 %.

Introduction

High-speed steel is of high heat hardness. When the cutting temperature reaches 600 °C, its hardness remains at or above 60 HRC, therefore it is commonly used in the manufacturing of cutlery steel. Among its components, carbon ensures the formation of sufficient volume of carbide; Cr can improve hardenability; W and Mo can improve heat hardness. In the tempering process after quenching, carbide which has been separated from W and Mo will be hardened for the second time. V can improve the hardness and wear resistance of the steel [1].

High-speed steel contains a large number of carbides of high hardness, high wear resistance, high strength and high surface accuracy. Due to the complexity of heat process, high-speed steel is far from widely use, only limited to the cutlery manufacturing in a very long time.

Recent years, with the trend of large-scale use, high-speed steel has been more and more widely used in die-casting mold manufacturing. It is increasingly significant that the working life of high-speed steel is longer than that of Cr12. The steel can be used to manufacture parts of high machining precision, good consistency and reliable quality, which can be used in martial and astronautic industries.

The volume of remained austenite has a significant effect on the hardness and wear resistance of steel. Studies in China and abroad have shown [2–13] such significant influence of remained austenite on the properties of the steel. W18Cr4V is a common used high-speed steel. Because of the limited research on high-speed steel W18Cr4V as mold making material, researches to obtain and optimize new parameters for the processing of such materials are valuable in practice.

In mold making process, machine and heat process are given priority. Because of a wide range of programs, steps in production process are multiple and long production runs are involved. The heat processing cycle plays most part in the entire production process. Due to the large amount of electricity consumption, heat process accounts for a considerable proportion of processing costs of the whole (set) products. For the need to ensure design accuracy and to meet the processing and application requirements, research on the optimization of heat processing parameters, practical methods of technological detection, the shortening of the heat processing cycle and the reduction of energy consumption must be carried out to achieve suitable mechanical economic precision [14].

The Influence of Material Surface

HARDNESS RESEARCH

Different quenching and tempering temperatures, that makes high-speed steel W18Cr4V creates different volumes of retained austenite. Therefore we have to research the influence of retained austenite on hardness and wear resistance of the high-speed steel W18Cr4V.

For high speed steel W18Cr4V production mold, usually adopts the process route of [15]:

rough processing → products-in-progress
→ heat process (quenching at 1,250 °C–1,300 °C and tempering three to four times at 550 °C–570 °C)
→ intensive processing → finished products

In theory, making mould using high speed steel W18Cr4V, after quenching and three to four times tempering, quenching temperature of 1,250 °C–1,300 °C, the tempering temperature is 550 °C–570 °C, in order to meet the process requirements.

HEAT TREATMENT PROCESS

The main chemical components of high-speed steel W18Cr4V are listed in Table 1 [1, 15].

Table 1. The main chemical components of W18Cr4V w (%).

C	W	Cr	V	Si	Mn	Mo
0.70 — 0.80	17.50 — 19.00	3.80 — 4.40	1.00 — 1.40	≤0.40	≤0.40	≤0.30

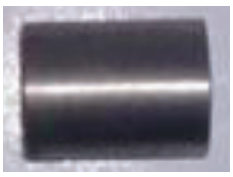

Figure 1. Physical map of the sample before heat treatment.

Figure 2. Hardness test specimen after heat treatment physical map.

Ferromagnetism is used to test the volume of retained austenite. This method takes advantage of non-magnetic austenite, strong magnetism of martensite and weak magnetic properties of carbides to measure the volume percentage of retainer austenite (vol %) in high-speed steel W18Cr4V. When the material organization changed, hardness and roughness was changed accordingly. We can intuitively measure the hardness of the sample after heat process and study the relevance between heat processing temperatures, the volume of retained austenite and surface hardness and roughness for general engineering purposes.

This paper studies the temperatures set for heat processing experiment, which are consistent with those in the actual production using high-speed steel W18Cr4V. All of the data are gained from the actual process parameters of W18Cr4V.

The SX2-10-13 high-temperature box-shaped resistance heated furnace, whose temperature ranges from 0 °C to 1,600 °C and temperature control accuracy ranges between ±3 °C, is used for heat process. The usually quenching temperature in engineering can be 1,050 °C, 1,100 °C, 1,150 °C, 1,200 °C or 1,250 °C. The tempering process will be the next.

The tempering temperature for high speed steel is usually set at 550 °C–570 °C. Tempering temperature of 300 °C–400 °C or so within the low temperature range is suitable for products with the strength requirements like molds. To verify the material properties of W18Cr4V at all tempering temperatures, the tempering temperatures of 200 °C, 350 °C, 450 °C and 570 °C are set.

This paper changes theoretical heat process parameters for high-speed steel die-casting W18Cr4V, where quenching and tempering (three to four times) temperatures are 1,250 °C–1,300 °C and 550 °C–570 °C respectively, into quenching temperature of 1,250 °C and then tempering once at 300 °C–400 °C and another time at 570 °C. This can greatly reduce power consumption and shorten the production run.

The traditional method of measuring the material properties is to use optical microscope to observe the structure of materials. However in practice, testing surface hardness and roughness is most adopted, whose effect is more direct and intuitive.

High speed steel material is used for making molds, tempered at 300 °C–400 °C after being quenched. To obtain tough and stable martensite, another tempering at 570 °C ±10 °C must be carried out to further eliminate internal stress.

Hardness is measured by HR-150DT Rockwell electric hardness measuring.

Test three samples for each group and 5 points for each sample after the surface of samples has been ground. Test a total of 15 data points, 3 groups, and calculate the average.

RESEARCH ON HEAT TREATMENT PROCESS PARAMETERS ON THE MATERIAL EFFECT

Microscopic constitution

After quenching and tempering procedures, the main metallurgical constituents of high-speed steel W18Cr4V will be martensite and austenite (Figure 5). In heat process, there is no obvious change in the type, shape, distribution of carbides. In term of high-speed steel W18Cr4V, change in the quenching and tempering temperatures will result in change in the relative volume of martensite and austenite within a wide range and the volume of retained austenite has a direct influence on the material properties.

Influence of quenching and tempering temperatures on retained austenite

Heat process does not change the basic type and morphology of carbide phase in high speed steel. Its influence on the volume of carbides is also very limited whereas it has significant influence on the relative volume of martensite and austenite in the matrix.

Table 2 indicates the results from measuring the volume and surface hardness of retained austenite by ferromagnetism.

See formula (1), which expresses the testing principle.

$$A_r\,\% = [\,(\alpha_0 - \alpha)\,/\alpha_0] \times 100\,\% \qquad (1)$$

Where,

$A_r\,\%$ retained austenite;

α_0 deflection angle of galvanometer being tested;

α deflection angle of galvanometer of the measured sample.

The measured values of retained austenite are linked to form austenite curve according to quenching and tempering temperatures as shown in Figure 3, where the solid lines indicate the actually measured values and dotted lines indicate the trends. The arrow points to is the direction of the increase in the volume of retained austenite.

In Figure 3, the differently shaped symbols stand for different volumes of retained austenite.

According to Figure 3, quenching and tempering temperatures will have a significant influence on the volume of residual austenite. The higher the quenching temperature, the more the residual austenite whereas the higher the tempering temperature the less the residual austenite, i.e., there is a gradually increasing trend of the volume of retained austenite from the lower right corner to the upper left corner.

The lower the quenching temperature the less the carbon and alloy in austenite dissolved, the higher the terminal temperature for the transformation of martensite (M_f point) the poorer the stability of austenite. In the process of quenching and then cooling, the martensitic transformation is more complete. After quenching, less residual austenite is obtained and the higher the quenching temperature the more the carbon, vanadium, chromium and molybdenum soluble in austenite. The higher the stability of austenite and the lower the M_f. In the process of quenching, the transformation of martensite is inadequate whereas more retained austenite is generated, which means that retained austenite increases with the rise of quenching temperature.

From Table 2, the different quenching temperatures have a influence on the surface hardness of high speed steel W18Cr4V, which is summarized and illustrated with the curve as shown in Figure 4.

According to Figure 4, at the quenching temperature of 1,150 °C, and after double tempering, the surface hardness of W18Cr4V reaches the maximum.

INFLUENCE OF RETAINED AUSTENITE ON SURFACE HARDNESS

High-speed steel W18Cr4V's main constituents are martensite and austenite. The toughness of austenite is high while that of martensite is low. When the amount of austenite in the steel is increased, the hardness of the steel seems to have a decreas-

Table 2. The measured values of residual austenite and the surface hardness of W18Cr4V after being quenched and double tempered.

group	heating temperature		retained austenite vol %	hardness HRC
	quenching	tempering		
1	1,050 °C	200 °C+570 °C	40.1	60.9
		350 °C+570 °C	37.8	60.0
		450 °C+570 °C	11.7	60.3
		570 °C+570 °C	5.2	58.3
2	1,100 °C	200 °C+570 °C	47.4	61.8
		350 °C+570 °C	43.7	60.7
		450 °C+570 °C	17.1	59.4
		570 °C+570 °C	6.6	57.8
3	1,150 °C	200 °C+570 °C	59.4	65.8
		350 °C+570 °C	54.4	64.9
		450 °C+570 °C	32.2	64.6
		570 °C+570 °C	18.9	61.4
4	1,200 °C	200 °C+570 °C	71.4	59.5
		350 °C+570 °C	67.7	58.9
		450 °C+570 °C	49.0	60.7
		570 °C+570 °C	22.8	60.1
5	1,250 °C	200 °C+570 °C	81.9	54.7
		350 °C+570 °C	73.7	55.6
		450 °C+570 °C	51.0	56.2
		570 °C+570 °C	41.7	55.7

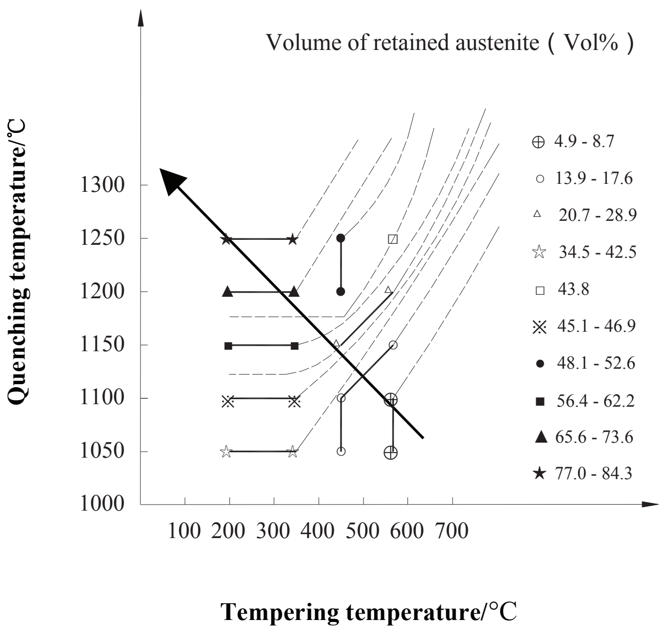

Figure 3. Austenite curve.

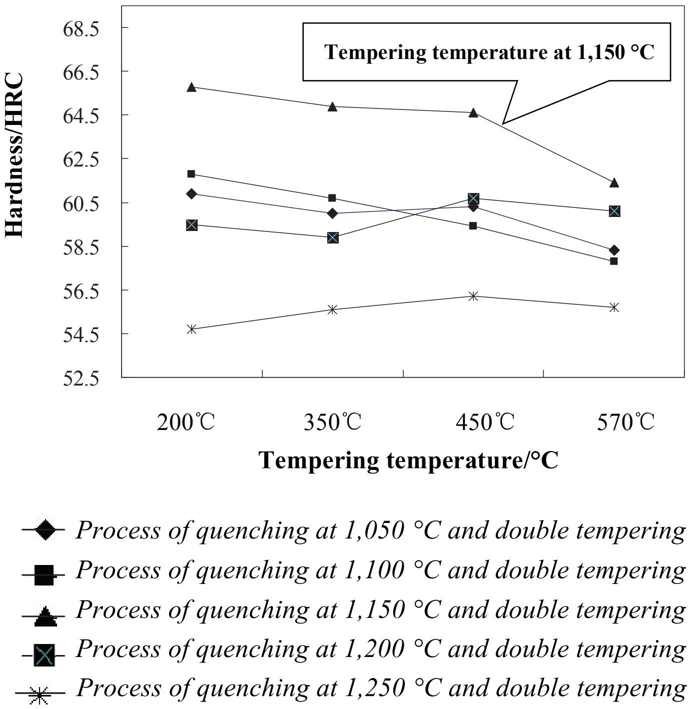

Figure 4. Measured surface hardness of high-speed steel W18Cr4V after being quenched at different temperatures and double tempered.

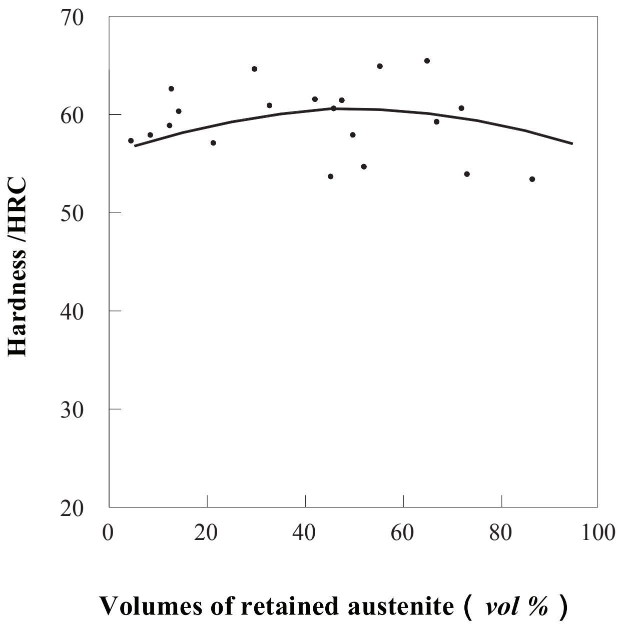

Figure 5. Influence of residual austenite on the surface hardness.

ing trend. When the volume of retained austenite reaches 30 %–55 %, the hardness reaches the peak. The reason is that when there is excessive retained austenite, the amount of carbides remains the same. Whereas martensite of higher hardness decreases, which together result in the lower hardness. Conversely, when there is inadequate retained austenite, a higher tempering temperature is required, part of the martensite will be decomposed into cementite and ferrite of very low hardness, which cause the hardness to decrease.

As per the processing experience, the harder the processed material is, the more wear-resistant the surface. According to Figure 5, the relation between surface hardness and the volume of retained austenite forms a quadratic open downward curve. Where the volumes of retained austenite range from 30 % to 55 %, the surface hardness is high, which is favorable for the formation of surface precision. Where there is too much or too little retained austenite in the material, the wear extent will increase and wearing resistance goes down.

One reason for austenitic phase of better toughness is that the particles can work well in preventing cracks from spreading in the process of abrasion. When there is inadequate retained austenite, the crack will emerge and spread rapidly and cause the material to peel off and to be less wear resistant. Where there is excessive austenite in the steel, the austenite phase of lower hardness can not effectively prevent particles from abrasion or keep the wear-resistance of hard carbides, which will make carbides prominent in the abrasion and cause them to peel off earlier. This will in turn weaken the wear-resistance and thereby surface precision of the material.

It has been found in the actual operation that quenching at 1,150 °C and tempering once at 300–400 °C and another time at 570 °C can on one hand first help separation of MC and M3C, then refinement and uniformity of carbides, and thus secondary hardening and improved toughness; on the other hand, as about 5–7 % lower bainite is generated during tempering at 300–400 °C, the dislocation density of lower bainite is lower than that of tempered martensite, which makes the growth and recrystallization of the carbides difficult and thus can help improve red hardness and the useable life of the mold.

Some documentation [16] suggests that during the tempering at 300–400 °C, the carbon in martensite in high-speed steel decreases, alloy cementite is separated from the martensite while retained austenite remains the same. The study indicates that when the tempering temperature is below 450 °C, it is hard for austenite to change into martensite.

When the tempering temperature increases to 550 °C, which promotes the separation of oversaturated carbon from martensite, there is limited change in the volume of retained austenite. When the tempering temperature reaches 570 °C, driving forces for martensitic phase transformation increase, more retained austenite changes into martensite in the tempering process. When the tempering temperature continues to rise, the more complete the martensitic transformation, the less the amount of residual austenite.

This implies that tempering at lower temperatures improves the comprehensive mechanical properties of materials, which achieves high hardness while maintaining adequate toughness. The new tempering process not only improves hardness, but also maintains adequate toughness and extends product life. In other words, in actual operation, the adoption of quenching at 1,150 °C and double tempering at 300–400 °C and 570 °C meets the practical requirements of engineering.

As stated above, the retained austenite is neither too much nor too little in steel are not in favour of the increase in hardness. The volume of retained austenite to a certain extent can achieve the most favourable wear-resistance and hardness. The experiment proves that the hardness reaches the peak when the volume of retained austenite ranges from 30 % to 55 %, which is appropriate for high-speed steel W18Cr4V.

Surface Roughness Study

THE STUDY ON QUENCHING AND DOUBLE TEMPERING TREATMENT

Grinder model: M1420
Speed: 2,500 r/min
Feed: 0.03−0.05 mm·r^{-1}

When measuring roughness, a stylus will be placed directly on the surface to read the value of roughness (R_y) [17]. Five data points will be taken for each of total three samples and R_{yavg} is the average of the 15 R_ys taken [18].

INFLUENCE OF RETAINED AUSTENITE ON SURFACE ROUGHNESS

After the heat process of quenching and tempering first at 300 °C—400 °C and then at 570 °C, the influence of heat processing parameters on material properties can be concluded, which enables the most favourable heat processing parameters to be selected by measuring the surface roughness of high speed steel W18Cr4V.

ROUGHNESS MEASUREMENT

Sample data points can be taken and measured using the JB-6C roughness microscope. The results of roughness measurement using the JB-6C roughness microscope are shown in Table 3.

Influence of different quenching temperatures on the surface roughness of high-speed steel W18Cr4V is shown in Table 3. Figure 6 summarizes the data in Table 3.

According to Figures 4 and 6, stable volumes of martensite can be obtained by the new heat process of quenching at 1,150 °C and double tempering at 300 °C–400 °C and 570 °C respectively to achieve the highest surface hardness and the lowest surface roughness.

Comparison of Two Programs of Heat Process

THE THEORETICAL PROCESS OF HIGH-SPEED STEEL W18CR4V

Theoretically three to four tempering processes at 550 °C–570 °C should be carried out after quenching at 1,250 °C–1,300 °C to eliminate retained austenite, obtain stable martensite and either reduce or eliminate the internal stress produced by the heat process. Under such condition surface hardness and roughness will be measured to obtain high hardness, wear-resistance and red hardness, improve and meet the needs of projects. The above processes should be taken to deal with heat process and measure surface hardness and roughness.

Table 3. The measured values of the suface roughness of high-speed steel W18Cr4V after quenching and double tempering.

Group	Heating temperature		Surface roughness R_{yavg} /μm
	quenching	tempering	
1	1,050 °C	200 °C+570 °C	2.347
		350 °C+570 °C	2.383
		450 °C+570 °C	2.371
		570 °C+570 °C	2.386
2	1,100 °C	200 °C+570 °C	2.327
		350 °C+570 °C	2.315
		450 °C+570 °C	2.292
		570 °C+570 °C	2.281
3	1,150 °C	200 °C+570 °C	2.287
		350 °C+570 °C	2.258
		450 °C+570 °C	2.240
		570 °C+570 °C	2.260
4	1,200 °C	200 °C+570 °C	2.362
		350 °C+570 °C	2.370
		450 °C+570 °C	2.337
		570 °C+570 °C	2.314
5	1,250 °C	200 °C+570 °C	2.386
		350 °C+570 °C	2.360
		450 °C+570 °C	2.347
		570 °C+570 °C	2.327

THE STUDY ON QUENCHING AND THREE TIMES' TEMPERING PROCESSES

Table 4 shows the measured values of the surface hardness and roughness according to the theoretical process. Figure 7 summarizes the data in Table 4.

According to the values of surface roughness (Ry) in Table 4, similar values of surface roughness are obtained at different tempering temperatures while the quenching temperature is either 1,050 °C–1,100 °C or 1,200 °C–1,250 °C. This shows that there is no obvious difference in surface roughness at the quenching temperatures of 1,050 °C, 1,150 °C and 1,250 °C. According to the economic precision machining principles, the optimal heating and quenching temperature is 1,150 °C.

The results of measurement imply that two and three tempering processes make no obvious difference in the surface hardness and roughness.

COMPARISON OF TIME SPENT ON THE HEAT PROCESS

The time spent on the new heat process is 60 % of that on the theoretical process. The same time will be spent on the machining and cooling processes whereas that on the heat process will be different (see Table 5).

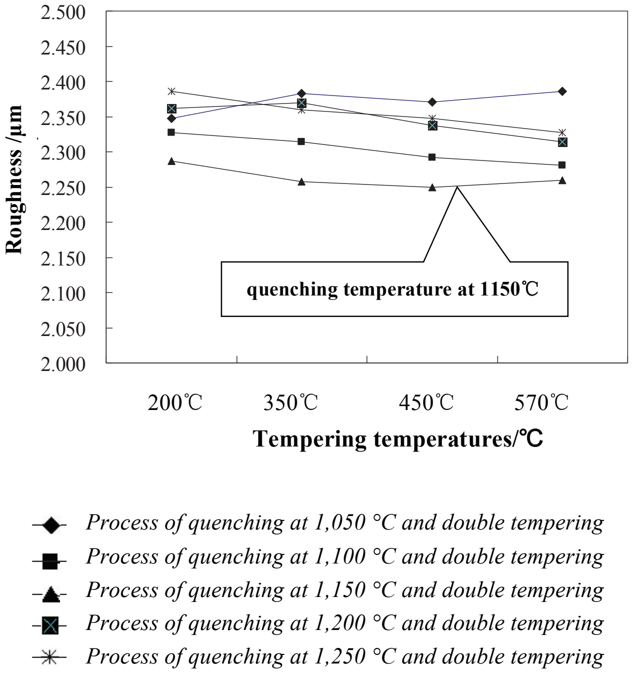

Figure 6. The measured value of surface roughness of high-speed steel W18Cr4V at different quenching temperatures and after double tempering.

Table 4. The measured values of the surface hardness and roughness of high-speed steel W18Cr4V after quenching and three tempering processes (570 °C).

Group	Heating temperature		Hard-ness HRC	Surface roughness R_{yavg} /µm
	quenching	tempering		
1	1,050 °C	570 °C	57.6	2.316
2	1,100 °C	570 °C	58.5	2.263
3	1,150 °C	570 °C	61.6	2.249
4	1,200 °C	570 °C	60.8	2.269
5	1,250 °C	570 °C	57.3	2.333

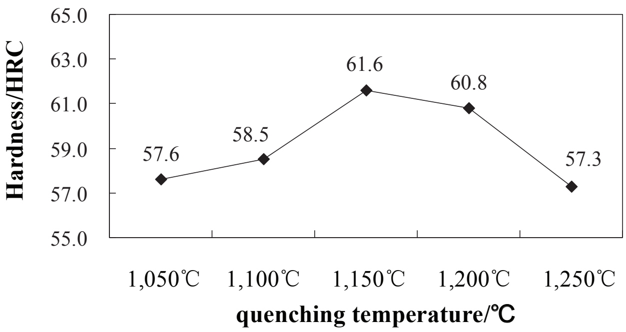

Figure 7. The measured values of hardness of high-speed steel W18Cr4V after quenching and three tempering (570 °C) processes in each group.

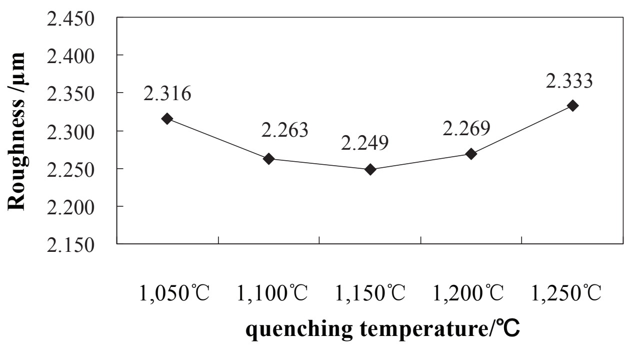

Figure 8. The measured values of roughness of each group of sample high-speed steel W18Cr4V after quenching and three tempering (570 °C) processes.

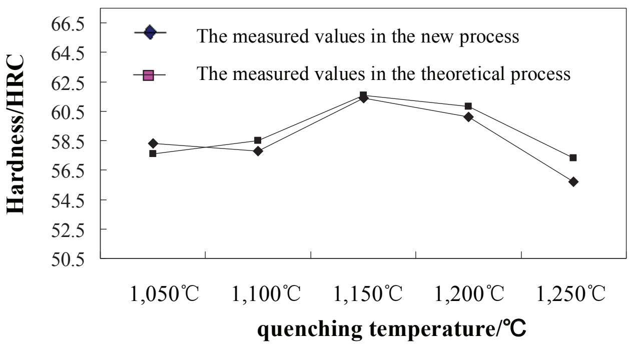

Figure 9. Comparison of measured values of hardness of high-speed steel W18Cr4V after two and three tempering processes respectively.

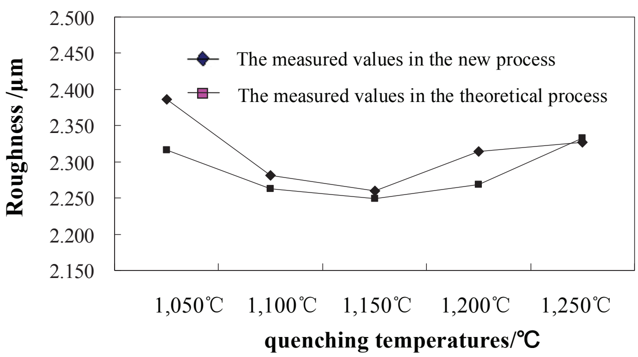

Figure 10. Comparison of the measured values of surface roughness of high-speed steel W18Cr4V after two and three tempering processes respectively.

The program of group 1 takes a total of 4.5 h whereas that of group 2 takes a total of 7.5 h. Obviously, the time spent on the new process of group 1 is only 60 % of that on the traditional process of group 2 and less energy is consumed.

ENERGY-SAVING EFFECT

The improved process parameters, the quenching temperature is improved from 1,250 °C to 1,150 °C, tempering temperature is improved from 570 °C, three times, to for (300 °C–400 °C), one time, 570 °C, one time. Quenching furnace heating power of 5 KW, tempering furnace heating power is 2.5 KW.

The new technology to save electricity is:

(22.5 - 14.2) / 22.5 = 36.9 %

NEW TECHNOLOGY AND PROCESS THEORY OF MOLD IN PERFORMANCE COMPARISON

Table 7 compares the properties from the heat process under the new technology and the theoretical process, of which:

Program 1:
quenching at 1,150 °C, tempering at 350 °C +570 °C, respectively is adopted.

Program 2:
quenching at 1,250 °C, tempering at 570 °C, three times is adopted.

In contrast, we can believe that almost the same for between the new technology and the theory to the mold hardness, roughness. It proves that the improved heat treatment process can meet the requirements.

ACTUAL EFFECT AND EXTEND THE APPLICATION

The author has tried the optimization of heat process of double tempering by designing and manufacturing die-casting molds many times and achieved good results in punching parts of military micro motors and small motors using those molds.

Conclusion & discussion

The volume of retained austenite has significant influence on the hardness, wear resistance and surface roughness of high-speed steel W18Cr4V. The relation between the values of hardness and volumes of retained austenite forms a quadratic open downward curve.

The quenching and tempering temperatures have significant influence on the volume of retained austenite in the high speed steel W18Cr4V. The higher the quenching temperature is the more the retained austenite, the higher the tempering temperature the less the retained austenite.

When high-speed steel W18Cr4V is quenched at 1,150 °C and tempered once at 300 °C–400 °C and another time at 570 °C, the volume of retained austenite will be 30 %–55 % (vol %) and high surface hardness, grindability and low surface roughness will be achieved.

For the die-casting molds, the highest hardness and the lowest surface roughness will be achieved at the quenching temperature of 1,150 °C and tempering temperature of 300 °C–400 °C for the first time and 570 °C the other time.

The time spent on the new heat process is 60 % of that on the theoretical process. The lower quenching and tempering temperatures are needed in the new process, which reduces electric energy consumption. That can reduce electric power consumption by nearly 40 %.

In this paper, energy consumption data (Table 6) is the experimental data (in lab). Heat treatment process parameters have been applied in the mold processing.

Table 5. Comparison of times spent on the heat process under the new technology and the traditional process. Unit: h.

Technics / Group	quenching	tempering		
		1st	2nd	3rd
1	1.5	2	1	
2	1.5	2	2	2

Table 6. Comparison of energy consumption spent on the heat process under the new technology and the theoretical process. Unit: KW·h.

Program	The new technology of electric consumption	The theory process of electric consumption
Quenching	(1,150 °C/1,250 °C) × 5 × 1.5 = 6.9	5 × 1.5 = 7.5
Tempering	(350 °C/570 °C) × 2.5 × 1 = 2.3 (570 °C/570 °C) × 2.5 × 2 = 5.0	2.5 × 6 = 15
Totally	14.2	22.5

Table 7. Comparison of properties from the heat process under the new technology and the theoretical process.

Program	Hardness HRC	Surface roughness R_{yavg} /μm
1	63.9	2.259
2	58.6	2.354

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