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Optimization in Spheroidized Annealing of Two AISI 1022 Low Carbon Steels Used in Bolt Industry

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Abstract - The quality of spheroidize annealed steel wire affects the forming quality of screws. Various parameters affect the quality of spheroidized annealing such as spheroidized annealing temperature, prolonged heating time, furnace cooling time and flow rate of nitrogen. The effects of spheroidized annealing parameters affect the quality characteristics of wires, such as tensile strength and hardness. In this study, Taguchi method is used to obtain optimum spheroidized annealing conditions to improve the mechanical properties of two AISI 1022 low carbon steel wires, W_A and W_B. The main quality characteristic of spheroidized annealing wires is tensile strength with a target value of 39 kgf/mm^2. It is revealed experimentally that, for wire W_A, spheroidized annealing temperature and prolonged heating time are the significant factors, however, for wire W_B, spheroidized annealing temperature and furnace cooling time are the significant factors to influence the mechanical properties of steel wires.

***Keywords*:** spheroidized annealing, forming quality, tensile strength, Taguchi method.

1. Introduction

Spheroidizing provides the needed ductility for cold heading [1]. Spheroidization of cementite lamellae through spheroidize annealing improve the ductility of steel [2-4]. O'Brien and Hosford [5] investigated spheroidization of medium carbon steels, AISI 1541 and AISI 4037, used in the bolt industry with two process cycles, intercritical cycle and subcritical cycle. Das et al.[6] studied a cold heading quality steel wire obtained from two different sources, which are used for manufacturing one automobile fastener. Both wires are spheroidize annealed and phosphate coated. The microstructures, compositions, and mechanical were evaluated to establish the characteristics of a good stock wire that can improve the tool life leading to higher productivity and product quality. The spheroidizing treatment consumes the most time of bolt manufacture. Commercial spheroidization of coils usually takes many hours.

For wire-manufacturers, some companies simply purchase steel wires, cold reduce, and spheroidize them before selling to bolt manufacturers; some companies are bolt manufacturers who spheroidize the wires themselves before cold heading. Most companies were using a subcritical process, simply heating to below the lower critical and holding.

A cold heading quality AISI 1022 steel wire is usually used to manufacture self drilling screw and tapping screw. Wires are obtained from two sources identified as W_A (ϕ5.5mm) and W_B (ϕ6.5mm). The quality of wire W_A is better than wire W_B, while wire W_B is cheaper. Before cold heading, both of these wires are spheroidize annealed after drawing wire coil to the same wire size with section-area reductions of about 60% for wire W_A and about 70% for wire W_B, respectively.

The quality of spheroidize annealed wire affects the forming quality of screws. Various parameters affect the quality of spheroidized annealing such as spheroidized annealing temperature, prolonged heating time, furnace cooling time and flow rate of nitrogen (protective atmosphere). The effects of spheroidized annealing parameters affect the quality characteristics of wires, such as tensile strength, hardness. In this study, to improve the mechanical properties of two AISI 1022 low carbon steel wires, Taguchi method is used to optimize spheroidized annealing conditions.

2. Optimal Experiment

Two AISI 1022 low carbon steel wires were investigated in this research. Their chemical compositions are listed in Table 1.

Table 1: Chemical composition of AISI 1022 low carbon steel wires (wt.%).

Wire	C	Mn	P	S	Si	Ni	Cr	Cu	Ti	Al
W_A	0.22	0.76-0.77	0.012-0.013	0.002-0.008	0.02-0.04	0.01-0.03	0.04	0.01-0.08	-	0.030-0.034
W_B	0.19-0.22	0.73-0.79	0.012-0.029	0.003-0.010	0.03-0.07	0.00-0.01	-	0.01-0.02	0.0570-0.0754	0.0291-0.0494

Four process parameters with three levels listed in Table 2 were selected as the experimental factors in this study. Every factor had three levels to spheroidize wires to evaluate the mechanical properties of wires. The parameters of Level 2 were the original spheroidized annealing process parameters for wires W_A and W_B. The orthogonal array table, $L_9(3^4)$, is used as experimental design for these four factors.

Table 2: Experimental factors and their levels for L_9 orthogonal array.

Factor		Level 1	Level 2	Level 3
A	Spheroidized annealing temperature (°C)	695	700	705
B	Flow rate of nitrogen (Nm^3/hr)	5	10	15
C	Furnace cooling time (hr)	7.5	8.0	8.5
D	Prolonged heating time (hr)	7	7.5	8

In this study, the main quality characteristic of spheroidized annealing wires is tensile strength with a target value of 39 kgf/mm^2. Each test result, including ten specimens, followed by each fabricated process and transformed to S/N ratio (signal to noise ratio). The S/N ratio for the nominal-the-best response is [7]

$$S/N = -10\log[(\mu - m)^2 + S^2] \qquad (1)$$

Where μ is average of each test result, *m* is target value, and *S* is standard deviation.

Analysis of variance (ANOVA) is an effective method to determine the significant factors and the optimal fabrication conditions to obtain optimal quality. For Taguchi method, the experimental error is evaluated with ANOVA to carry out the significance test of factors. The nature of interaction between factors is considered as experimental error [7]. As the effect of a factor in comparison to the experimental error is sufficiently large, it is identified a significant factor. The confidence level of a factor is evaluated with experimental error to identify the significant factor influenced the material property of spheroidized annealing wire.

3. Results and Discussion

The results of tensile strength (average and standard deviation) and S/N ratio respectively for wires W_A and W_B are shown in Table 3. The tensile strength varies from 37.6 to 41.5 kgf/mm2 for wire WA, and varies from 37.5 to 42.8 kgf/mm2 for wire WB. The deviation of the test results for wire WA is obviously smaller than wire WB.

3.1. Wire WA

With analysis of variance (ANOVA), the confidence levels listed in Table 4 might identify the significant factor influenced the material property of wire WA. The contribution of a factor is the percentage of sum of square (SS), that is, the percentage of the factor variance to the total quality loss [7]. The effect of a factor may be pooled to error if its confidence level or contribution is relatively small. For S/N ratio, the contribution of spheroidized annealing temperature (A) is 87.0% higher than other factors. The contribution of prolonged heating time (D) is 10.2%, which is the second one.

With pooling of errors, the confidence levels are 99.9% and 95.4% respectively for spheroidized annealing temperature (A) and prolonged heating time (D), Therefore, both factors, especially the spheroidized annealing temperature, are significant which may be used to decrease the variance [7]. The factor of furnace cooling time (C) is not significant for S/N ratio, but is significant (100% confidence level) for quality characteristic, which may be used as an adjustment factor. The factor of flow rate of nitrogen (B) is not significant for either S/N ratio or quality characteristic, which may be used to reduce the cost.

Table 3: Tensile test results and S/N ratio for each experimental factor.

	A: Spheroidized annealing temperature (°C)	B: Flow rate of nitrogen (Nm^3/hr)	C: Furnace cooling time (hr)	D: Prolonged heating time (hr)	Wire W_A			Wire W_B		
					Tensile strength (kgf/mm^2)	*S*	S/N ratio	Tensile strength (kgf/mm^2)	*S*	S/N ratio
L1	695	5	7.5	7.0	40.5	1.73	-7.27	42.0	2.71	-12.14
L2	695	10	8.0	7.5	37.6	1.93	-7.55	37.6	1.93	-7.55
L3	695	15	8.5	8.0	37.9	1.53	-5.46	42.8	2.38	-13.04
L4	700	5	8.0	8.0	40.5	1.45	-6.23	37.8	0.85	-3.54
L5	700	10	8.5	7.0	40.7	1.75	-7.65	38.9	3.00	-9.56
L6	700	15	7.5	7.5	41.5	1.35	-9.04	37.5	1.99	-7.97
L7	705	5	8.5	7.5	38.5	1.09	-1.45	38.0	2.27	-7.89
L8	705	10	7.5	8.0	39.7	0.82	-0.41	37.7	2.29	-8.39
L9	705	15	8.0	7.0	39.8	1.11	-2.88	37.5	1.02	-5.38

Table 4: Variance analysis table for wire W_A. (a) Quality characteristic; (b) S/N ratios.

(a)

Factor	SS	DOF	Var	F	Confidence	Contribution
A	75.17	2	37.59	15.93	100.0%	22.5%
B	4.89	2	2.45	1.04	64.1%	1.5%
C	39.72	2	19.86	8.42	100.0%	11.9%
D	23.02	2	11.51	4.88	99.0%	6.9%
Error	191.15	81	2.36	S_{exp} = 1.54		
Total	333.96	89	*At least 99.0% confidence level			

Pooling of errors

Factor	SS	DOF	Var	F	Confidence	Significance
A	75.17	2	37.59	15.91	100.0%	Yes
B	Pooled					
C	39.72	2	19.86	8.41	100.0%	Yes
D	23.02	2	11.51	4.87	99.0%	Yes
Error	196.04	83	2.36	S_{exp} = 1.54		
Total	333.96	89	*At least 99.0% confidence level			

(b)

Factor	SS	DOF	Var	Contribution
A	64.27	2	32.13	87.0%
B	1.06	2	0.53	1.4%
C	1.02	2	0.51	1.4%
D	7.54	2	3.77	10.2%
Total	73.88	8		100.0%

Pooling of errors

Factor	SS	DOF	Var	F	Confidence	Significance
A	64.27	2	32.13	62.05	99.9%	Yes
B	Pooled					
C	Pooled					
D	7.54	2	3.77	7.28	95.4%	Yes
Error	2.07	4	0.52	S_{exp} = 0.72		
Total	73.88	8	*At least 95.0% confidence level			

SS: sum of square; DOF: degree of freedom; Var: variance; F: F-test; S_{exp}: experimental error.

Fig. 1 presented the factor response diagrams of four factors respected to quality characteristic and S/N ratio. It is revealed that, for the four factors, the original levels were not the optimum fabricating parameters to obtain the target tensile strength for wire W_A. Obviously for the significant factors, spheroidized annealing temperature (A) and prolonged heating time (D), the optimum conditions are respectively A3 (spheroidized annealing temperature, 705°C), D3 (prolonged heating time, 8 hr). The S/N ratios of the other two factors, flow rate of nitrogen (B) and furnace cooling time (C), are relatively small, as shown in Fig. 1(b). The quality characteristic of flow rate of nitrogen (B), as shown in Fig. 1(a), is relatively small, too, which can be a factor to reduce the cost, therefore, B1 (flow rate of nitrogen, 5 Nm^3/hr) is chosen as the optimum condition. However, the quality characteristic of furnace cooling time (C) is obviously important, as shown in Fig. 1(a), which can be a adjustment factor, and C2 (furnace cooling time, 8 hr) is chosen as the optimum condition.

In order to confirm the robust design of results, wire W_A was fabricated followed the optimum conditions. Fig. 2 shows the original and optimum probability distributions respectively for tensile strength and hardness of wire W_A. The optimum average of tensile strength is 39.34 kgf/mm^2, which is closer than the original one, while, the deviation decreases about 30.6% as comparing with the original result. The optimum average of hardness 131.40 HV is obviously decreased as compared to the original averaged hardness 141.30 HV, and also the deviation decreases about 43.5% as comparing with the original result. The optimum results improve the ductility and the strength of wire W_A, and so the formability is improved.

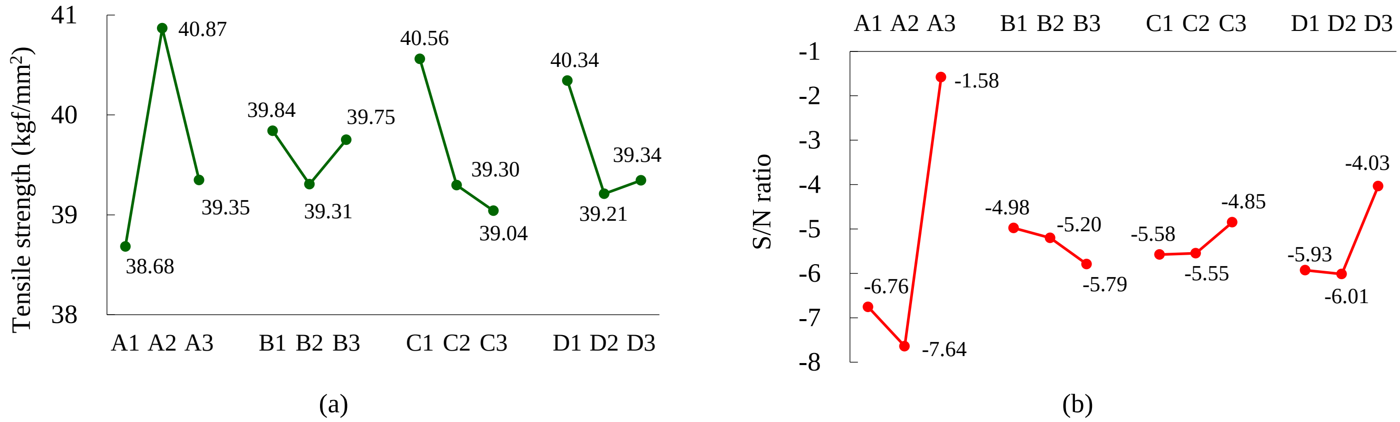


Fig. 1: The factor response diagrams for wire W_A. (a) Quality characteristic; (b) S/N ratios.

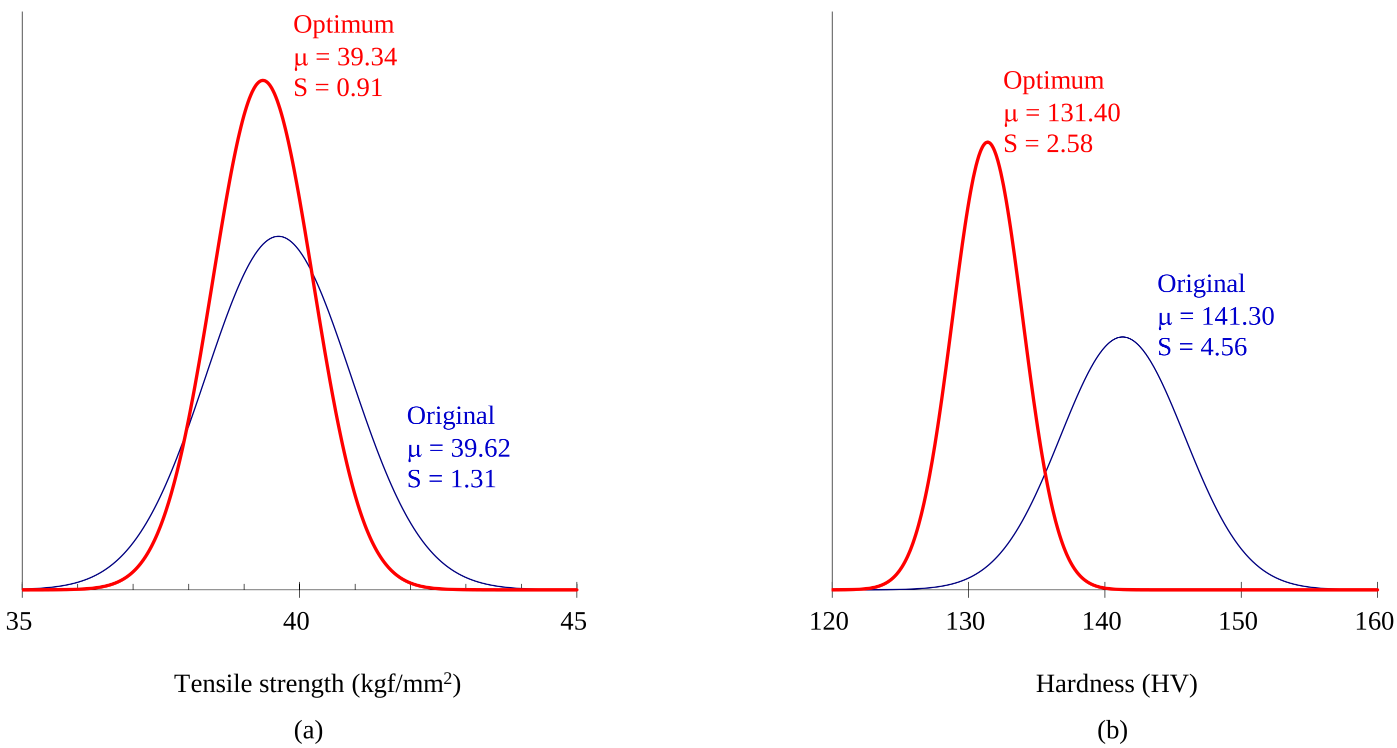


Fig. 2: The probability distribution diagrams for wire W_A. (a) Tensile strength; (b) Hardness.

3.2. Wire W_B

With analysis of variance (ANOVA), the confidence levels listed in Table 5 might identify the significant factor influenced the material property of wire W_B. For S/N ratio, the contribution of furnace cooling time (C) is 54.3% higher than other factors. The contribution of spheroidized annealing temperature (A) is 40.6% which is the second one. With pooling of errors, the confidence levels are 98.7% and 99.3% respectively for spheroidized annealing temperature (A) and furnace cooling time (C). Therefore, both factors are significant which may be used to decrease the variance [7]. The factor of prolonged heating time (D) is not significant for S/N ratio, but is significant (99.5% confidence level) for quality characteristic, which may be used as an adjustment factor. The factor of flow rate of nitrogen (B) is not significant for either S/N ratio or quality characteristic, which may be used to reduce the cost.

Table 5: Variance analysis table for wire W_B. (a) Quality characteristic; (b) S/N ratios.

(a)

Factor	SS	DOF	Var	F	Confidence	Contribution
A	172.62	2	86.31	16.70	100.0%	22.7%
B	28.32	2	14.16	2.74	92.9%	3.7%
C	80.48	2	40.24	7.78	99.9%	10.6%
D	60.56	2	30.28	5.86	99.6%	8.0%
Error	418.70	81	5.17	S_{exp} = 2.27		
Total	760.68	89	*At least 99.0% confidence level			

Pooling of errors

Factor	SS	DOF	Var	F	Confidence	Significance
A	172.62	2	86.31	16.02	100.0%	Yes
B	Pooled					
C	80.48	2	40.24	7.47	99.9%	Yes
D	60.56	2	30.28	5.62	99.5%	Yes
Error	447.03	83	5.39	S_{exp} = 2.32		
Total	760.68	89	*At least 99.0% confidence level			

(b)

Factor	SS	DOF	Var	Contribution
A	28.73	2	14.36	40.6%
B	1.37	2	0.68	1.9%
C	38.38	2	19.19	54.3%
D	2.26	2	1.13	3.2%
Total	70.74	8		100.0%

Pooling of errors

Factor	SS	DOF	Var	F	Confidence	Significance
A	28.73	2	14.36	15.82	98.7%	Yes
B	Pooled					
C	38.38	2	19.19	21.15	99.3%	Yes
D	Pooled					
Error	3.63	4	0.91	S_{exp} = 0.95		
Total	70.74	8	*At least 95.0% confidence level			

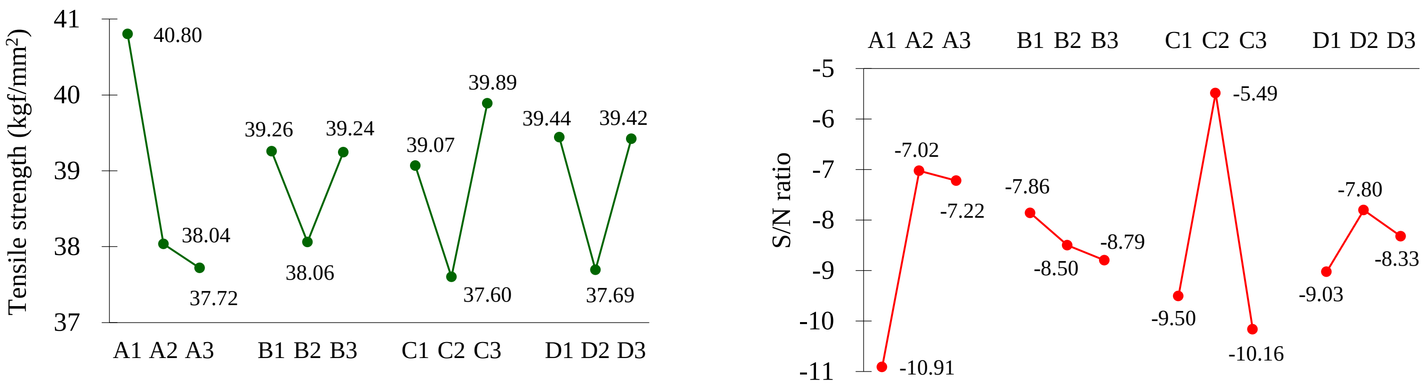
SS: sum of square; DOF: degree of freedom; Var: variance; F: F-test; S_{exp}: experimental error.

Fig. 3 presented the factor response diagrams of four factors respectively respected to quality characteristic and S/N ratio. It is revealed that, for the four factors, the original levels, except flow rate of nitrogen (B), were the optimum fabricating parameters to obtain the target tensile strength for wire W_B. For the significant factors, spheroidized annealing temperature (A) and furnace cooling time (C), the optimum conditions are respectively A2 (spheroidized annealing temperature, 700°C), C2 (furnace cooling time, 8 hr). The S/N ratios of the other two factors, flow rate of nitrogen (B) and prolonged heating time (D), are relatively small, as shown in Fig. 3(b). The quality characteristic of flow rate of nitrogen (B), as shown in Fig. 3(a), is relatively small, too, which can be a factor to reduce the cost, therefore, B1 (flow rate of nitrogen, 5 Nm^3/hr) is chosen as the optimum condition. However, the quality characteristic of prolonged heating time (D) is relatively important, as shown in Fig. 3(a), which can be a adjustment factor, and D2 (prolonged heating time, 7.5 hr) is chosen as the optimum condition.

To confirm the robust design of results, wire WB was fabricated followed the optimum conditions. Fig. 4 shows the original and optimum probability distributions respectively for tensile strength and hardness of wire WB. The optimum average of tensile strength is 39.60 kgf/mm2, which is slightly larger than the target tensile strength, while, the deviation increases about 26.9% as comparing with the original result. The optimum average of hardness 138.90 HV is increased as compared to the original averaged hardness 138.80 HV, although the deviation decreases about 34.8% as comparing with the original result. The optimum results obviously do not improve the ductility of wire WA. The quality of strength is not improved, either, because of the increase of deviation. Therefore, the formability of wire WB is not improved through this optimum operation.

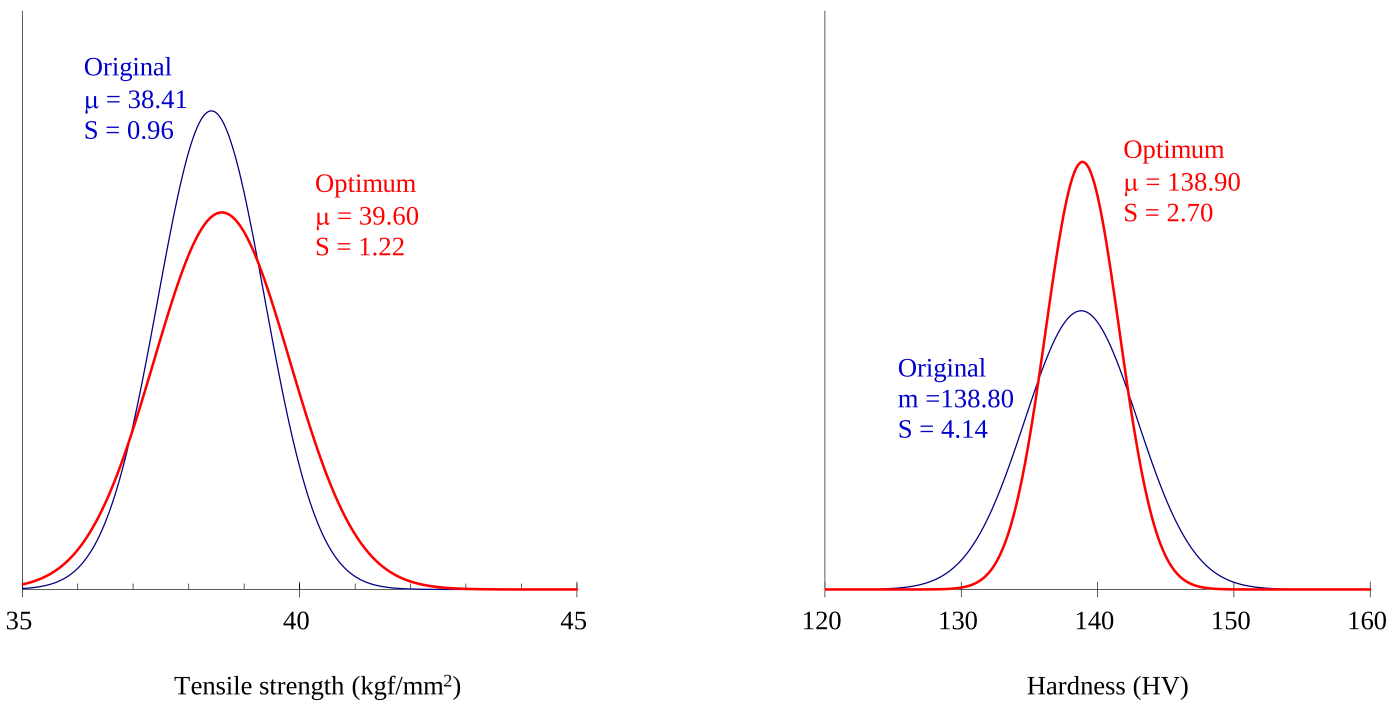
Through the optimization in spheroidized annealing of two AISI 1022 low carbon steels, WA and WB, both of the averaged tensile strengths are close to the target tensile strength, and the quality is improved for wire WA, but not for wire WB. The averaged hardness is decreased for wire WA, and the quality is improved, so the formability is also improved.

However, for wire WB, instead of decreasing, the averaged hardness is greater than wire WA, therefore, the formability of wire WB is not improved. This result is due to the composition of titanium in wire WB, as listed in Table 1, since adding 0.015wt% titanium could increase the hardenability of steel [8] and may cause excess inclusion to damage the surface quality and to reduce the formability [9].



(a) (b)

Fig. 3: The factor response diagrams for wire W_B. (a) Quality characteristic; (b) S/N ratios.



(a) (b)

Fig. 4: The probability distribution diagrams for wire W_B. (a) Tensile strength; (b) Hardness.

4. Conclusion

The quality of spheroidize annealed steel wire affects the forming quality of screws. Four factors affect the quality of spheroidized annealing such as spheroidized annealing temperature, prolonged heating time, furnace cooling time and flow rate of nitrogen (protective atmosphere). The effects of spheroidized annealing parameters affect the quality characteristics of wires, such as tensile strength, hardness. In this study, Taguchi method is used to obtain optimum spheroidized annealing conditions to improve the mechanical properties of two AISI 1022 low carbon steel wires, W_A and W_B. The main quality characteristic of spheroidized annealing wires is tensile strength with a target value of 39 kgf/mm^2. It is revealed experimentally that, for wire W_A, spheroidized annealing temperature (A) and prolonged heating time (D) are the significant factors; the optimum conditions are spheroidized annealing temperature as 705°C, prolonged heating time as 8 hr, furnace cooling time as 8 hr, and flow rate of nitrogen as 5 Nm^3/hr; and the optimum averaged tensile strength is 39.34 kgf/mm^2, the optimum averaged hardness is 131.40 HV. The qualities of mechanical properties are obviously improved, and so the formability. For wire W_B, spheroidized annealing temperature (A) and furnace cooling time (C) are the significant factors; the optimum conditions are spheroidized annealing temperature as 700°C, prolonged heating time as 7.5 hr, furnace cooling time as 8 hr, and flow rate of nitrogen as 5 Nm^3/hr; and the optimum averaged tensile strength is 39.60 kgf/mm^2, the optimum averaged hardness is 138.80 HV. However, the qualities of mechanical properties are not evidently improved, neither the formability, which may be due to the composition of titanium. These results may be used as a reference for wire-manufacturers.

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