Effect of cold rolling and ageing treatment on the interface morphology and mechanical properties of maraging steel/medium-entropy alloy multilayer composite

Baoxi Liu1,2,3, Zhuoyu Li*, Cuixin Chen1,2,3, Weibing Guo1,2,3, Bingchen Yang1, Bo Yang1, Kailun Liu1,*, Yifei Ge1 and Fuxing Yin1,2,3

1 School of Materials Science and Engineering, Hebei University of Technology, Tianjin 300130, People’s Republic of China
2 Tianjin Key Laboratory of Materials Laminating Fabrication and Interface Control Technology for Advanced Materials, Hebei University of Technology, Hebei University of Technology, Tianjin 300130, People’s Republic of China
3 Research Institute for Equipment Materials, Hebei University of Technology, Tianjin 300130, People’s Republic of China

E-mail: liubauxiliubo@126.com

Keywords: multilayer steel, cold rolling, ageing treatment, interface instability mechanism, CoCrNi medium-entropy alloy

Abstract

The cold rolling and subsequent ageing treatment of hot-rolled 18Ni300/CoCrNi multilayer composites were carried out to analyse the high work hardening ability of medium-entropy alloy (CoCrNi alloy) and the ageing precipitate strengthening effect of maraging steel (18Ni300). The results show that with the rise of cold rolling reduction, the ratio constitute layer and interface transition layer thicknesses are gradually decreased, and the interface shape changes from a wavy state, which is mainly due to the serious work hardening of the CoCrNi layer. Meanwhile, the tensile strength continuously increased. When the multilayer composite is cold-rolled to 0.5 mm, its tensile strength reaches more than 2 GPa, and the fracture elongation remains at approximately 7%. After ageing, the superior tensile strength is as high as 2825 MPa, which is attributed to the synergistic effect of work hardening, precipitation strengthening and strong interface bonding strengthening.

1. Introduction

Achieving the superior strength and toughness of metal structural materials is an unremitting goal pursued by materials workers worldwide throughout their lives. In general, strength and toughness are not compatible, due to the inversion phenomenon of strength-toughness. Namely, increasing the strength will often lead to a decrease in ductility and toughness. In Homer’s ‘The Iliad’, Achilles’s shield is made of a magical material, which is comprised of two layers of bronze, two tiers of tin, and one of gold. The sequence of laminates possessed the following structure: bronze/tin/gold/tin/bronze. Interestingly, the superior interface toughness of the laminate was demonstrated by the fact that Aeneas’s spear penetrated the first and second layers but became stuck in the gold layer [1–3].

Recently, with further research, it has been discovered that the introduction of multilayer interfaces in metal materials not only serves as aesthetic design but this special structure also causes many unexpected effects. For example, M. Pozuelo [4] successfully fabricated multilayer steel containing 70 layers of alternating ultrahigh carbon steel and low carbon steel sheets by roll bonding. By three-point bending and shear testing, it was found that the impact toughness of the multilayer steels was 70 and 1.5 times higher than that of ultrahigh carbon steel and mild carbon steel, respectively. Tetsuo Oya et al [5] investigated the tensile behaviours of hot-rolled multilayer WT780C/SUS304 steels and showed that a soft tough SUS304 layer and strong interface bonding can delay the localized necking and plastic instability of the hard layer during the tensile deformation process, which effectively improves the ductility of the multilayer steel [6, 7]. Toshihiko Koseki et al [8] oversaw a background for the development, design, fabrication, properties, and applications of multilayer composites and found that multilayer steel has outstanding comprehensive mechanical properties due to interfacial delamination and
tunnel crack toughening mechanisms. In addition, many studies have shown that multilayer composites are much better than monolithic metal materials in terms of their physical, chemical and mechanical properties [9, 10].

Maraging steel is widely used in the aerospace and military industries due to its superior strength, good weldability and formability, which are attributed to the ageing precipitation of Mo, Ti elements and maraging steel as well as to its ultralow carbon content. However, the low strain hardening exponent and low ductility of maraging steel greatly limit its further development and application. However, medium-entropy alloys have high ductility/toughness and high work hardening ability [11–14]. In the present work, we demonstrate that the multilayer structure design of maraging steel and medium-entropy alloy using vacuum hot rolling can compensate for the low ductility and low work hardening ability of maraging steel. These multilayer composites improve the strain hardening capability and ductility of maraging steel and improve the yield strength of the CoCrNi medium-entropy alloy, realizing comprehensive mechanical properties. However, after hot rolling, the tensile strength of maraging steel/medium-entropy alloy multilayer composites cannot compete with that of ultrahigh strength maraging steel, which limits the commercial use of maraging steel/medium-entropy alloy multilayer composites. To further improve the yield strength of medium entropy alloys and the strain hardening ability of maraging steel, the changes in the layer and interface morphologies, mechanical properties and the effects of ageing treatment on the mechanical properties of cold rolled multilayer composites were studied by cold rolling and ageing treatment [15, 16]. This work will provide a theoretical and experimental framework for the strengthening and toughening of multilayer composites.

--

Figure 1. The fabrication process and experimental setup of 18Ni300/CoCrNi multilayer composites. (a) The stacking sheets were put into a metal box; (b) vacuum and seal; (c) vacuum hot roll bonding; (d) rolling mill; (e) scanning electron microscopy; (f) electron probe microanalysis; (g) tensile machine; (h) billet; (i) dimensional drawing of tensile specimens.
2. Experimental

The manufacturing method and experimental setup of the multilayer composite are shown in figure 1. Thirty metal sheets with diameters of 60 mm and thicknesses of 0.5 mm were cut from 18Ni300 and CoCrNi blocks. Their chemical compositions are shown in table 1. The metal sheets were burnished with abrasive paper. The 18Ni300 and CoCrNi metal sheets were alternately stacked to 60 layers. IV. The metal sheets were put into a metal box, and carbon steel plates were welded to the metal box. V. A vacuum pump was used to keep the vacuum in the box below $10^{-2}$ pa. VI. After the hollow pipe was heated, it was quickly sealed with a hydraulic tong. VII. The metal box containing multilayer stacking sheets was heated to 1100 °C for 40 min to ensure that the base sheets were completely austenitized. VIII. The billet was sent to the hot rolling mill for multiple passes until the material thickness reached 4 mm, with a total rolling reduction ratio of 86.7%, and then air cooled to room temperature, which is named ht. The material was cut from the middle section along the rolling direction,

![Figure 2](image2.png)

**Figure 2.** The preparation process of 18Ni300/CoCrNi multilayer composites.

![Figure 3](image3.png)

**Figure 3.** SEM and EPMA mapping microstructure of 18Ni300/CoCrNi multilayer composites with different cold rolling reduction ratios. (a) cr3; (b) cr2; (c) cr1; (d) cr0.5.

| Table 1. Chemical compositions of raw 18Ni300 and CoCrNi medium-entropy alloy. |
|-----------------|--------|--------|------|--------|--------|--------|
| Element         | C      | Ni     | Co   | Cr     | Mo     | Ti     | Al   | Fe    |
| 18Ni300         | $\leq0.03$ | 18–19  | 8.5–9.5 | —     | 4.6–5.2 | 0.5–0.8 | 0.1  | bal.  |
| CoCrNi          | —     | 34.61  | 34.74 | 30.65  | —     | —     | —    | —    |

2. Experimental

The manufacturing method and experimental setup of the multilayer composite are shown in figure 1:1. Thirty metal sheets with diameters of 60 mm and thicknesses of 0.5 mm were cut from 18Ni300 and CoCrNi blocks. Their chemical compositions are shown in table 1. The metal sheets were burnished with abrasive paper. The 18Ni300 and CoCrNi metal sheets were alternately stacked to 60 layers. IV. The metal sheets were put into a metal box, and carbon steel plates were welded to the metal box. V. A vacuum pump was used to keep the vacuum in the box below $10^{-2}$ pa. VI. After the hollow pipe was heated, it was quickly sealed with a hydraulic tong. VII. The metal box containing multilayer stacking sheets was heated to 1100 °C for 40 min to ensure that the base sheets were completely austenitized. VIII. The billet was sent to the hot rolling mill for multiple passes until the material thickness reached 4 mm, with a total rolling reduction ratio of 86.7%, and then air cooled to room temperature, which is named ht. The material was cut from the middle section along the rolling direction,
Figure 4. EPMA element distribution along the interface boundary of 18Ni300/CoCrNi multilayer composites. (a)-(d) cold rolling; (e)-(h) ageing treatment.
and 5 small strips of 50 mm × 20 mm were used for the following process. Herein, one small strip was aged (485 °C for 4 h) and named IX. The remaining 4 small strips were subjected to different cold-rolling deformation ratios along the raw rolling direction until the material thickness reached 3 mm, 2 mm, 1 mm, and 0.5 mm, which were recorded as cr3, cr2, cr1, and cr0.5, respectively. X. A part of the cold-rolled steel plate cr3, cr2, cr1, cr0.5 was cut for ageing treatment (the ageing temperature of 18Ni300/CoCrNi multilayer composite material is 485 °C for 4 h), and the treated steel plates were marked as cr3 age, cr2 age, cr1 age and cr0.5 age, respectively. The preparation process of the multilayer composites is shown in figure 2.

Electron probe microanalysis (EPMA, JEOL 8530F) and scanning electron microscopy (SEM, JEOL 7100F) were used to observe the interface shape, the types of precipitates at the interface, and the thickness of the diffusion layer. A microhardness tester (HMV-G-XY-S) was used to measure the specimen hardness at 490.7 mN and held pressure for 10 s. A UTM5100G tensile machine was used to measure the tensile properties of the specimens. As shown in figure 1(i), the initial strain rate of the tensile specimens was 1.67 × 10⁻³ s⁻¹.

3. Results and discussion

3.1. Microstructure

Figures 3(a)–(d) shows the SEM and EPMA microstructure 18Ni300/CoCrNi multilayer composites of cr3, cr2, cr1 and cr0.5. As seen from the figure, when the cold rolling reduction ratio is low, the interface shape is flat, indicating that the deformation behaviour between 18Ni300 and CoCrNi is consistent at the beginning stage, and it presents a high uniform plastic deformation capacity. However, with the increase in the cold rolling reduction ratio, the interface becomes increasingly uneven and wavy. When the cold rolling reduction ratio rise to 75%, the CoCrNi layer has slight localized necking. When the cold rolling reduction ratio continues to rise to 87.5%, an obvious localized necking phenomenon occurs in the CoCrNi layer. Herein, at the high cold rolling deformation stage, the CoCrNi layer shows higher hardness and severe strain concentration behaviour than the 18Ni300 layer, leading to obvious plastic deformation instability and localized necking behaviours [17–19]. Therefore, with the increase in the cold rolling reduction ratio, the deformation of the 18Ni300 layer and CoCrNi layer becomes increasingly uncoordinated, and the wave-like interface and localized necking become more serious. M. Reihanian and M. Naseri used analytical models to predict that the critical strain for necking and fracture increased with increasing thickness ratio, strength coefficient ratio and work-hardening exponent of the hard phase during the cumulative roll bonding (ARB) of metallic multilayer composites [20].

Figure 4(a)–(d) shows the EPMA elements of the distribution along the interface boundary of the 18Ni300/CoCrNi multilayer composite. There is a small amount of Al₂O₃ and TiN at the interface of multilayer composites, which are generated because Al and Ti on the side of maraging steel have strong chemical activity in the heating and insulation process before hot rolling, and they easily react with oxygen and nitrogen in the air [21]. This phenomenon shows that the oxidation and nitriding on the surface of maraging steel cannot be prevented in a 10⁻² vacuum state. This demonstrates that as the cold rolling reduction ratio boosts, the size of the alumina Al₂O₃ around the interface gradually decreases. When the cold rolling reaches 0.5 mm, there is almost no alumina along and around the interface, and the thickness of the Ti segregation zone also decreases gradually. This may be because during the cold rolling process, the interface oxides break into many dispersed fragments.
due to rolling force and frictional shear stress and evenly dissolve into the metal matrix. Meanwhile, cold rolling deformation will also cause the evolution of the transition layer, making the Ti segregation zone thinner.

Figures 4(e)–(h) shows that at the low ageing temperature of 485°C for 4 h, there is no obvious element diffusion behaviour, and more oxides appear. The Ti segregation behaviour on the maraging steel does not change, which shows that the ageing treatment has no significant effect on the interface element distribution and diffusion behaviour.

The cold rolling deformation may lead to a decrease in the interface transition layer, which shows an interface enhancement effect. Therefore, during the hot rolling process, element diffusion along the interface will decrease the mechanical properties of the multilayer composites [10]. To gain superior mechanical properties, a narrower transition layer is needed. Figure 5 shows the interface element diffusion distances of multilayer composites with different cold-rolling and ageing states. The values are listed in table 2. With a rise in the cold rolling reduction ratio, the transition distances of Fe, Co, Cr, and Ni gradually decrease. When the cold rolling reaches 0.5 mm, the thickness of the transition zone decreases to approximately 2 μm. However, it is thick enough to maintain certain interface bonding. Table 2 shows that the diffusion distance of Co increases significantly after ageing, while the ageing process has little effect on the diffusion of the other three elements.

### 3.2. Mechanical properties

Figure 6(a) shows the effect of the cold rolling reduction ratio of the 18Ni300/CoCrNi multilayer composites on the hardness values of the 18Ni300 and CoCrNi layers. The hardness value of the CoCrNi layer after hot rolling is lower than that of the 18Ni300 layer. After cold rolling, the hardness values of the two layers improve, and the hardness value of the CoCrNi layer improves faster than that of the 18Ni300 layer. When cold rolled to 3 mm (25%), the hardness value of the CoCrNi layer exceeds that of the 18Ni300 layer. Herein, the soft and hard layers in the multilayer composites change, and the CoCrNi layer begins to serve as a hard phase layer. Variations in hardness can be used to explain the uneven local necking phenomenon noted in figure 3(d). The necking phenomenon is caused by the difference in hardening rates and flow stresses between the 18Ni300 layer and CoCrNi layer. With the rise in the cold rolling reduction ratio, the work hardening of CoCrNi becomes increasingly severe, and the difference in hardness between the two layers gradually increases. Hence, the CoCrNi layer shows localized necking, resulting in uneven deformation and periodic necking of the CoCrNi layer as a whole. During the cold rolling process, the hard (CoCrNi) and soft (18Ni300) layers produce strain incompatibility at the interfaces, resulting in a wavy interface [10, 20]. Figure 6(b) shows the hardness variation of the 18Ni300 layer and the CoCrNi layer after ageing treatment. The hardness value of the 18Ni300 layer significantly increased, and it became a hard layer rather than a CoCrNi layer. In our previous work [21], we show that a nanosized η-Ni3Ti phase precipitates in the 18Ni300 layer after ageing, which strengthens the 18Ni300 layer. Yong Lian et al also uncovered the η-Ni3Ti phase with a length of ~20 nm and a width of ~5 nm in maraging steel ageing after cold rolling [22].

![Figure 6. Microhardness distribution of 18Ni300/CoCrNi multilayer composites. (a) cold rolling; (b) ageing treatment.](image)

| Distance (μm) | cr3 | cr2 | cr1 | cr0.5 | cr3 age | cr2 age | cr1 age | cr0.5 age |
|--------------|-----|-----|-----|-------|---------|---------|---------|---------|
| Fe           | 3.8 | 3   | 2.1 | 1.7   | 3.5     | 3.4     | 2.1     | 1.8     |
| Co           | 3.4 | 2.7 | 2.2 | 2.2   | 4       | 3.3     | 2.6     | 2.3     |
| Cr           | 4.5 | 4.2 | 3.4 | 2.6   | 4.8     | 4.4     | 3.4     | 2.7     |
| Ni           | 4.2 | 3.8 | 3   | 2.4   | 4.2     | 3.7     | 3       | 2.5     |
Figure 7 shows the engineering stress-strain curves of 18Ni300/CoCrNi multilayer composites under different conditions. The specific values are listed in Table 3. Figure 7(a) is a comparison of the tensile properties of 18Ni300/CoCrNi multilayer composites with different cold rolling reduction ratios. From the figure, we can see that the tensile strength of the composites with multiple layers continues to increase with an increasing cold rolling reduction ratio. When cold rolled to a thickness of 0.5 mm, the tensile strength of the multilayer composite material exceeds 2 GPa, which is mainly due to the ultrahigh strain hardening ability of the CoCrNi alloy. Herein, it is surprising that the multilayer composites that were cold rolled from 1 mm to 0.5 mm and the tensile strength significantly improved by approximately 700 MPa. On the one hand, the rise in tensile strength is due to refined crystalline strengthening. With an increase in the rolling reduction ratio, the grains in the 18Ni300 layer and CoCrNi layer are refined, the number of grain boundaries is gained, the ability to hinder dislocation movement is enhanced [23], and the strength of the multilayer composites is improved. On the other hand, the improve in strength is due to work hardening. With an increase in the cold rolling reduction ratio, the number of high-density dislocations in the multilayer increases [24], which hinders the further deformation of multilayer composites and leads to an increase in the strength of multilayer composites. With the rise in the cold rolling reduction ratio, the elongation after fracture of the multilayer composites decreases visibly. Even a small cold rolling deformation (cr3) has a great influence on the elongation after fracture of multilayer composites. However, as the cold rolling deformation continues to rise, the decline rate of elongation after fracture decreases.

![Figure 7](image-url) Tensile stress-strain curves of 18Ni300/CoCrNi multilayer composites. (a) cold rolling; (b) ageing treatment.

![Figure 8](image-url) SEM mapping of tensile fracture of 18Ni300/CoCrNi multilayer composites with different cold-rolled reduction ratios. (a)–(b) cr3; (c)–(d) cr2; (e)–(f) cr1; (g)–(h) cr0.5.

Table 3. Tensile properties of 18Ni300/CoCrNi multilayer composites.

|                | ht  | cr3 | cr2 | cr1 | cr0.5 | age  | cr3 age | cr2 age | cr1 age | cr0.5 age |
|----------------|-----|-----|-----|-----|-------|------|---------|---------|---------|----------|
| $\sigma_s$ (MPa) | 594 | 883 | 1108| 1307| 1892  | 1036 | 1364    | 1685    | 1732    | 2696     |
| $\sigma$ (MPa)  | 857 | 976 | 1203| 1340| 2027  | 1255 | 1498    | 1781    | 1924    | 2827     |
| $\delta$ (Percent) | 30.4| 13.4| 10.5| 8.6 | 7     | 24.3 | 11.9    | 8.1     | 5.5     | 4.5      |
which may be related to the decrease in dislocation sources caused by dislocation chocking in the CoCrNi layer, which weakens its strain hardening ability. Figure 7(b) shows the stress-strain curve of the 18Ni300/CoCrNi multilayer composite after ageing treatment. After ageing treatment, the tensile strength of cold-rolled to 0.5 mm multilayer composite exceeds 2.8 Some studies have shown that an ageing treatment at this temperature has little effect on the strain hardening of cold rolled maraging steel [22]. The high-density dislocation interaction caused them to stack and intertwine, which seriously hindered dislocation movement. At the same time, the high-density dislocations improved the nucleation centre density and diffusivity of precipitated nucleating elements in maraging steel and promoted the precipitation of the $\eta$-Ni$_3$Ti phase. These precipitated phases nucleate preferentially on the screw dislocation line. By increasing the dislocation density, the dispersion of precipitated phases during the ageing process can be improved, which provides more nucleation points for precipitation strengthening in the ageing process and achieves a strengthening effect.

3.3. Fracture characteristics

Figure 8 shows the tensile fracture characteristics of the 18Ni300/CoCrNi multilayer composite with different cold rolling reduction ratios. Figures 8(a)–(b) is a 25% (cr3) fracture photo of the cold rolling reduction ratio. When the cold rolling reduction ratio is low, both the 18Ni300 layer and the CoCrNi layer are distributed with many small dimples. The greater the distance from the interface, the larger the size of the dimples, which belong to ductile fracture; the pores are flat, and there are many stratification cracks at the interface. With a further rise in the cold rolling reduction ratio (50%), the cracks at the interface do not easily propagate along the interface to form continuous stratification cracks due to the influence of the rolling force, as shown in figures 8(c)–(d). When the cold rolling reduction ratio is increased to 75% (cr1), the interlamination materials are distributed in steps, the holes disappear, and only a few of the harder oxides are present near the interlayer material and interface, as shown in figures 8(e)–(f). After cold rolling to 0.5 mm, the interface combination of the two layers becomes optimal, and there are almost no delamination cracks, as shown in figures 8(g)–(h). Cold rolling
reduces the content of intermetallic inclusions and pores around the interface and makes it difficult for cracks to form at the interface, thus improving the bonding strength of the interface. Figure 9 shows SEM mapping of the tensile fracture of the 18Ni300/CoCrNi multilayer composites with ageing treatment. It can be seen from the figure that the difference of the number of stratification cracks between cr1 age and cr0.5 age is significantly less than that of cr3 age compared with cr2 age, which can be used to explain why the ratio of elongation decline slows down with the rise of the cold rolling reduction ratio. With increasing rolling force, the bonding strength of the interface is improved. In the tensile process, the ductile layer inhibits the propagation of cracks in the hard layer and delays the fracture of multilayer composites.

3.4. Strengthening mechanism of 18Ni300/CoCrNi multilayer composites by cold rolling deformation and ageing

Figure 10(a) shows the XRD patterns of multilayer composites with different cold rolling reduction ratios. Since no other diffraction peaks were detected after 60°, the only diffraction peaks observed were in the range of 40° ~ 60°. With an increase in the cold rolling reduction ratio, the intensity of the (111)γ and (200)γ diffraction peaks representing the FCC structure of the CoCrNi alloy gradually decreases. With an increase in the cold rolling reduction ratio, the full-width half-maximum gradually increases. According to Scherrer’s formula:

\[ D = \frac{K\lambda}{B\cos\theta} \]

where K is the Scherrer constant, D is the average thickness of the grain perpendicular to the crystal plane, B is the full-width half-maximum of the measured sample, θ is the diffraction angle, and λ is the x-ray wavelength [25].

It can be predicted that the full-width half-maximum will be larger and the grain size will be smaller, indicating that the inner grain size of the CoCrNi layer is refined after cold rolling. Meanwhile, the increase in dislocation density in martensitic steel is also conducive to the precipitation of a more dispersed Ni3Ti phase during ageing. Figure 10(b) shows the XRD patterns of the 18Ni300/CoCrNi multilayer composites after ageing treatment. Compared with the hot-rolled CoCrNi alloy, the (111)γ peak strength increased obviously after ageing, which may be due to the recovery of the CoCrNi alloy, resulting in a decrease in the number of residual stresses and defects.

4. Conclusions

In this paper, the interface shape and tensile properties of 18Ni300/CoCrNi multilayer composites with different cold rolling deformations and ageing treatments were studied. The results showed that:

With an increase in the cold rolling reduction ratio, the layer thickness and transition layer thickness gradually decrease, and the interface oxide decreases; simultaneously, the interface shape changes from a flat state to a wave-like state, leading to severe localized necking of CoCrNi layer. The tensile strength increases with an increasing cold rolling reduction ratio. When the cold rolling reaches 0.5 mm, the tensile strength of the material exceeds 2 GPa, and the elongation remains at approximately 7% under the strengthening effect of work hardening and grain refinement. Ageing treatment can effectively improve the tensile strength of multilayer composites by ageing precipitate strengthening. The tensile strength of the 18Ni300/CoCrNi multilayer composite improves from 2027 MPa to 2825 MPa after ageing treatment.

Acknowledgments

This work is supported financially by the National Natural Science Foundation of China (NSFC) under grant no. 51701061, the Joint Fund for Steel Research of the National Natural Science Foundation of China and Baowu Steel Group Corporation Limited (no. U1860114), the Foundation Strengthening Program (no.2019-JCJQ-142), and the National Natural Science Foundation of China (no. 51705129).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID iDs

Baoxi Liu https://orcid.org/0000-0001-5370-7497
Cuixin Chen https://orcid.org/0000-0001-5418-9441
Weibing Guo https://orcid.org/0000-0002-1634-7557
Kailun Liu https://orcid.org/0000-0002-6896-2471

References

[1] Syn C K, Sherby O D, Wadsworth J and Lewandowski J J 1996 Mechanical behaviour of laminated metal composites Int. Mater. Rev. 41 169–97
[2] Sherby O D 1999 Ultrahigh carbon steels, damascene steels and ancient blacksmith ISIJ Int. 39 637–48
[3] Jeffrey W and Donald R L 2006 Ancient and modern laminated composites — from the great pyramid of gizeh to Y2K Mater. Charact. 45 289–313
[4] Pozuelo M, Carreno F and Ruano O A 2006 Delamination effect on the impact toughness of an ultrahigh carbon–mild steel laminate composite Compos. Sci. Technol. 66 2671–6
[5] Oya T, Tiesler N and Kawanishi S 2010 Experimental and numerical analysis of multilayered steel sheets upon bending J. Mater. Process. Technol. 210 1926–33
[6] Hao Q, Zhang M D, Huang C X, Xiao S Y, Han D and Weng Y Q 2017 Ultrahigh Charpy impact tenacity (~450 J) achieved in high strength ferrite/martensite laminated steels Sci Rep. 7 41459
[7] Hsia J K, Suo Z and Yang W 1994 Cleavage due to dislocation confinement in layered materials J. Mech. & Phys. Solids 42 877–96
[8] Kosič T, Iwoue J and Nambu S 2014 Development of multilayer steels for improved combinations of high strength and high ductility Mater. Trans. 55 5227–37
[9] Seok M Y et al 2016 Decoupling the contributions of constituent layers to the strength and ductility of a multi-layered steel Acta Mater. 121 164–72
[10] Liu B X et al 2020 A new route to fabricate multiple laminated steel with multiscale hierarchical structure Mater. Charact. 169 110606
[11] Deng H W et al 2019 Tailoring mechanical properties of a CoCrNi medium-entropy alloy by controlling nanotwin-HCP lamellae and annealing twins Mater. Sci. Eng. A 774 241–6
[12] Praveen S, Bae J W, Asghari-Rad P, Park J M and Kim H S 2018 Annealing-induced-hardening in high-pressure torsion processed CoCrNi medium entropy alloy Mater. Sci. Eng. A 734 338–40
[13] Sathiyamoorthi P, Asghari-Rad P, Bae J W and Kim H S 2019 Fine tuning of tensile properties in CrCoNi medium entropy alloy through cold rolling and annealing Int. J 113 106578
[14] Du X H et al 2020 Dual heterogeneous structures lead to ultrahigh strength and uniform ductility in a co-Cr-Ni medium-entropy Alloy Nat. Commun. 11 2390
[15] Yu W X et al 2018 Revealing extraordinary strength and toughness of multilayer TWIP/ Maraging steels Mater. Sci. Eng. 727 70–7
[16] Choi E, Ostadrahimi A and Park J 2020 On mechanical properties of NiTi SMA wires prestrained by cold rolling Smart Mater. Struct. 29 065009
[17] Liu B X et al 2020 Deformation behavior and strengthening mechanisms of multilayer SUS304/ Cr17 steels with laminate /network interface Metall Mater. Trans. A 51 3658–73
[18] Gao K et al 2019 The deformation characterization, fracture behavior and strengthening–toughening mechanisms of laminated metal composites: a review Met—Open Access Metall. 10 4
[19] Yu H et al 2014 A deformation mechanism of hard metal surrounded by soft metal during roll forming Sci. Rep. 4 5017
[20] Reihanian M and Nasiri M 2015 An analytical approach for necking and fracture of the hard layer during accumulative roll bonding (ARB) of the metallic multilayer Mater. Des. 89 1213–22
[21] Chen C X et al 2021 Multilayer maraging/CoCrNi composites with synergistic strengthening–toughening behavior Front in Mater 7 619315
[22] Yong L et al 2017 Effects of cold rolling on the microstructure and properties of Fe-Cr-Ni-Mo-Ti maraging steel Mater. Sci. Eng. A 712 663–70
[23] Hayashi T et al 2009 Microstructure evolutions at severely-deformed austenite/martensite interfaces of a layer-integrated steel ISIJ Inter. 49 1406–13
[24] Li L et al 2010 Characteristics of the cold-rolling texture in a multi-layered material composed of SUS301 and SUS420J2 Steels Mater. Trans., JIM 51 911–7
[25] Li W et al 2020 Amperometric H2S sensor based on a Pt-Ni alloy electrode and a proton conducting membrane Sens Actuators B Chem 311 127900