Analysis of failures encountered during rolling of rings of maraging steel

Analyse des Versagens von martensitaushärtenden Stahlringen durch Walzen

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Large-sized rings of maraging steel X 2 NiCoMo 18 8 5 (Werkstoff Nr. 1.6359) find application in aerospace. The rings are required to demonstrate high strength and fracture toughness in both radial and axial directions. The processing is accordingly carried out under controlled conditions to realize a microstructure capable of attaining the specified strength and toughness after heat treatment. The rings rolled during initial trials failed to attain the required fracture toughness. Precipitation of carbonitrides at prior austenitic grain (PAG) boundaries in the temperature range 820 – 980 °C contributed to the failure. Efforts were made to do final rolling through this temperature range, to prevent a microstructure comprising of PAG boundaries decorated by carbonitrides from evolving. To this end relatively low preheating temperatures (1100 – 1150 °C) were adopted. Failures were encountered in realizing the desired final size and shape of the rings. The mill tripped before the ring rolling could be completed. Failure was analyzed and it was concluded that the problem was due to the high flow stress levels encountered during ring rolling and the relatively low radial loads the mill was capable of delivering.

Keywords: Maraging steel, Ring rolling, Embrittlement, Flow stress, Temperature, Strain rate, Strain

Ringe aus martensitaushärtendem Stahl X 2 NiCoMo 18 8 5 (Werkstoff Nr. 1.6359) mit großen Abmessungen werden in der Raumfahrt eingesetzt. Es ist notwendig, dass die Ringe hohe Festigkeit und Bruchzähigkeit aufweisen, und zwar in beiden Richtungen - radial und tangential. Die Bearbeitung wird dementsprechend unter kontrollierten Bedingungen durchgeführt, um ein optimales Mikrogefüge zu realisieren und die spezifizierte Festigkeit und Zähigkeit nach der Wärmebehandlung erreichen zu können. Die Ringe, die bei den anfänglichen Versuchen gewalzt wurden, konnten die geforderte Bruchzähigkeit nicht aufweisen. Ausscheidung von Karbonitriden auf den Voraustenitkorngrenzen in dem Temperaturbereich 820 – 980 °C trug zum Versagen bei. Es wurde versucht, das letzte Walzen durch diesen Temperaturbereich durchzuführen, um die Entstehung eines Mikrogefüges, bei dem die Karbonitride die Korngrenzen besetzen, zu vermeiden. Um das zu leisten, wurden relative niedrige Vorheiztemperaturen adaptiert. Allerdings ist es nicht gelungen, die gewünschte Gestalt und Größe der Ringe zu realisieren. Bevor das Ringwalzen vollendet werden konnte, hatte sich das Walzwerk ausgeschaltet. Der Fehlschlag wurde analysiert. Man kam zu der Schlussfolgerung, dass das Problem mit dem Folgenden zu tun hatte: die hohen Fliessspannungsniveaus, denen während des Ringwalzens begegnet wurde und die relativ niedrigen radiale Kräfte, die das Walzwerk liefern konnte.

Schlüsselworte: Martensitaushärtender-Stahl, Ringwalzen, Versprödung, Fließspannung, Temperatur, Dehngeschwindigkeit, Dehnung

1 Introduction

Large sized rings of maraging steel X 2 NiCoMo 18 8 5 (Werkstoff Nr. 1.6359) are required for fabrication of satellite launch vehicles. The rings have an outside diameter reaching up to 3 m, wall thickness in the range 60 – 120 mm and height 150 – 320 mm. The rings are required to be produced to high levels of both strength and toughness in longitudinal as well as axial direction. It is hence necessary to process the rings under controlled conditions to realize a microstructure which is capable of attaining the specified strength and toughness after the final heat treatment comprising of solution treatment and aging.

Rings rolled during initial trials failed to meet the specified mechanical properties, particularly the fracture toughness (K_{Ic}) requirement. Microstructural examination of the rolled rings revealed that the prior austenitic grains (PAGs) were somewhat elongated in the tangential direction and the PAG boundaries were decorated with carbonitride particles. It was concluded that thermal embrittlement occurred resulting in the K_{Ic} falling short of the required minimum.

Efforts were then made to carry out the final part of the rolling through the thermal embrittlement range, aiming to prevent a microstructure comprising of PAG boundaries decorated with carbonitride particles from evolving. However the efforts did not meet with success with mill tripping before the rolling operation got completed. A study / analysis of the failure was carried out and the paper presents details of the study and the findings.

2 Material

The rings were made of DIN grade X 2 NiCoMo 18 8 5 (Werkstoff Nr. 1.6359) (Fe-18.5 %Ni-7.5 %Co-4.8 %Mo-0.4 %Ti) maraging steel. It belongs to the family of carbon-free 18 % Ni maraging steels with 0.2 % yield strength level of 1700 MPa after the final heat treatment. The material is produced in the form of large rings, the conversion from ingot taking place by hot working comprising of hot forging in a high capacity press and rolling on ring rolling mills. The dimensions of three important types of rings in the as-rolled con-

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Table 1. Dimensions of as-rolled rings (mm)
Tabelle 1. Abmessungen der Ringe (mm) im gewalzten Zustand

Ring type	Outside diameter	Inside diameter	Height
X	2850	2660	350
Y	2885	2685	240
Z	2050	1750	180

dition are given in Table 1. The minimum specified values for UTS, 0.2% PS and K_{Ic} were 1765 MPa, 1725 MPa and 90 MPa$\sqrt{m}$ respectively in both longitudinal and transverse directions. Samples are drawn from test rings parted from the rolled and heat-treated rings in both tangential and radial direction and tested for strength and K_{Ic}: The final heat-treatment given to the rolled rings comprises of (i) solution treatment at 820 °C followed by air cooling or water quenching and (ii) aging at 480 °C for 3 to 4 hours. Additional austenitising treatments are now given preceding the 820 °C solution treatment to improve the mechanical properties of the rings [1].

3 Experiments and results

The initial batches of rings (campaign A) were produced by pre-heating the starting stock to 1200/1250 °C, soaking at this temperature followed by ring rolling. The rolling mill had a capacity of 350 MT in the radial direction and 260 MT in the axial direction. The effort was to give a high reduction (~ 50%) in the last pass to get a well worked, fine grained micro structure after rolling. It was noticed that the radial forces exerted by the mill approach the rated capacity of the mill during rolling, and in fact for rolling of the X type ring, the maximum force available from the mill had to be used to complete the rolling. Rings were air-cooled after rolling and subjected to a final heat-treatment comprising of solution treatment at 820 °C followed by aging for 3 to 4 hours at 480 °C. Evaluation of the mechanical properties of the rings was carried out in both tangential and radial directions. It was found that the K_{Ic} values were lower than the specified minimum of 90 MPa$\sqrt{m}$. K_{Ic} values in the tangential direction were particularly low, typically in the range 75–80 MPa$\sqrt{m}$. K_{Ic} values in the radial direction were generally in the range 80–85 MPa$\sqrt{m}$.

Microstructural examination of the rolled rings revealed a somewhat elongated grain structure elongation being in the tangential/circumferential direction. There was no evidence of recrystallisation and PAG boundaries were found decorated with carbonitride particles. *Figure 1* gives the scanning electron micrograph of fracture surface of the material. It is a predominantly intergranular failure. Secondary cracks running along grain boundaries can also be seen.

Efforts were made in campaign B to suppress the carbonitride precipitation by water quenching the rings immediately after ring rolling (in place of air cooling in campaign A). There was an improvement in the K_{Ic}, the minimum value now obtained being 80 MPa$\sqrt{m}$, but this was not enough to meet the customer's specification.

It was believed that the decoration of grain boundaries with carbonitride particles was responsible for the observed low K_{Ic} values. An attempt was made in the subsequent campaign (campaign C) to carry out hot working through the temperature range for precipitation of carbonitrides. The aim was to prevent a microstructure of PAG boundaries decorated with carbonitride particles from evolving. *Figure 2* shows schematically the proposed hot working schedule. It was taken note that rings of low alloy steels of similar size were rolled by using pre-heating temperatures in the range 1100–1150 °C. Zechmeister et al., [2] showed that K_{Ic} of maraging steel embrittled by grain boundary precipitation of titanium carbonitrides can be considerably improved by a sufficiently high amount of hot forming in the temperature range in which thermal embrittlement occurs. By destroying the grain boundary network of carbonitrides, the hot working contributes to improvement in $K_{Ic.}$ This study thus supported the usefulness of hot working through the carbonitride precipitation range to keep embrittlement at bay. It was also believed that a low finishing temperature was conducive to realizing a fine grain size/refined microstructure in the rings. To this end a relatively low pre-heating temperature was adopted (1100–1150 °C as opposed to 1200–1250 °C adopted for campaigns

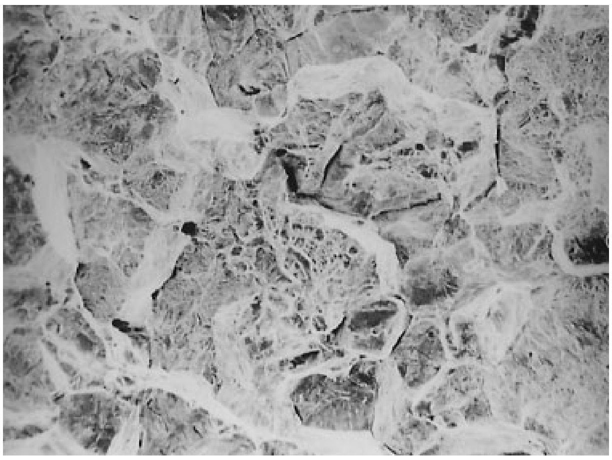

Fig. 1. Scanning electron fractograph of a broken test specimen with a relatively low fracture toughness (75–80 MPa$\sqrt{m}$) (Magnification x150)

Abb. 1. Rasterelektronenbruchbild einer gebrochenen Probe mit relativ niedriger Bruchzähigkeit (75–80 MPa$\sqrt{m}$)

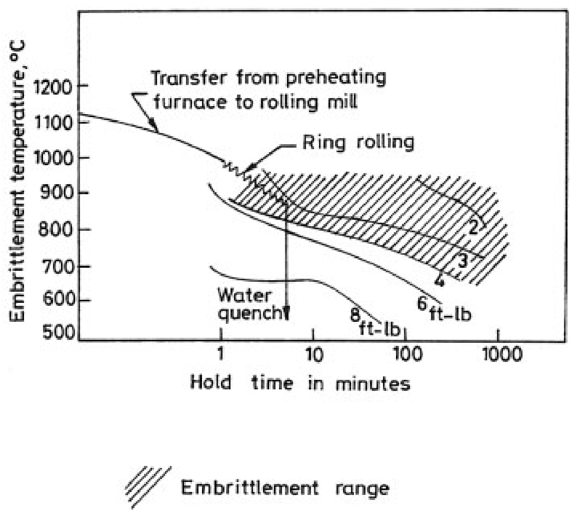

Fig. 2. Proposed hot working schedule (schematic)

Abb. 2. Der vorgeschlagene Plan für die Heißbearbeitung

Fig. 3. Scanning electron fractograph of a broken test specimen with a relatively high fracture toughness (95 – 102 MPa$\sqrt{m}$) (Magnification x150)

Abb. 3. Rasterelektronenbruchbild einer gebrochenen Probe mit relativ hoher Bruchzähigkeit (95 – 102 MPa$\sqrt{m}$)

A&B). However failures were encountered in realizing the desired final size and shape of the rings. The mill tripped before ring rolling could be completed. The incompletely rolled rings had often non-uniform wall thickness, non-rectangular cross section and considerable distortion / ovality was noticed.

With failure in campaign C, the pre-heating temperatures for the stock were revised upward to 1200/1250 °C for the next campaign (D). This lead to satisfactory completion of the ring rolling operations in that the aimed final dimensions of the rings were realized with acceptable levels of distortion / ovality. However consistently high fracture toughness values could be obtained only after resorting to a two- or three-stage solution treatment following the hot working operation [1]. *Figure 3* shows the scanning electron micrograph of fracture surface of broken test specimen cut from test ring drawn from X type ring after three stage solution treatment. It can be seen that the fracture is transcrystalline. The fracture toughness values were in the range 95 – 102 MPa$\sqrt{m}$.

4 Discussion

Failures to realize the required K_{Ic} in the campaigns A&B were related to grain boundary precipitation of carbonitrides. The grains were elongated in the circumferential / tangential direction and the 820 °C treatment was not effective in causing recrystallisation of the elongated grain structure. The PAG boundaries aligned in the tangential direction and decorated with carbonitride particles thus provided easy crack propagation paths when K_{Ic} was tested in the tangential direction. The rings after hot-rolling were allowed to cool through the embrittlement range (980 – 820°C) and the well studied phenomenon of thermal embrittlement in maraging steel leads to preferential precipitation of carbonitride particles at the PAG boundaries. Poor K_{Ic} values in the tangential direction were the consequence.

The flow stress of maraging steels is highly sensitive to the processing parameters. Avadhani [3, 4] carried out detailed studies, among others, on the functional dependence of flow stress of maraging steel grade X 2 NiCoMo 18 8 5 and 0.3C CrMoV steel on the temperature, strain rate and

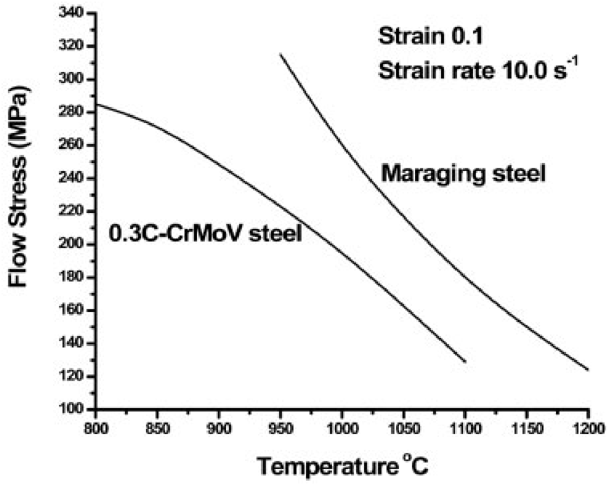

Fig. 4. Variation of flow stress of maraging steel and 0.3C-CrMoV (ESR) steel with temperature at a high strain rate

Abb. 4. Änderung der Fließspannung des martensitanshärtenden Stahls und 0.3C-CrMoV (ESR) Stahls als Funktion der Temperatur bei einer hohen Dehngeschwindigkeit

strain. Figures 4 to 7 summarize the results obtained by him for the two steel grades on a comparative basis. *Figure 4* shows the variation of flow stress as a function of temperature at a strain level of 0.1 and a relatively high strain rate of 10.0/sec. The much faster increase in the flow stress of maraging steel with decreasing temperature in comparison to 0.3C CrMoV steel is obvious. *Figure 5* presents similar data except that it is generated at a relatively low strain rate of 0.1/sec. *Figure 6* shows the variation of flow stress with change in strain rate. The higher sensitivity of flow stress of maraging steel to strain rate compared to 0.3C CrMoV steel is seen from Fig. 6, flow stress of maraging steel increasing at a faster rate with increasing strain rate. During ring rolling strain rates increase with deformation and are generally high (1 – 20/sec). *Figure 7* shows the variation of flow stress with strain. In comparison to the flow stress of 0.3C CrMoV steel, the flow stress

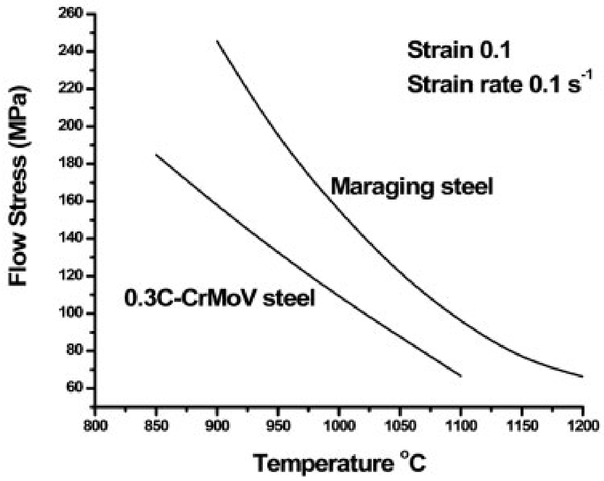

Fig. 5. Variation of flow stress of maraging steel and 0.3C-CrMoV (ESR) steel with temperature at a low strain rate

Abb. 5. Änderung der Fließspannung des martensitanshärtenden Stahls und 0.3C-CrMoV (ESR) Stahls als Funktion der Temperatur bei einer niedrigen Dehngeschwindigkeit

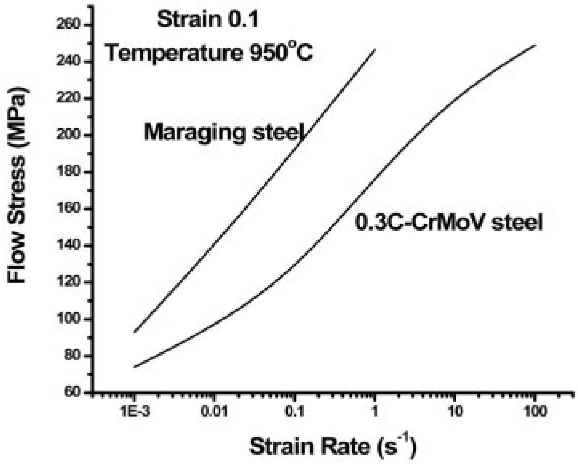

Fig. 6. Variation of flow stress of maraging steel and 0.3C-CrMoV (ESR) steel with strain rate

Abb. 6. Änderung der Fließspannung des martensitanshärtenden Stahls und 0.3C-CrMoV(ESR) Stahls als Funktion der Dehngeschwindigkeit

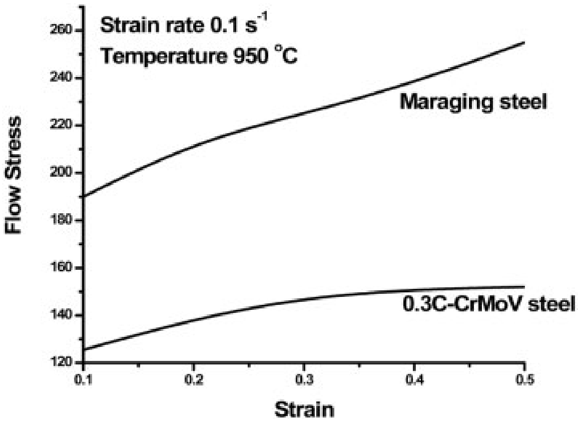

Fig. 7. Variation of flow stress of maraging steel and 0.3C-CrMoV (ESR) steel with strain

Abb. 7. Änderung der Fließspannung des martensitanshärtenden Stahls und 0.3C-CrMoV(ESR) Stahls als Funktion der Dehnung

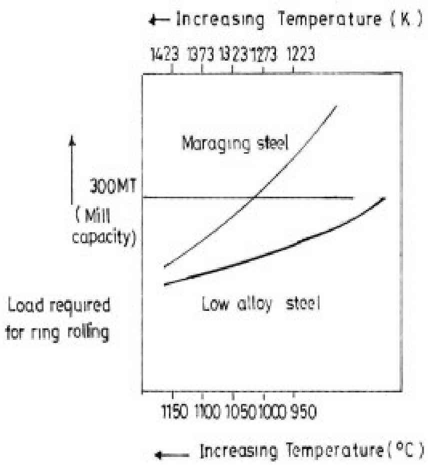

Fig. 8. High flow stress of maraging steel at relatively low rolling temperatures resulting in mill overloading.

Abb. 8. Hohe Fließspannung des martensitanshärtenden Stahls bei relativ niedrigen Temperaturen hatte eine Überlastung des Walzwerks zur Folge

of maraging steel shows higher rate of increase with strain up to 0.5 strain.

It follows that the reduced temperature adopted for hot working taken together with relatively high strain rates prevalent during ring rolling and the relatively high strains attempted contributed to large increase in flow stress of maraging steel. Even when rolling was done with pre-heating in the range 1200 to 1250 ºC, mill had to exert forces at its maximum rated level in the radial direction; with preheating in the range 1100 to 1150 ºC, the large increase in the flow stress of the steel has pushed up the tonnage required for rolling beyond the capacity of the mill. Consequently the mill stalled and rolling got interrupted. This is illustrated schematically in *Figure 8*.

It was possible to roll low alloy steel rings of similar size after pre-heating at 1100–1150ºC, not only because of their relatively low flow stress at the rolling temperature but also because their flow stress is much less sensitive to variations in rolling temperature, strain rate and strain.

5 Summary

Large rings of maraging steel X 2 NiCoMo 18 8 5 (Werkstoff Nr. 1.6359) find application in aerospace. For this application the rings should demonstrate high strength and fracture toughness in both radial and axial directions. The rings rolled initially failed to attain the required fracture toughness. Precipitation of carbonitrides at prior austenitic grain boundaries in the temperature range 820–980 ºC led to the failure by causing thermal embrittlement.

Ring rolling was then attempted aiming to deform the steel through the thermal embrittlement range and thus prevent decoration of grain boundaries with carbonitrides. In the process, however, the mill got stalled and the ring rolling operation could not be completed.

The problem was traced to the high flow stress levels occurring during rolling and the relatively low mill capacity in the radial direction. There is a strong functional dependence of flow stress of maraging steel on temperature. Consequently attempt to roll with preheating at reduced temperatures resulted in the material offering too high a resistance to deformation, leading to stalling of the mill. The high strain rate sensitivity of flow stress of maraging steel is also a relevant factor, considering that ring rolling involves relatively high strain rates. The fast increase of flow stress of maraging steel with increasing strain also contributed to the problem, as relatively high strains were attempted during ring rolling.

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